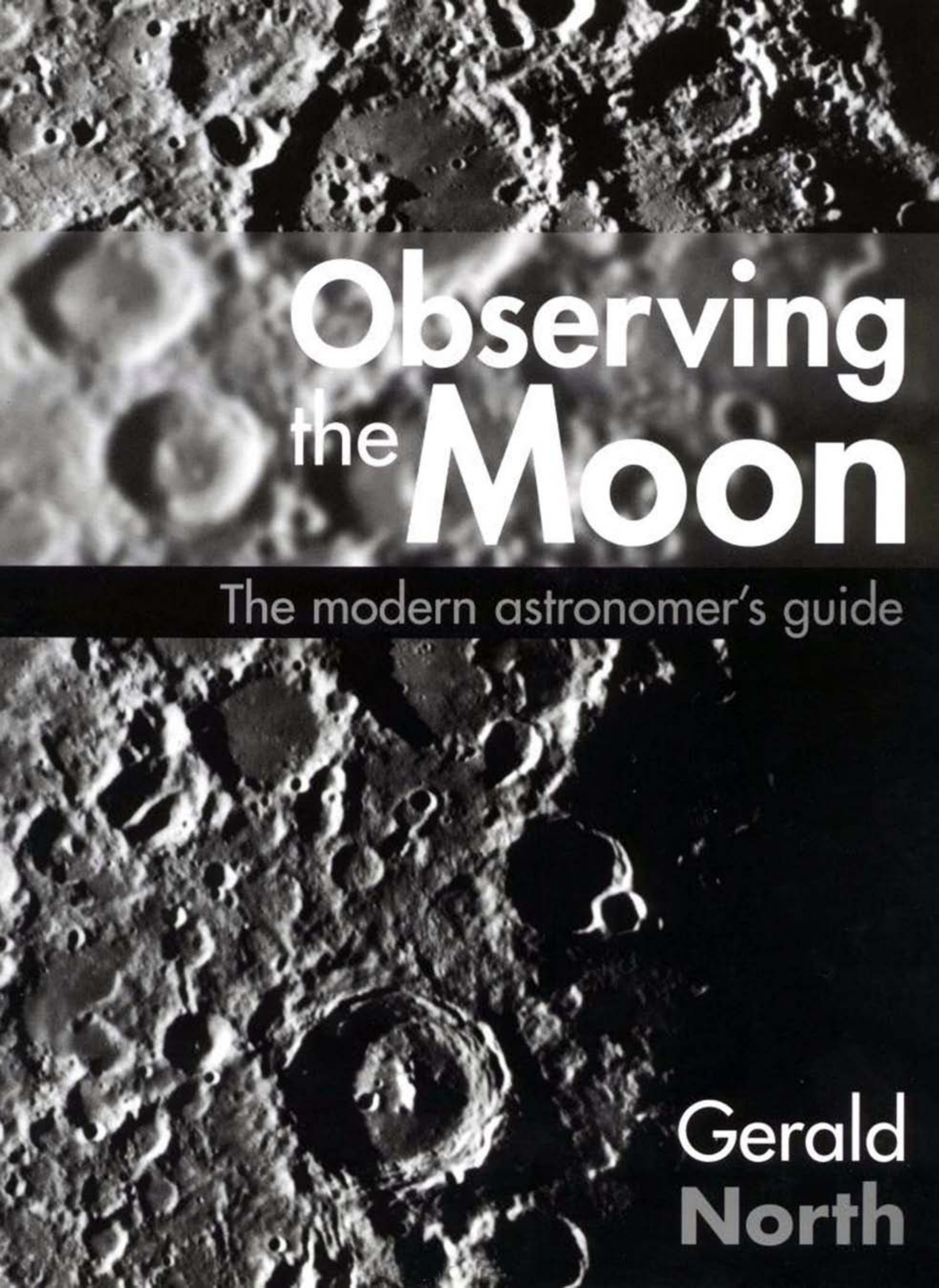

Observing the Moon

The modern astronomer's guide

Gerald North

Written by an experienced and well-known lunar observer, this is a 'hands-on' primer for the aspiring observer of the Moon. Whether you are a novice or are already experienced in practical astronomy you will find plenty in this book to help you 'raise your game' to the next level and beyond. The author provides extensive practical advice and sophisticated background knowledge of the Moon and of lunar observation. The selection/construction of equipment and optimizing of existing equipment for such projects as drawing, photographing and CCD imaging of the Moon are covered, together with analysis and computer processing of images, and much, much, more.

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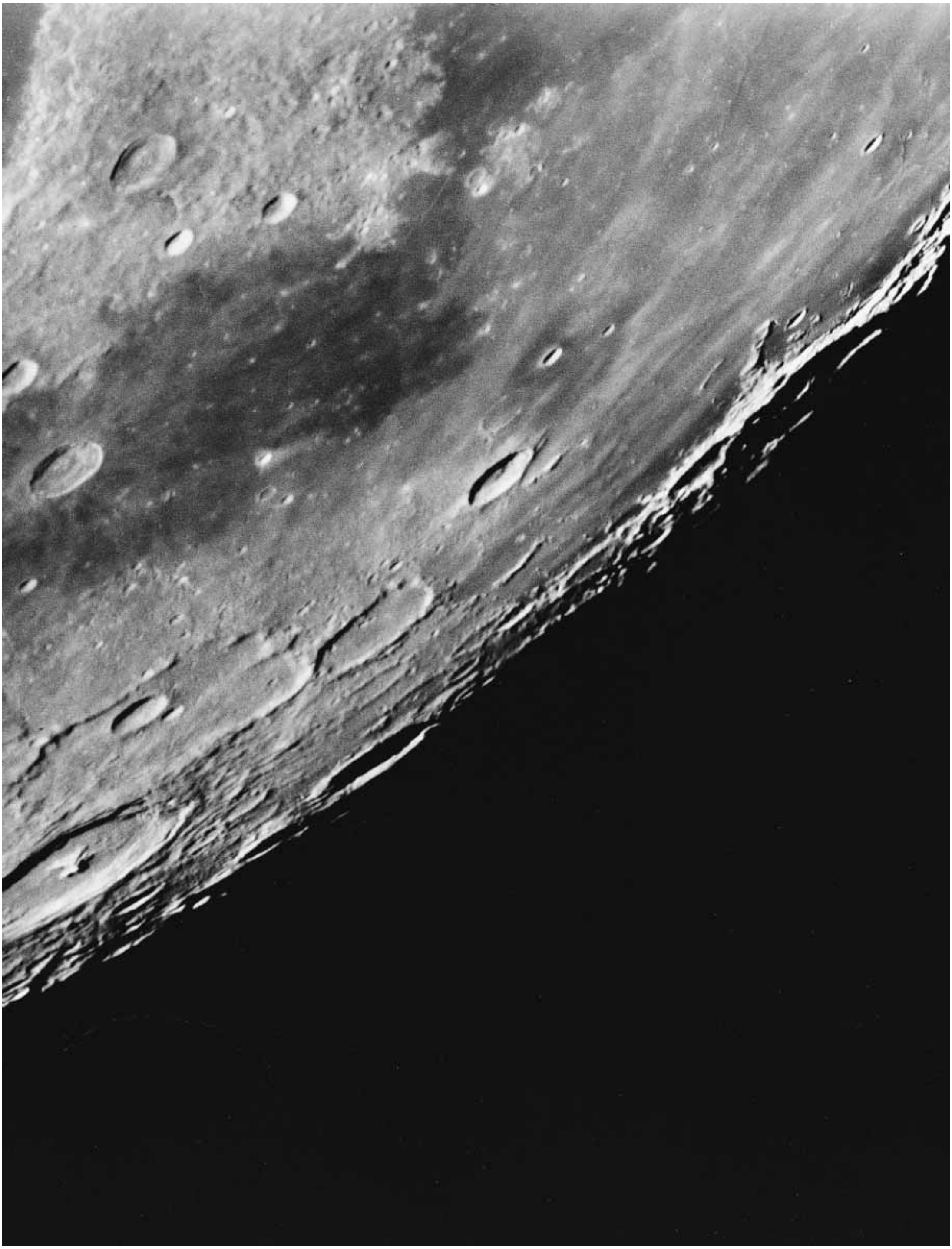
Learn what scientists have discovered about our Moon and what mysteries remain still to be solved. Find out how you can take part in the efforts to solve these mysteries, as well as enjoying the Moon's spectacular magnificence for yourself!

GERALD NORTH graduated in physics and astronomy. A former teacher and college lecturer, he is now a freelance astronomer and author. A long-term member of the British Astronomical Association, he has served in several posts in their Lunar Section. His books include the acclaimed *Advanced Amateur Astronomy*, which has become a classic guide for astronomers wishing to raise their observing to the next level.



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GERALD NORTH BSc

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PREFACE

Interest in the Moon periodically ebbs and flows, like the tides it causes in our oceans. The years leading up to the *Apollo* manned landings marked a particularly high tide. Since then there has been a very deep low tide – but the tide is turning once again. Recently we have had the *Clementine* and *Lunar Prospector* probes and professional studies of the Moon are on the increase. It is not unreasonable to expect that within the next two or three decades people will be walking once again on the eerie lunar surface. When it does happen we will be back to stay this time.

We already know a great deal about our Moon but many mysteries remain. A few of these mysteries might be solved by the modern-day backyard observer. Nonetheless, there are many other motives for the amateur devoting time and energy to study the Moon, or any of the other celestial bodies, through his/her telescope, aside from any wish to do cutting-edge science. I will not waste space listing the other possible motives here. All that really matters is that you, the reader of this book, have an interest in the Moon which you wish to explore. If so, then this is the book for you!

I intend this book to be a 'primer', a guide for the interested amateur astronomer who is yet to become a lunar specialist. Of course I have provided details about practical matters, such as equipment and techniques, but I have also included a limited amount of the history of the study of the Moon and, particularly, of lunar science. Without the science (and to a less important extent, the history) the subject would be sterile and any practical work beyond simple sight-seeing would be pointless.

To 'shoehorn' everything I needed to say into the book-length available has not been easy. The facts of commercial life apply to books as to any other commodity. This book is highly illustrated and was expensive to produce because of this. To keep the cost to you from becoming astronomical in every sense of the word, I have had to keep its length to within very tight limits set by the publisher. Consequently, time and time again I have had to refer you, the reader, to other publications to expand on points that I had not room enough to adequately cover in this book.

However, that shortcoming is also a strength. As I said, this book is a 'primer'. It is certainly not intended to be the definitive history of lunar studies, nor of our scientific understanding of the Moon. I can't really say that it is the last word on practical techniques and equipment for the practising amateur astronomer, either. What I can claim for this book is that it contains enough working knowledge to give any tyro lunar observer a flying start. Beyond that, this book is intended to be a 'springboard' to further studies and practical work. Please do follow up the references I give. Go beyond that and seek further ones on your own. Your knowledge of the Moon and how it has been studied will expand beyond any limits set by the finite size of any one single-volume work.

I hope you like this book and find it interesting. Much more importantly, I hope that you discover for yourself the thrills of examining the Moon's mountains, craters and other surface structures through your telescope's eyepiece. Aside from the awesome spectacle of the views, you will find real fascination in understanding how the Moon got to be as it is.

Gerald North
Bexhill on Sea

ACKNOWLEDGEMENTS

I am very grateful to the following people for allowing me to reproduce examples of their work in this book: Terry Platt, Gordon Rogers, Tony Pacey, Nigel Longshaw, Andrew Johnson, Roy Bridge, Cmdr. Henry Hatfield, and Martin Mobberley. Special thanks are also due to Dr T. W. Rackham and Manchester University, England, to Professor E. A. Whitaker and the Lunar and Planetary Laboratory, University of Arizona, USA, and to the National Aeronautics & Space Administration (NASA) for allowing me to reproduce many of their excellent photographs. Full acknowledgements are given in the captions accompanying the illustrations within this book. In addition, Mr John Hill has freely given of his advice on matters involving computers and the Internet and has gone to considerable trouble to furnish me with materials. To all these people I am very deeply grateful.

Gerald North
Bexhill on Sea

CHAPTER 1

"Magnificent desolation"

No, not a still from a science-fiction movie but a real (*Apollo 17*) astronaut by the 'Station 6 Boulder' on the North Massif of the Moon's Taurus–Littrow Valley! The South Massif can be seen on the far side of the Valley. The *Apollo 17* mission in December 1972 was the last manned expedition to the Moon's airless surface. (NASA photograph.)

Feverishly excited, I sat cross-legged in front of the family television set and watched the fuzzy, indistinct, shapes of Neil Armstrong and Buzz Aldrin moving about amid the grey wash that was the surface of the Moon. The fact that the picture was of poor quality because it had been beamed back to Earth through a quarter of a million miles of space did little to dampen my enthusiasm. I could also make out part of the spidery form of their space vehicle extending from the grey wash into the black stripe that represented the airless sky over the Moon. The sound quality was also poor. The words of those first men on the Moon sounded crackly and wheezy and so were often difficult to decipher. Nonetheless I listened hard. I may well have been a mere boy at the time but my sense of the significance of what I was witnessing was intense. I heard Neil Armstrong's words before he stepped onto the lunar soil. I heard Buzz Aldrin describe the scenery around him as "magnificent desolation". I wished I was there with them to see it.

I was born just after the beginning of what used to be called 'the Space Age'. As far back as I can remember I have been interested in things scientific and technical and have been infected with a particular passion for matters astronomical. I avidly read books about science and astronomy. By the time of that first Moon landing I had acquired an old pair of binoculars and had been bought a very small terrestrial telescope. Whenever I was allowed to go outside after dark I turned these humble instruments towards the Moon and gazed at the dark patches and the craters that they imperfectly revealed. The proper astronomical telescope I yearned for was at that time beyond my means.

It is difficult for those who were not around at the time to imagine the feverish excitement and air of expectation that gradually built up through the 1960s as the world's space agencies rapidly made the advances towards that first manned Moon landing. As well as a huge variety of merchandising such as books, booklets, posters, and kits to make plastic models of various rockets, television companies enthusiastically broadcast news items and informative programmes about the 'space race'. Our television screens were also awash with many science-fiction shows – *Doctor Who* and *Space Patrol* (called *Planet Patrol* in the USA) being particular favourites of mine – that featured space travel to other worlds. The fantasy shows reflected the public's yearning for real astronauts to travel through space and walk on real alien worlds. I very much shared that yearning.

The next few years brought further advances and more space missions. The pictures and sound got clearer. The Christmas of 1970 was significant for me in that my parents bought me a 'proper' astronomical telescope. It was a 3-inch (76 mm) Newtonian reflector. Yes, it was still smaller than the size of instrument recommended for useful work but I shall never forget the thrill of turning it to the Moon for the first time and seeing the large iron-grey lunar 'seas' and the rugged mountain ranges and magnificent craters come into sharp focus.

A few years were to pass before I was able to graduate to more powerful telescopes. I was to spend many hours 'learning my craft' at the eyepiece of that first 'proper' one. I didn't know it then but observing the Moon through telescopes was to become an important part of my life. After graduating in astronomy and physics, I was even to spend several years as a guest observer of the Royal Greenwich Observatory and so get to use professional telescopes to carry out, amongst other projects, lunar research.
I must have spent several thousands of hours of telescope time observing the Moon. You might have thought that I would be tired of it by now. Absolutely not! I hope to show you why not in the pages of this book. I hope that you, like me, will be thrilled anew every time you view the spectacle of our neighbouring world's "magnificent desolation".

1.1 AN ORBITING ROCK-BALL

Even today there are people (amazingly, even some in our western society) who are unaware of the Moon's true nature and status. I should hope that this does not apply to any of the readers of this book. However please let me, for completeness if for no other reason, state some of the basic facts. The Moon is a solid, rocky, body with an equatorial diameter of 3476 km. It orbits the Earth at a mean distance of 384 000 km. Though often appearing brilliant in the night sky, the Moon does not emit any light of its own generation. It shines purely by reflected sunlight (and a small amount of fluorescence caused by the re-radiation at visible wavelengths of invisible short-wave solar radiations and absorbed kinetic energy from solar-wind bombardment).

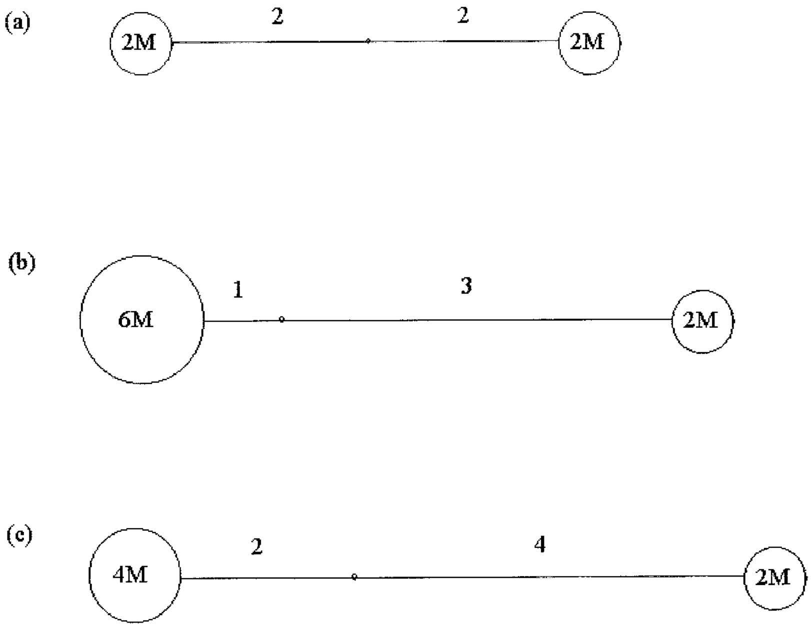


Figure 1.1 The positions of the barycentre for bodies of differing masses. The distances of each of the barycentres from the bodies are in the inverse ratios of their masses in each of these cases.

The Moon's diameter is over a quarter of that of the Earth (12 756 km for comparison) and this has led many to consider the Earth and Moon as a double-planet system, rather than as a true parent planet (the Earth) and attendant satellite (the Moon). Certainly the statement that "the Moon orbits the Earth" is an approximate one. In truth both orbit their *barycentre*, or common centre of mass. For two co-orbiting bodies of equal mass the centre of mass of the system lies exactly half-way between their centres (see Figure 1.1(a)). In the case of one body being more massive than the other, the barycentre is still in mid-space but is shifted towards the more massive body. In fact the ratio of the distances from each body to the barycentre is in the inverse ratio of their masses. This point is illustrated by Figure 1.1(b) and 1.1(c). In the case of the Earth and Moon, the Moon's mass is 7.35×10^{22} kg and that of the Earth is 5.98×10^{24} kg (81 times more massive). This results in the ratio of the distances from the centre of the Moon to the barycentre and from the centre of the Earth to the barycentre being 81:1. Put another way, the barycentre lies 1/82 of the way along a line joining the centre of the Earth to the centre of the Moon. 1/82 of 384 000 km is a little under 4700 km and so the barycentre lies inside the Earth's globe. The Earth may 'wobble' as the Moon orbits but the statement about the Moon orbiting the Earth is approximately true and I, at least, think that this fact qualifies the Moon as the Earth's satellite rather than them both being regarded as a double planet.

1.2 PHASES AND ECLIPSES

Nowadays most people are aware that the Sun acts as the central hub of our Solar System and that the planets orbit at various distances from it. I have detailed elsewhere the story of how the ancients came to realise this (*Astronomy Explained*, published by Springer–Verlag in 1997) but suffice it to say here that the researches of Copernicus and Galileo at the end of the sixteenth and beginning of the seventeenth centuries were pivotal. Of course, one body was **not** displaced from its location of orbiting the Earth, as the ancients had previously believed was the case for all the bodies of the Solar System: the Moon.

The Moon's *sidereal period*, the time it takes to complete one circuit of the Earth, is 27.3 days. At the beginning of the seventeenth century Johannes Kepler had determined that the orbits of the planets about the Sun were elliptical, rather than being circular in form as had been thought by Copernicus. The Moon's orbit is also elliptical. At the point of closest approach, *perigee*, the Moon's distance is 356 410 km. This increases to 406 679 km at *apogee*.

Figure 1.2 provides the usual elementary explanation of how the Moon's *phases* are produced over a complete cycle, or *lunation*. What the diagram does not reveal is why it is that the length of the cycle is not 27.3 days, the same as the sidereal period. The reason is that while the Moon is making its circuit of the Earth, the Earth itself is moving along its own orbit around the Sun. Hence the direction of the sunlight changes a little with time, instead of being fixed as implied in the diagram. Consequently, the Moon has to go a little further than one circuit round the Earth to go from one new Moon to the next. So, the length of a lunation, or *synodic period* is 29.5 days.

As well as the phases, *Earthshine*, often called "the old Moon in the New Moon's arms" is another commonly recognised phenomenon. Figure 1.3 shows it well. Most obvious to the naked eye when the Moon is little more than a thin crescent but seen more often with optical aid, this is caused by reflected light from the Earth shining on the Earth-facing part of the Moon experiencing night. Leonardo da Vinci is credited as being first to correctly explain this effect. In part, the Earthshine is easiest to see when the Moon's crescent is thin because there is not so much glare from the sunlit portion. Also, when the Moon appears as a crescent from the Earth, the Earth appears gibbous from the surface of the Moon. One could say that the apparent phase of the Earth as seen from the Moon is the opposite of that of the Moon seen from the Earth. So, when the Moon's crescent is thin the amount of reflected light from the Earth shining on the Moon is nearly at its maximum. Apart from the foregoing, the apparent brightness of the Earthshine also depends on the amount of cloud cover in the Earth's atmosphere (as seen from the surface of the Moon, the Earth would appear

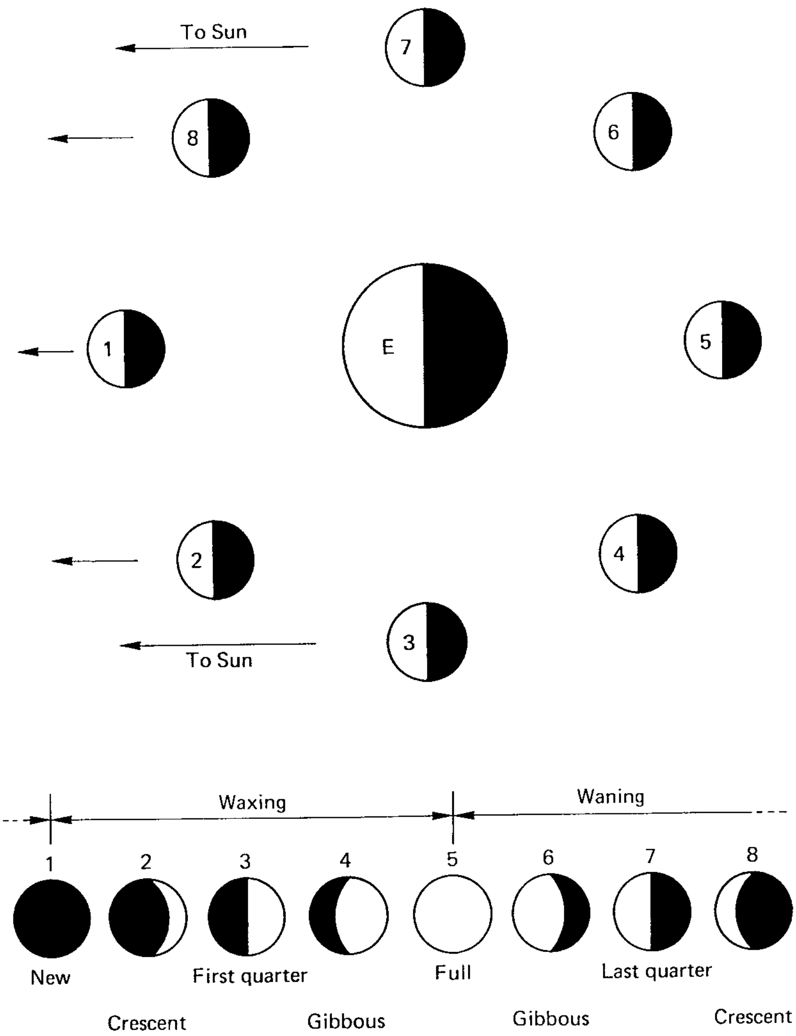


Figure 1.2 The phases of the Moon. The upper section of the diagram illustrates the Moon in various positions in its orbit, while the corresponding phases that we see from the surface of the Earth are shown in the lower section.

at its most brilliant when largely covered in highly reflective clouds). Finally, the observing conditions local to the observer also have an important bearing. Poor transparency and haze both inhibit the visibility of Earthshine, just as one would expect.

Another way that Figure 1.2 is inaccurate is in that it does not reveal the true three-dimensional relationship between the Earth, the Moon and the Sun. Realising that the Earth casts a huge cone-shaped shadow into space, one might imagine that every full Moon our satellite ought to pass into this shadow cone (see Figure 1.4). Of course such, *lunar eclipses* do occur but certainly not at the time of every full Moon. Neither do *solar eclipses* occur at

Figure 1.3 Earthshine. (a) Photographed by the author with an ordinary camera fitted with a 58 mm f/2 lens on *3M* Colourslide 1000 film.

every new Moon (Figure 1.5), even though the diagram might suggest that the Moon should pass exactly between the Sun and the Earth at these times. What the diagram does not show is that the plane of the Moon's orbit about the Earth is inclined slightly (actually by about 5°) to the plane of the Earth's orbit about the Sun.

Figure 1.3 (*cont.*)
(b) A close-up, photographed by Tony Pacey on 1993 March 26^{d} 19^{h} 35^{m} UT, using his 305 mm f/5.4 Newtonian reflector. The sunlit portion of the Moon is heavily overexposed in this 12 second exposure on *Ilford* FP4 film.

A useful concept in astronomy is that of the *celestial sphere*. In this the sky that surrounds the Earth is represented as the inner surface of a sphere, the Earth itself being a tiny dot at the centre of the sphere. All the stars, celestial bodies and the paths along which any of the celestial bodies appear to move can be shown as projections onto this imaginary sphere. Figure 1.6 shows such a celestial sphere on which is projected the monthly orbit of the Moon. Also shown is the yearly apparent path of the Sun across

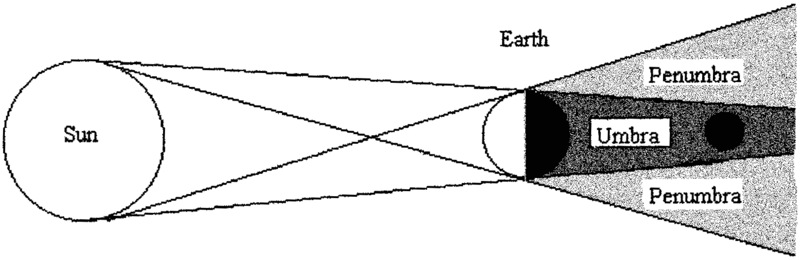


Figure 1.4 Lunar eclipses. With the Moon (black disk) in the position shown, a total lunar eclipse would be the result. This diagram is grossly out of scale for the sake of clarity.

the sky, which results from our orbit around the Sun (in effect the Sun appears to move once around the sky, through the constellations of the Zodiac, taking one year to complete one circuit). The Sun's annual path across the sky is known as the *ecliptic*.

The different inclinations of the Moon and Earth's orbital planes are reflected in the inclinations of the ecliptic and the Moon's path on the celestial sphere. Note how the Moon's path and the ecliptic cross at two diametrically opposite points on the celestial sphere. Where the Moon crosses the ecliptic going from north to south it is said to be at its *descending node*. Crossing south to north, it is then at its *ascending node*.

Notice how the only times the Moon and the Sun can appear exactly together in the sky (put another way, both be in the same direction as seen from Earth) are when both are at either the ascending node or both at the descending node at the same instant. Remembering that the condition for eclipses to occur is that the Earth, Sun and the Moon must simultaneously lie along the same straight line at the time of full Moon (for a lunar eclipse) or new Moon (for a solar eclipse), it is not hard to see why eclipses are relatively rare. For the vast majority of lunations new Moons occur with the Moon appearing just a little north or just a little south of the Sun in the sky. Similarly, the Moon manages to miss the Earth's shadow cone, passing either north or south of it, at the time of most full Moons.

The situation shown in Figure 1.4, very much out of scale for the sake of clarity, is that for a *total lunar eclipse*, where the Earth passes through the full shadow, or *umbra*. First the Moon enters the partial shadow, or *penumbra*. The dimming of the full Moon is only very slight at that time. As the Moon enters the umbra so a 'bite' begins to appear and the direct sunlight is progressively cut off. For a typical total lunar eclipse it will take about an hour for the Earth's shadow to completely sweep across the Moon's surface (see Figure 1.7). Then all the direct sunlight will be cut off. The only light reaching the surface of the Moon then is that refracted and scattered by the Earth's atmosphere. Usually the Moon then looks very strange, bathed as it then is by a copper-coloured glow. For an eclipse of maximum duration, *totality* lasts about an hour and then the umbral shadow leaves the Moon over the course of another hour, or so.

How much dimming there is, and the precise colourations seen, vary from eclipse to eclipse (and can even vary during the course of an eclipse). Also, the size of the Earth's umbral shadow can vary a little from eclipse to eclipse, so altering the precise timings and the durations of the eclipses. There is no mystery about these variations. They reflect the state of the Earth's atmosphere at the time of each of the eclipses.

Actually, it might be that for a particular eclipse the Moon is not close enough to its orbital node and may only partially enter the umbral shadow. In that case a *partial lunar eclipse* results. If the Moon misses the umbra altogether, the result is then termed a *penumbral eclipse,* though most casual observers will be hard-pressed to spot the very slight dimming that results. On average, about two lunar eclipses are visible each year from somewhere on the Earth's surface.

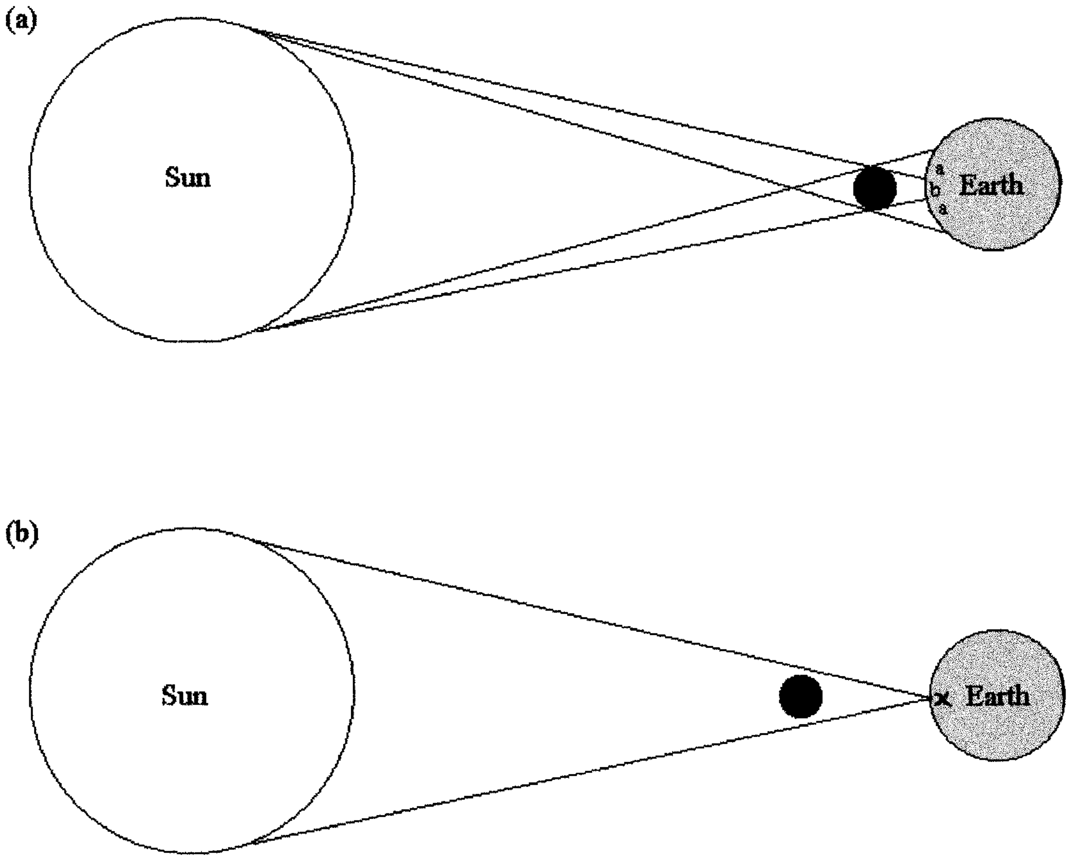


Figure 1.5 Solar eclipses. (a) An observer stationed at *b* would see a total solar eclipse, while someone in the regions shown as *a* would see a partial eclipse. (b) An observer at position *x* would see an annular eclipse. The diagrams are grossly out of scale for the sake of clarity.

Observing lunar eclipses

Given that eclipses vary from one to another, there is some real scientific value in observing them, even though the changes are due to differing geometry and the state of the Earth's atmosphere and not due to any change on the Moon. Moreover, the observations can be made using the naked eye, binoculars, or telescopes. Images of the Moon can be recorded by means of drawings, photography, video cameras or CCD astrocameras. You will find information about all of these techniques in the relevant chapters of this book.

The darkness of a lunar eclipse can be rated using the *Danjon scale*. A Danjon 0 eclipse is the darkest. At mid-totality the Moon is almost invisible. A Danjon 1 eclipse is very dark, with a deep-brown or grey umbra, and surface details on the Moon are difficult to make out. A Danjon 2 eclipse is usually deep red, or reddish brown in colour, though near the edge of the umbra the Moon can look bright orange. A Danjon 3 eclipse is brighter still, though the umbra still looks coppery red and its edge is often coloured bright yellow. A Danjon 4 eclipse is the brightest, with the Moon looking bright orange or even yellow at mid-totality.

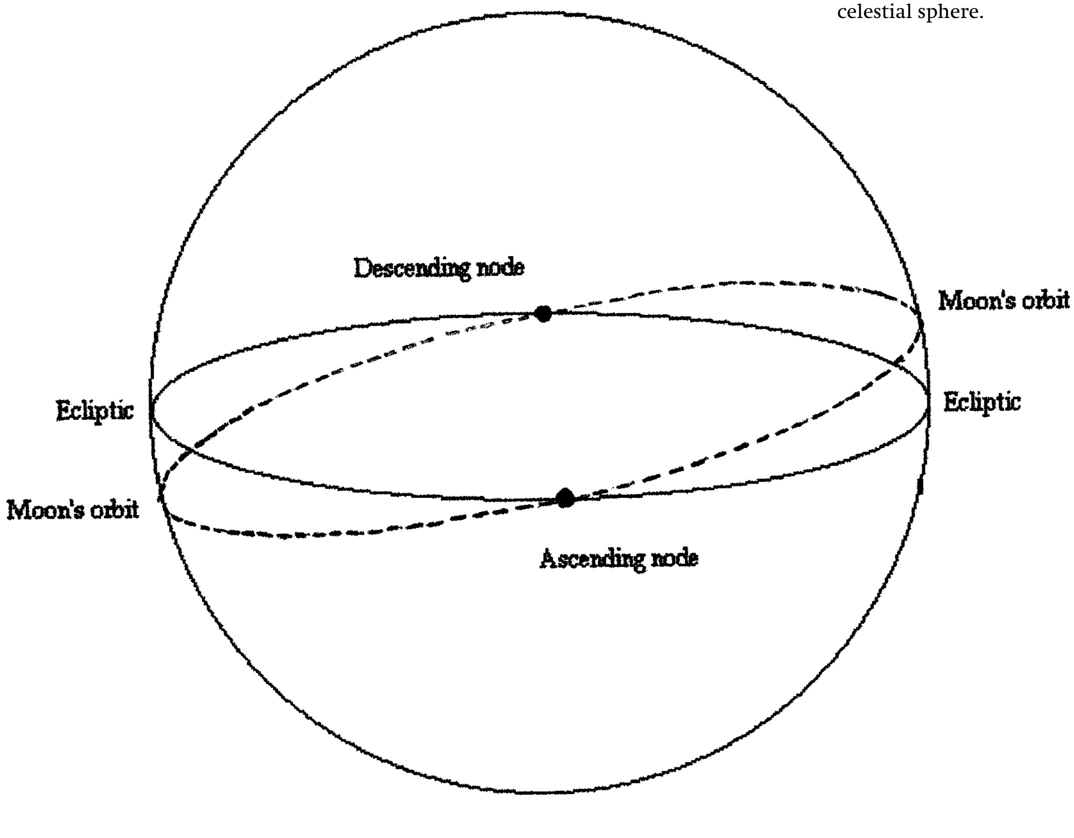


Figure 1.6 The orbit of the Moon projected onto the celestial sphere.

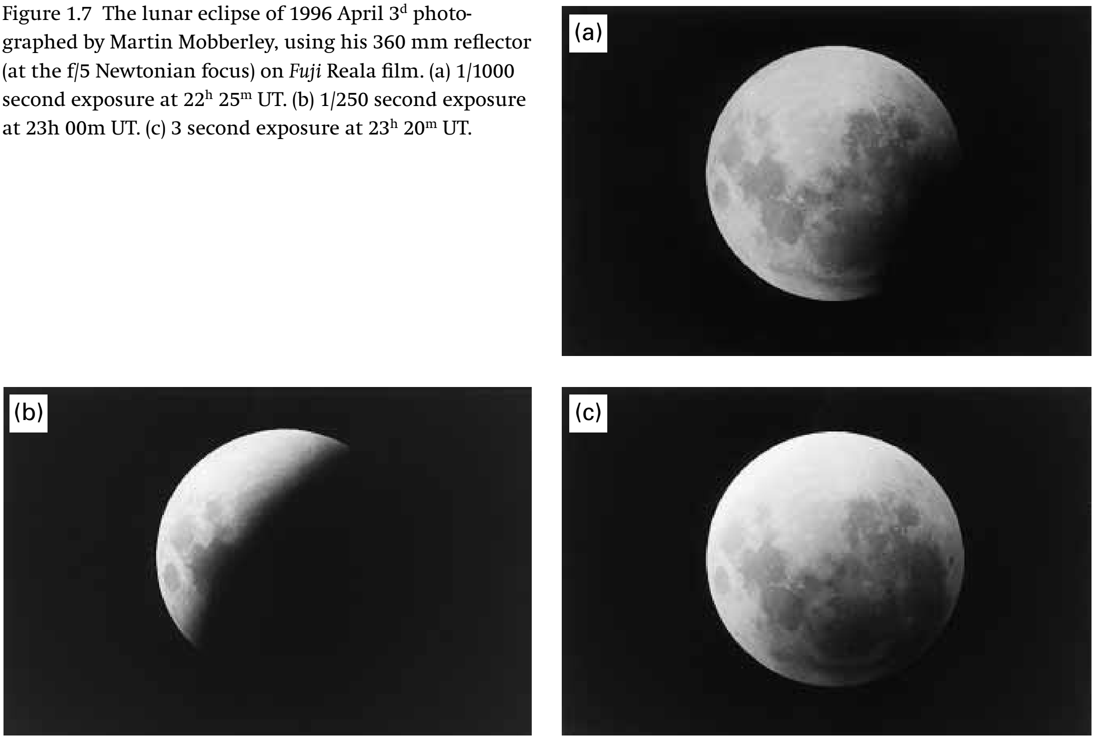


Figure 1.7 The lunar eclipse of 1996 April 3^{d} photographed by Martin Mobberley, using his 360 mm reflector (at the f/5 Newtonian focus) on *Fuji* Reala film. (a) 1/1000 second exposure at 22^{h} 25^{m} UT. (b) 1/250 second exposure at 23h 00m UT. (c) 3 second exposure at 23^{h} 20^{m} UT.

Contact times of the leading and departing edges of the umbra with the east and west limbs of the Moon and with particular lunar features are of interest, as are descriptions (best of all with photographs/images) of the appearances of the umbra (and any penumbral dimming) and the appearances of particular lunar features at stages during the progress of the eclipse. You might like to make a special search for any unusual appearances. The controversial subject of transient lunar phenomena (TLP) is covered in Chapter 9 of this book.

Perhaps I should emphasise that Figure 1.5, which illustrates how solar eclipses are formed, is also grossly out of scale for the sake of clarity. It has always struck me as a remarkable coincidence that the Sun and the Moon both appear to be virtually the same apparent size as viewed from the surface of the Earth. This is approximately ½° – roughly equivalent to a span of a centimetre as seen from a distance of 1 metre. It just so happens that the ratio of the actual diameter of the Sun to its distance from us is almost equal to that of the diameter of the Moon to its distance from us. As Figure 1.5 illustrates a *total solar eclipse* can only been seen from a restricted region on the Earth's surface at any given moment. In fact, owing to the Earth's rotation and the relative motions of the Earth and Moon (and

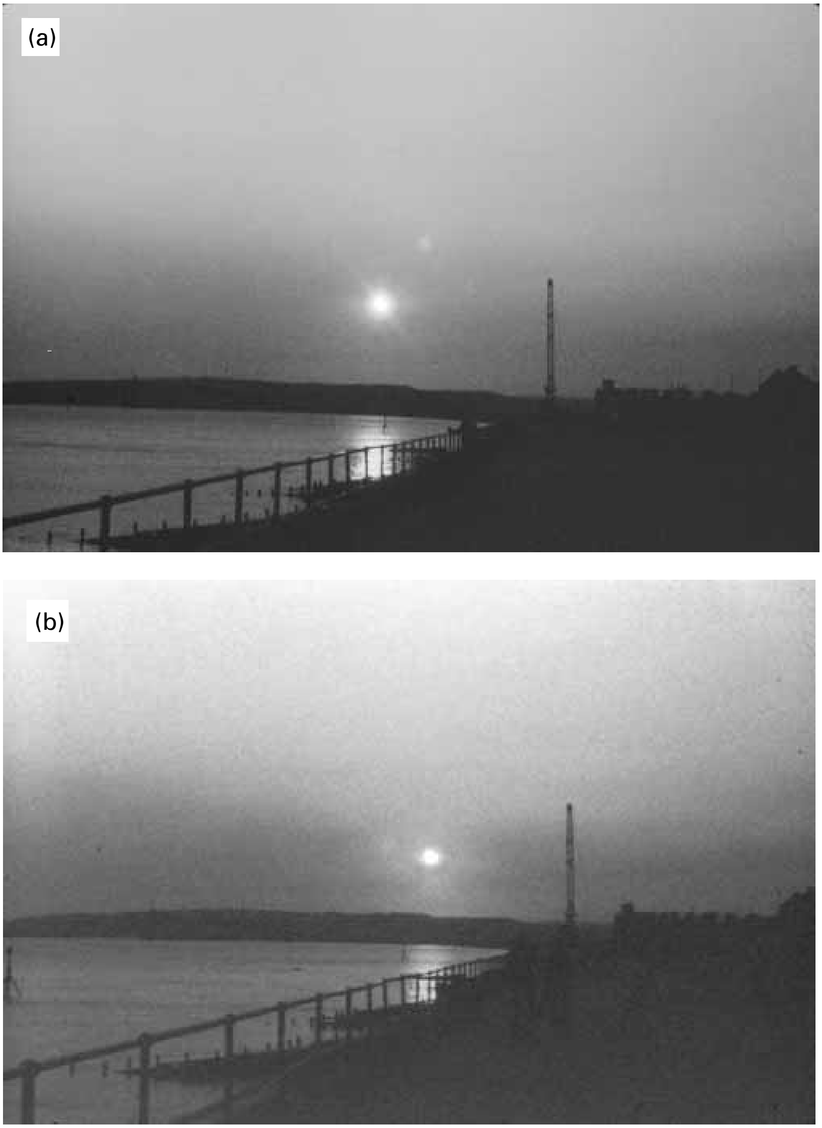


Figure 1.8 The partial solar eclipse of 1982 July 20^{d}, photographed by the author with a single-lens reflex camera (fitted with a 58 mm lens). 1/500 second exposures at f/16 on *Kodak* Ektachrome 400 film.
(a) Exposure at $19^{h}\ 26^{m}$ UT.
(b) Exposure at $19^{h}\ 33^{m}$ UT.

their relation to the Sun), this small region sweeps across the globe. A narrow track is generated across the surface of the Earth within which the eclipse can appear as total. All other regions will see, at best, a *partial solar eclipse* (see Figure 1.8).

The maximum duration of totality, as seen from any particular location, is about 8 minutes and it varies from eclipse to eclipse. The reason for the variation lies in the fact that the Earth's orbit about the Sun is slightly elliptical, as is the Moon's orbit around the Earth. Totality will last the

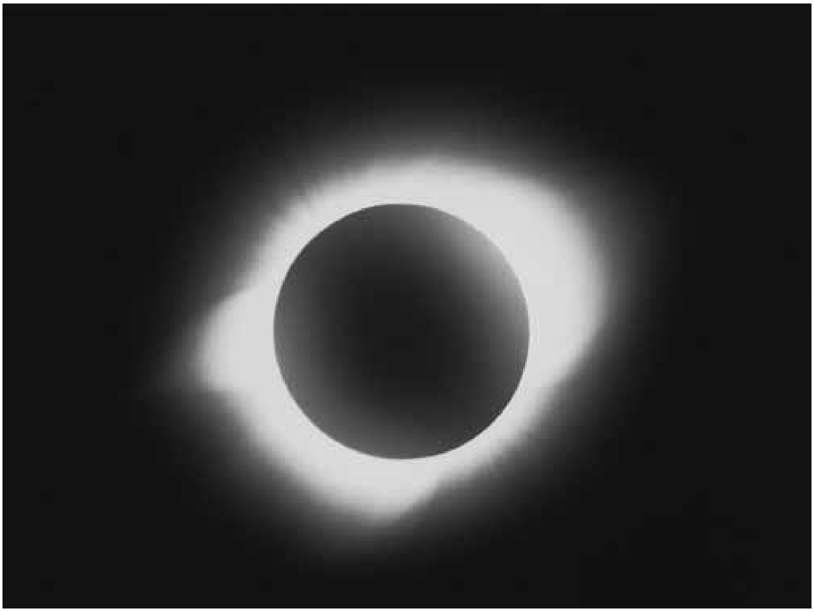


Figure 1.9 Total solar eclipse photographed by Martin Mobberley from Chile, 1994 November $3^d\ 12^h\ 20^m$ UT. Martin used a *Celestron* C90 catadioptric telescope (1000 mm focal length, f/11) for this 2 second exposure on *Fuji* Velvia film.

longest when an eclipse occurs at a time when the Earth is at its greatest distance from the Sun, or *aphelion*, and the Moon is at perigee. In the converse situation, with the Earth at *perihelion* and the Moon at apogee, the Moon's apparent size is actually slightly smaller than that of the Sun. At maximum eclipse the Sun's disk will not be completely hidden by the Moon and a thin ring of sunlight will surround the dark disk of the Moon. This is an *annular eclipse* and is illustrated in Figure 1.5(b).

A total solar eclipse is a spectacular thing to see. Over the course of about an hour a larger and larger 'bite' is taken out of the Sun as the (invisible against the daytime sky) disk of the Moon passes over it. Then the last sliver of solar photosphere disappears from sight. The sky rapidly darkens and the Sun's pearly *corona* comes into view (see Figure 1.9). Sometimes *solar prominences* can be seen over the edge of the Moon. After just a few minutes the first chink of sunlight peeks once again from behind the Moon and the sky rapidly brightens and the Moon slowly withdraws and the eclipse becomes a mere memory for those who witnessed it.

As the Moon moves around the Earth, the Earth–Moon system moves around the Sun. Every so often the Earth, Sun and Moon regain very similar positions relative to one another. This happens every 6585 days (a little over 18 years) and this period has been given the special name of the *Saros*. Ancients found the Saros useful in predicting lunar eclipses. A lunar eclipse happening on a particular day will be followed by one 6585 days later (of course, that is not to say that other lunar eclipses won't happen in-between these times – they will, but each lunar eclipse will be 'paired' with one happening one Saros period later). The Saros is rather less useful in predicting solar eclipses because it is not quite accurate enough.

1.3 GRAVITY AND THE TIDES

An oft-repeated fable is that Isaac Newton was sitting in his garden one day and chanced to see an apple fall from a tree. Newton's genius was such that he realised that the same force that operated to make the apple fall to the ground was responsible for keeping the Moon in orbit around the Earth. He also reasoned that it was quite likely that the same type of force operates between the planets and the Sun, keeping the Earth and the other planets in their orbits around our parent star. Whether or not it really was the falling apple that gave him his inspiration, Newton explored his ideas mathematically and he published his results in his masterly work, the *Principia*, in 1687.

Newton formulated a 'law' which he thought would be true for anywhere in the observable Universe:

> Any two bodies will attract each other with a force which is proportional to the product of the masses and is inversely proportional to the square of the distances separating them.

The law can be expressed in equation form:

$$F \propto Mm/r^2$$

or

$$F = GMm/r^2 \tag{1.1}$$

where F is the mutual attractive force, measured in newtons, M, m are the masses of the attractive masses, measured in kilograms, r is the distance of separation, measured in metres, and G is a constant of proportionality, usually known as either the *universal constant of gravitation*, or the *gravitational constant*.

Historically, getting a precise value for G was not an easy thing to do but by modern times a reliable figure has been arrived at by means of sophisticated laboratory experiments. Its value is 6.67×10^{-11} Nm^2 kg^{-2}. Knowing the masses of the Earth and the Moon, one can use the equation to work out the size of the attractive force between them. It amounts to a colossal 2×10^{20} N. As far as the Earth is concerned, most of this force acts on the solid part of the body, but a fraction of it acts on the Earth's fluid covering and so contributes to the generation of the ocean tides.

The pull of the Moon causes a bulging of the oceans in the direction of the Moon. In effect, the Earth's waters are 'heaped up' because of the attraction of the Moon. In addition, the Earth is also 'pulled away' from the

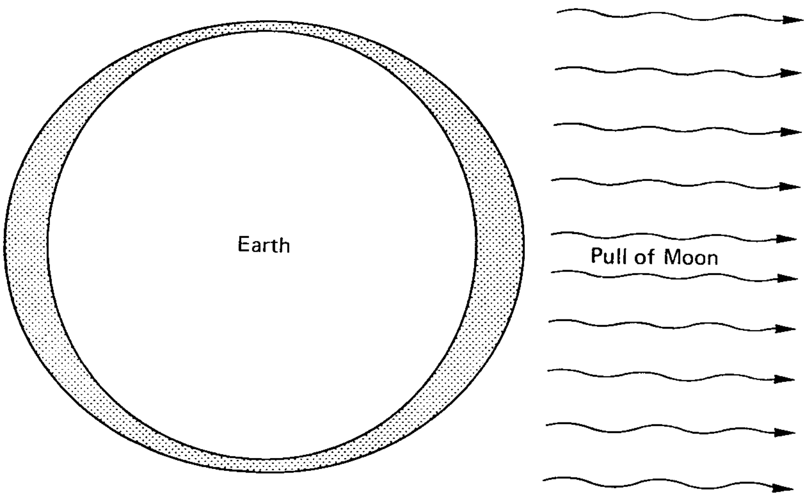


Figure 1.10 The main tide generating process.

water on the reverse side, so leaving a bulge of water on the opposite side of the Earth, as shown in Figure 1.10. As the Earth turns on its axis so each position on the Earth experiences two tides per day.

The Sun also contributes its own effect. Though the Sun is very much more massive than the Moon, it is very much further away and so the Sun's tidal force has only about half the magnitude of that of the Moon. Around the times of new Moon and full Moon, the tidal forces act along virtually the same straight line and so at these times the tidal amplitude is greatest, the sea levels rising and falling by the maximum amount. The situation is illustrated in Figure 1.11 and the tides at these times are known as *spring tides*. Near the times of first and last quarter Moon the Sun and Moon's tidal pulls are almost at right angles and so the resultant tides have their minimum amplitudes (see Figure 1.12). These are *neap tides*.

Local topographic features will have their effects on the tides that result at any given location (the situation is often quite complicated in bays and river estuaries, for instance) but the foregoing describes the situation on the global scale.

1.4 MORE ABOUT THE MOTIONS OF THE MOON – LIBRATION

That the Moon always keeps the same face presented to the Earth is obvious even to the casual observer and was well known to the ancients. The explanation for this is both obvious and yet fundamental: the Moon rotates on its axis with the same period that it takes to orbit the Earth. We say that the Moon has a *captured*, or *synchronous* rotation.

However, the careful observer who is armed with some optical aid will notice that the Moon's topographic features do not quite remain exactly

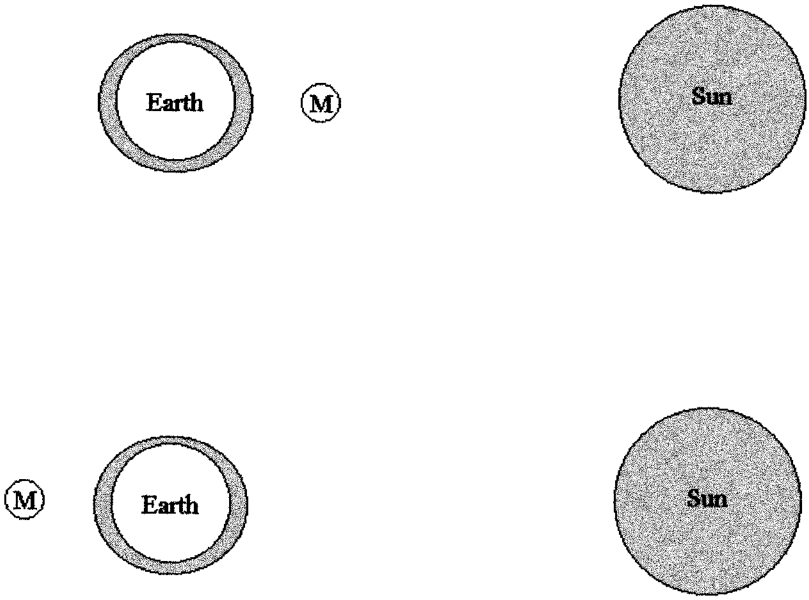


Figure 1.11 Spring tides are formed when the pulls of the Moon and Sun are aligned (even if pulling in opposite directions).

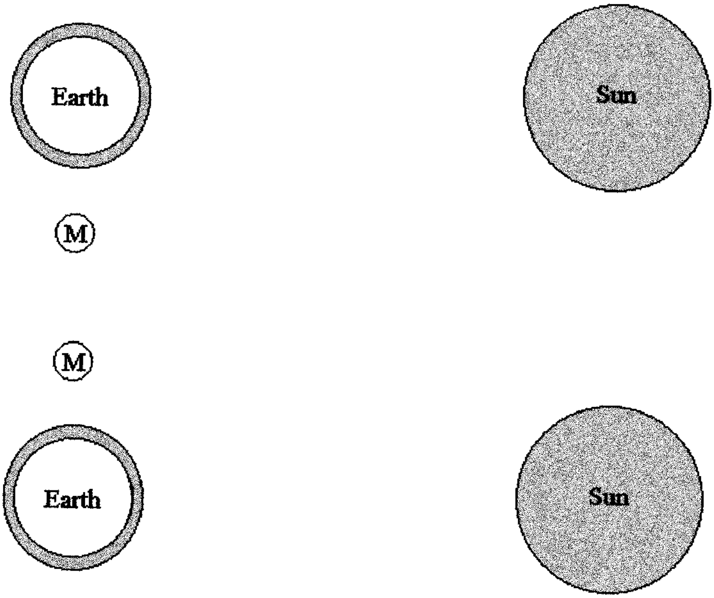


Figure 1.12 Neap tides are formed when the pulls of the Moon and the Sun are at right angles to each other.

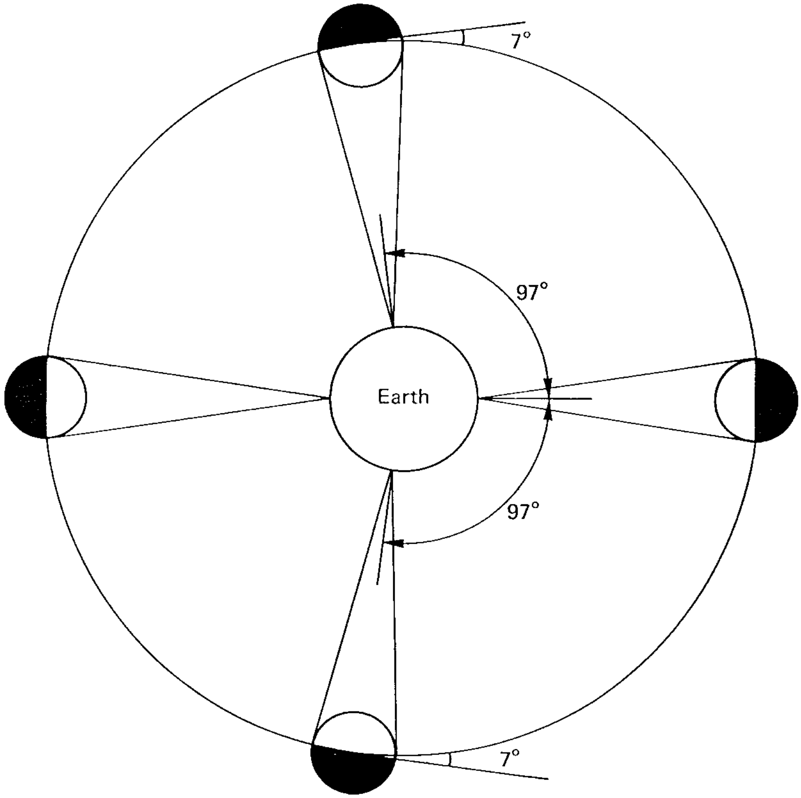


Figure 1.13 Libration in longitude. The Moon turns evenly on its axis but the Moon's speed varies around its elliptical orbit. Consequently the two motions are out of step, although the total time taken for one rotation is the same as the time taken for one complete orbit. The result is that the Moon appears (as seen from the Earth) to swivel back and forth in an east–west direction over the course of one lunation.

stationary on the visible disk over a lunation. In fact, the Moon appears to slightly nod up and down and rock to and fro over each lunar cycle. Moreover, the nodding and rocking differ slightly from one lunation to the next. This effect is termed *libration*.

If it wasn't for libration we could have mapped only 50 per cent of the Moon's surface before the advent of the space age. We were actually able to map 59 per cent of the Moon, using observations made over a series of years. Three separate effects operate to create libration: *libration in longitude*, *libration in latitude*, and *diurnal libration*.

Libration in longitude arises because of the elliptical shape of the Moon's orbit and the fact that its speed changes with its distance from the Earth. When the Moon is close to perigee it moves a little faster than when it is at apogee, the speed changing gradually from one situation to the other. However, the rotation rate of the Moon on its axis remains constant. The result is an apparent 7° east–west rotational oscillation of the Moon's globe during the course of a lunation. This effect is illustrated in Figure 1.13.

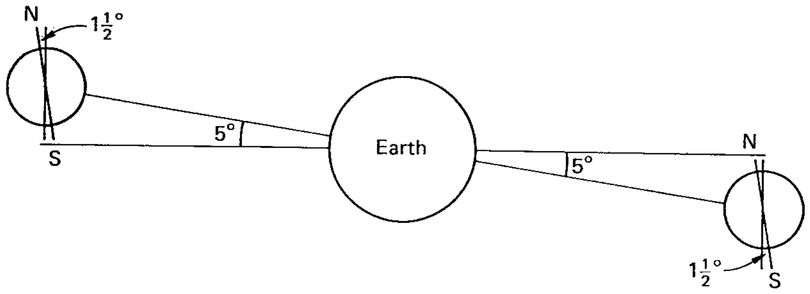


Figure 1.14 Libration in latitude.

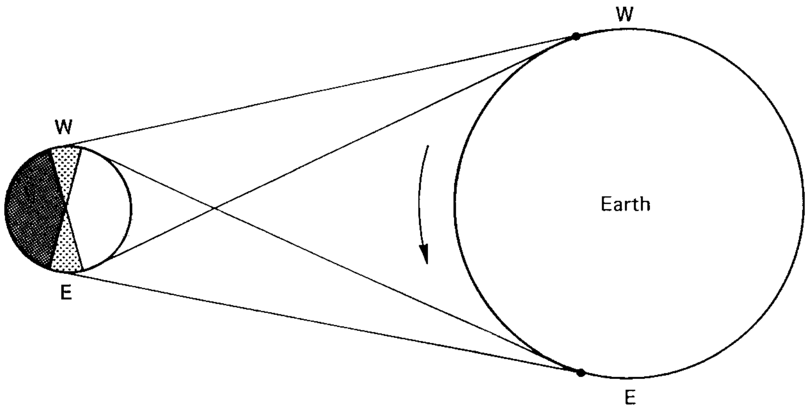


Figure 1.15 Diurnal libration.

The Moon's spin axis is not quite perpendicular to the plane of its orbit. In fact it is canted over at 1½° (by comparison, the inclination of the Earth's rotation axis to the perpendicular to the Earth's own orbital plane is 23½°). Added to this is the already mentioned 5° inclination of the Moon's orbit to the ecliptic (remembering that the ecliptic is, in effect, the projection of the Earth's orbital plane onto the celestial sphere). Taken together, these inclinations mean that we can see, alternately, up to 6½° beyond one pole, then the other (see Figure 1.14). This is libration in latitude.

Figure 1.15 shows how diurnal libration arises. As the Earth rotates, so an observer's viewpoint changes slightly with respect to the Moon. An Earth-based observer watching the Moon rising above the horizon will be able to see a little way further around one limb of the Moon, and then a little further round the other limb when the Moon is setting.

As you might imagine, the way these separate librations combine is complicated, and is made even more so by the fact that the Earth's and the Moon's orbit *precess* (the positions of the nodes shift with time). Consequently, librations differ with each lunation. Figure 1.16 shows well the effect of libration.

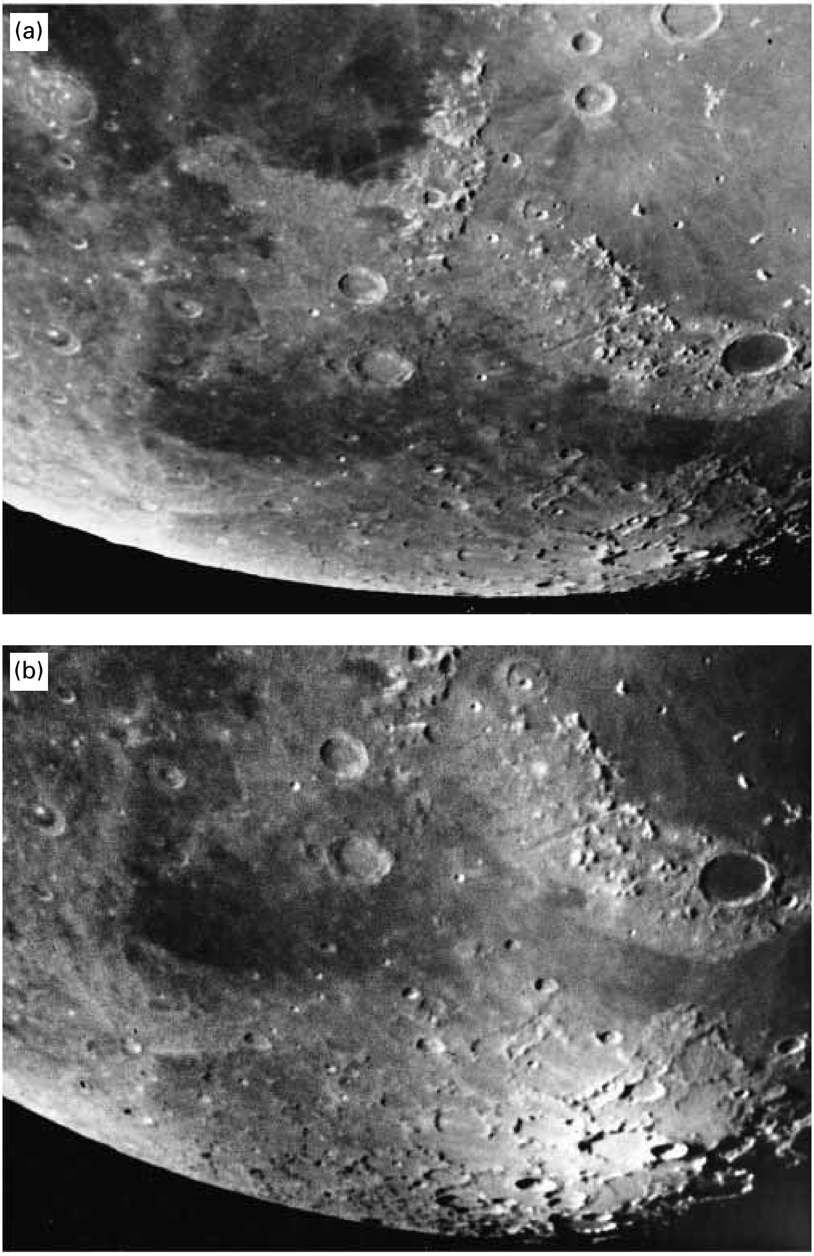


Figure 1.16 The effects of libration are illustrated well by these photographs taken by Commander Henry Hatfield, using his 12-inch (305 mm) Newtonian reflector: (a) was taken on 1966 May 29^{d} 21^{h} 03^{m} UT; (b) was taken on 1966 November 22^{d} 18^{h} 14^{m} UT. In both (a) and (b) the values of the libration in latitude are close to their most extreme possible, though all three types of libration may be variously prominent at any given time in combination.

1.5 CO-ORDINATES ON THE SURFACE OF THE MOON

Compare a pre-1960s map of the Moon with a modern one and you will notice that east and west are marked on it the opposite way round. On the classical scheme the Lunar 'sea' (dark area) known as the Mare Crisium was situated on the western side. This side of the Moon's face is the east on modern maps. The modern scheme is due to the *International Astronomical Union* (*IAU*) and is now the accepted standard.

Latitudes and longitudes can be assigned to positions on the Moon's globe in the same way that they can on the Earth. Co-ordinates that refer to the surface of the Moon are known as *selenographic*. Of course, libration affects the precise apparent positions of features on the lunar surface but a co-ordinate system has been derived that refers to the mean apparent positions – those that would correspond to zero libration.

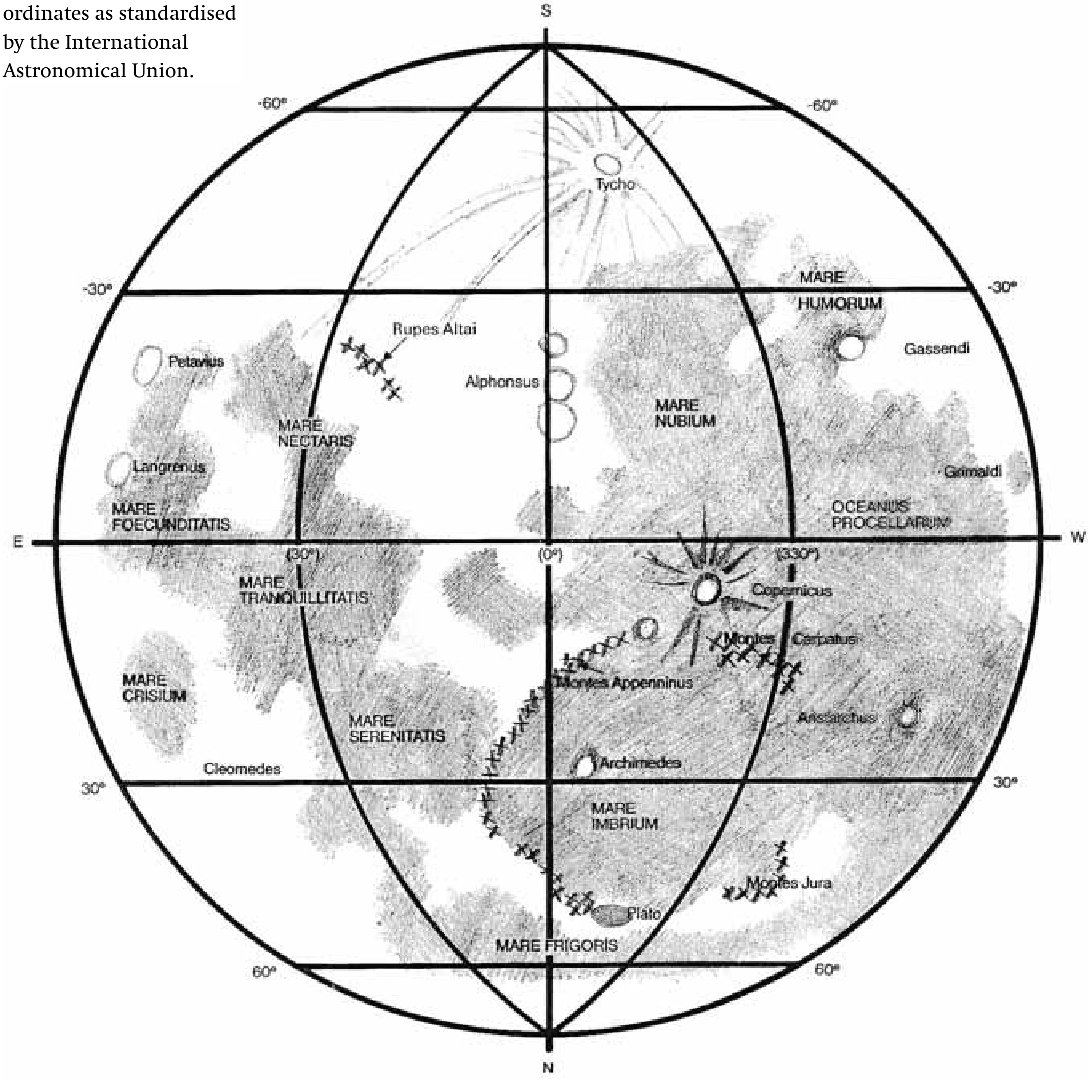
The mean centre of the Moon's disk corresponds to a *selenographic latitude* of 0° and a *selenographic longitude* also of 0°. Selenographic latitude is positive going northwards and negative going southwards, being +90° and −90° at the lunar north and south poles, respectively. Selenographic longitude increases eastwards (towards the Mare Crisium) and is 90° at the mean east limb. It further increases (on the part of the Moon turned away from the Earth) to 180° at the mean position antipodal to the Earth and round to 270° at the mean west limb. Now on the Earth-facing side again, the selenographic longitude increases further to 360° (equivalent to 0°) at the mean centre of the disk.

Figure 1.17 shows an outline map, illustrating the modern co-ordinate system. Notice that I have orientated it with south uppermost. This is to make it uniform with the maps and illustrations throughout the book and is because this book is intended to be of use to the practical observer. Most readers of this book will live in the Earth's northern hemisphere and will see the Moon inverted through a normal astronomical telescope (without the use of additional optical elements, such as a star diagonal), that is with this same orientation.

Just as on the Earth, the lines that pass through both poles and the equator (so forming *great circles* on the surface of the Moon) are known as *meridians*. These are lines of equal longitude. The lines which run parallel to the equator (so forming *small circles* over the surface of the Moon – only the equator is a great circle) are lines of equal latitude.

One can go on to define the co-ordinates of the *terminator*, the boundary between the sunlit and dark portions of the Moon as the cycle of lunar phases progresses. The *Sun's selenographic colongitude* is the selenographic longitude of the morning terminator on the Moon. Its value is 270° at new Moon, 0° at first quarter, 90° at full Moon and 180° at last quarter. In ephemerides it is often reckoned with respect to the mean centre of the Moon's disk and so libration can have an effect on the true position of the terminator on the Moon's surface. For instance, comparing a map of the Moon with the ephemeris value of the Sun's selenographic colongitude might suggest that the terminator should run through the middle of a particular feature at a particular time. When you go to the telescope at that time you might find, instead, that libration has carried the feature rather further into the sunlit portion, or alternately has hidden it entirely in the Moon's dark region!

Figure 1.17 Outline map of the Moon, illustrating the modern system of co-ordinates as standardised by the International Astronomical Union.



1.6 OCCULTATIONS

As the Moon sweeps around the Earth in its monthly orbit it passes in front of the planets and stars far beyond. When the Moon hides a more distant celestial body from our sight we say that it *occults* that body. A solar eclipse is an *occultation* of the Sun. Of course occultations of stars are much more frequent than solar eclipses.

Though an occultation is usually quite a simple affair, it is really quite fascinating to watch the edge of the Moon very slowly approach a star until suddenly the star vanishes from sight. Reappearances are also interesting, the once hidden star suddenly snapping into view. Of course, one would normally have to be armed with a prediction that a particular star was going to emerge at that point and time to be able to catch it happening.

The timings of stellar occultations used to be a valuable pursuit because it allowed us to derive knowledge of the Moon's orbit and its surface profile, as well as precise star positions, amongst many other things. In modern times some of these objectives have been better met by other means. However, occultation timings are still useful because the data generated can be used for certain other investigations. In particular, the long-term nature of occultation-timing data lends itself to the examination of the dynamical slowing of the Moon in its orbit. This slowing arises because of the Moon's tidal interaction with the Earth.

The binary nature of some stars can be revealed by this technique, even if they are too close for resolution by more conventional means. Instead of suddenly snapping out as they pass behind the lunar limb, some stars take a moment to fade. During a casual observation of an occultation, I found one star that had not yet found its way to the catalogues as being a binary. Of course, I reported my find.

In many fields in astronomy it is highly desirable for the observer to operate as part of a group. I should say that in occultation work it is an essential requirement. Many provincial societies have observing groups which collate their results and send them to either of the two main international occultation organisations. These are the *International Lunar Occultation Centre* (*ILOC*) in Tokyo, and the *International Occultation Timing Association* (*IOTA*) in St Charles, Illinois. In addition to processing observations, these bodies issue predictions of forthcoming occultations.

As well as the date and expected time of an event, the predictions give the designation of the star, its magnitude, its co-ordinates (right ascension and declination), whether the event is a disappearance (immersion) or a reappearance (emersion). These are obvious essentials for the serious observer. Another useful piece of data provided is the *position angle* of the event. Figure 1.18 shows the path of a hypothetical star behind the Moon (though one might equally say that the Moon passes in front of the star) during an occultation. Position angles are measured from the north point of the lunar disk increasing in an anticlockwise direction. Hence the north point of the disk has a position angle of zero degrees. The IAU west point (the classical eastern point) of the disk has a position angle of 90°, and so on.

Occultation timing is one of the decreasing number of projects that amateur astronomers can still usefully pursue with very modest equipment. Even a 60 mm refractor or 76 mm reflector will do provided the mounting is not too unsteady (the cheapest ‘department store’ telescopes may well have mountings which are too tremorous, making these abominations useless even for timing occultations, let alone the other observing projects the manufacturers would have us believe we will be able to carry out by using them).

A very rough formula that links the aperture of a telescope to the magnitude of the faintest star one could see with it is the following:

$$m_v = 4.5 + 4.4 \log D \qquad (1.2)$$

where D is the aperture of the telescope in millimetres and m_v is the faintest stellar magnitude observable. Various other formulae are published but

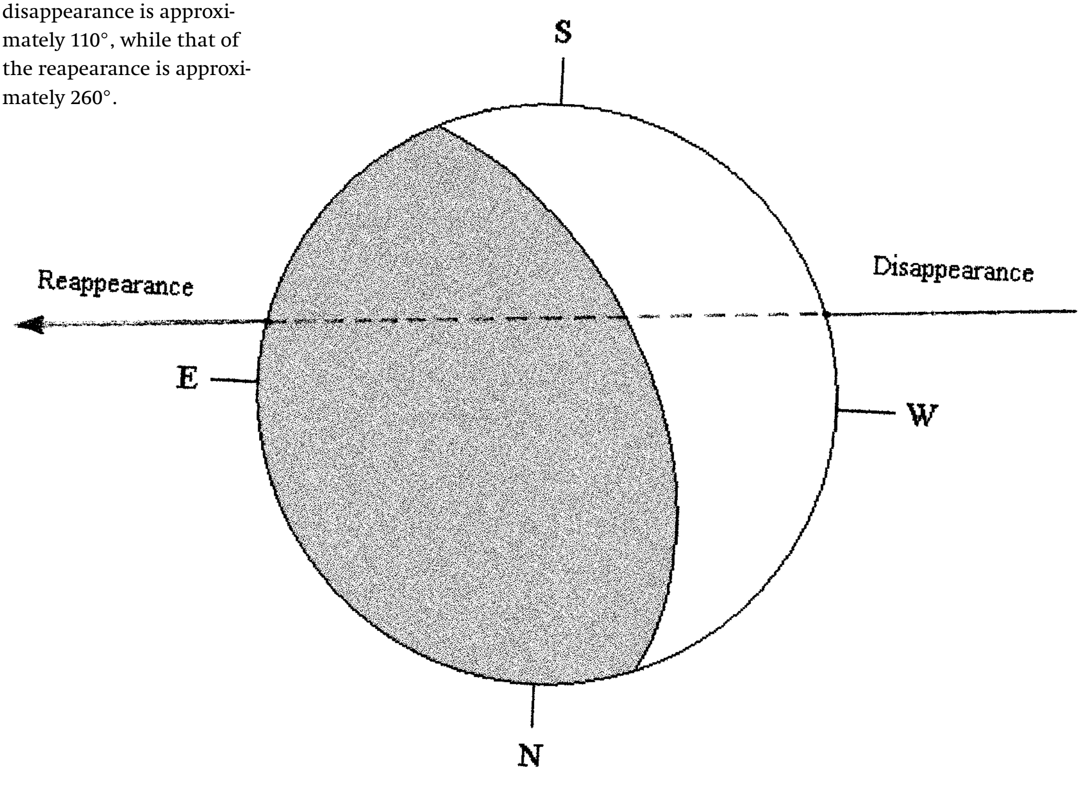


Figure 1.18 The path of a hypothetical star behind the Moon, during an occultation. The angles are exaggerated here for the sake of clarity. The position angle (measured from the north point, increasing in an anticlockwise direction) for the star at disappearance is approximately 110°, while that of the reapearance is approximately 260°.

Table 1.1. *Telescopic limiting stellar magnitudes, computed from the author's formula, which was based on a practical survey by Bradley E. Schaefer. Occultation observers can use these figures as a 'best case' guide; for instance an occultation of a star by the un-illuminated portion of a thin crescent Moon on a night of excellent clarity. The varying brightness of the Moon will mean that usually stars rather brighter than indicated here are the dimmest that will be seen close to the lunar disk. Of course, the figures given here will be several magnitudes over-optimistic for the case of an occultation of a star by the full Moon on a hazy night!*

Telescope aperture (inches)	Telescope aperture (mm)	Limiting magnitude m_v
6	152	14.1
8	203	14.7
10	254	15.1
12	305	15.4
14	356	15.7
16	408	16.0
18	457	16.2
20	508	16.4

this one is my own, which I have based on the published results of an extensive practical survey carried out by Bradley E. Schaefer, of the NASA – Goddard Space Flight Centre. Of course, this formula is merely a blanket guide since there are many factors to be taken into account in making any prediction of the limiting magnitude a particular observer will attain with a particular telescope under particular conditions of observation. However, based as it is on the practical experiences of a large sample of modern-day telescope users it should be more accurate than other formulae. Table 1.1 provides a selection of predictions of limiting magnitudes for telescopes with apertures covering the range generally used by occultation observers.

Mind you, this does not mean than one can necessarily expect to successfully observe an occultation of, say, a $14^{m}.1$ star by using a 6-inch (152 mm) telescope. The predictions given by the formula are for stars seen against a very dark sky background. Even if the occultation is by the Moon's dark limb and the brightly sunlit portion is out of the field of view, the light inevitably scattered from the sunlit portion into the sky around the Moon is sure to have some effect. If the star is occulted by the sunlit limb then one would be hard-pressed to see the event even if the star was a couple of magnitudes brighter than the value given by the formula. The extreme is, of course, an occultation by the full Moon!

I recommend beginning the setting up of your equipment at least half-an-hour before the event is predicted. You will need this time to locate the star (if the event is an immersion) and to make sure that everything is functional. As in other fields, a permanently mounted clock-driven telescope is a great convenience, though there is some merit in having a portable telescope if one's sky-access is limited. With a clock-driven telescope one can simply identify the star (using setting circles and/or a star chart) and then set it in the centre of the field of view. Then watch the approach of the Moon's limb (even a dark limb is usually visible, owing to Earthshine) and time the star's disappearance as accurately as you can. If the Moon's limb really is invisible (perhaps the sky transparency is rather poor) then all one can do is to resort to keeping an eye on the clock and only give full attention to the view through the telescope from about a minute or so before the predicted time of the event.

If your telescope does not have a clock-drive then you must contrive to move the telescope just a little before the event, in order that the occultation will happen with the star reasonably close to the centre of the field of view. Again, keeping an eye on the clock until a minute before the predicted time will help, together with an estimate of how much the star will drift in that minute (gauged from observing the star's drift in the field of view in the preceding minutes). Of course, it is only too easy to move the telescope too close to the time of the occultation and in that way lose the event!

A clock-drive is especially useful for observing emersions. Ideally the telescope is set on the star before it first disappears behind the Moon. Both immersion and emersion can then be timed. Otherwise, a computer-controlled telescope, or one with setting circles, could be used to set on the co-ordinates of the star given in the prediction if it is not possible to observe the immersion. One then has to keep a careful watch for the star's reappearance. The best an observer limited to using simpler equipment can do is to keep a careful watch on the lunar limb at the predicted position angle of the star's emersion.

Grazing occultations are especially interesting. As the name implies, this is where the star appears to graze the lunar limb and perhaps appears and disappears several times behind irregularities in the Moon's limb. In order to get the most useful work done, a co-ordinated team can be set up across the predicted track of the graze event. Provided all the timings are accurate and reliable, the results from the observers can be subsequently used to generate an accurate profile of the Moon's limb (though this is now largely only for personal interest) and a particularly precise fix for the Moon's position at the time of the event (this is still a valuable piece of information). I can't emphasise enough that to be of any real use the observer's timings must be accurate. The following notes detail how sufficient accuracy may be achieved.

1.7 TIMING AND RECORDING OCCULTATIONS

The traditional tools of the occultation observer are, apart from the telescope, his/her eye and a stopwatch. The aim is to record the time of the event as precisely as possible, ideally to an accuracy of 0.1 second. The first requirement is that the stopwatch is reliable, accurate, and easy to use. Beware tiny buttons (as on many digital watches) and an indefinite start/stop action. The second requirement is a source of accurate time signals. You could use the telephone time-service. More conveniently, you might use a radio tuned to whatever station you can receive time signals on in your area.

To make the timing start the stopwatch at a given time signal (whether from the telephone service or from the radio) and then, watching through the telescope, stop the stopwatch at the instant of the event. If the time of starting the stopwatch is A and the time of stopping it is B, then the time of the event is $A+B$. Remember the need for accuracy. Discard the observation if you fumble the stopwatch or are obviously 'caught unawares' and delay pressing the stopwatch button for a significant and undeterminable time. You will need to keep alert and have brisk reactions in order to achieve the desired 0.1 second accuracy.

Some observers have constructed their own electronic chronometers, which automatically record the time when a button is pressed on a handset. In theory this should be fine. However, the apparatus **must** itself be reliable and highly accurate. Incorrect timings are not merely useless. They are positively harmful to the analysis. Fortunately one can use radio, or telephone, time signals in order to check the running and accuracy of any home-made chronometer. Even if the long-term running of the device seems good, it is as well to check the device against a time signal shortly before, and again shortly after, the observing run.

If the chronometer is **consistently** running a little fast, or a little slow, then it can still be used. Obviously one then has to interpolate to correct the time recorded for the event. However, what is not permissible is a chronometer that changes its rate. The occultation observer should take the chore of keeping all timepieces monitored, or *rated*, as an important part of his/her work.

Using a video camera, or a dedicated CCD astrocamera, with the telescope is described in Chapter 5. Suffice it to say here that a video recording of the occultation can be made using a sensitive video camera or a CCD astrocamera. If the video machine or the camera has an on-screen 'sports-type' stopwatch then the event can, in theory at least, be timed with better accuracy than can be done by the traditional eye-and-stopwatch method. An American video machine operates at 30 pictures ('frames') per second and so the timing could be potentially accurate to 1/30 second. Most other countries use TV and video systems which utilise 25 frames per second, corresponding to a potential accuracy of 1/25 second. As before, it will be necessary to standardise the VCR's timer against accurate time signals, both before **and** after the observation, as well as rating it over a longer period.

Automation is possible if one is lucky enough to have a computer-operated telescope which one can use with a CCD/video system. After the initial set-up period the telescope can be left to 'do its own thing' while one is busy with some other activity. The set-up procedure must always include checking the timer against which the events are recorded. At the end of the session one extracts the results and closes down the equipment, once again checking the timer to make sure that it is still in synchronism with the standard time signals.

Along with the tabulated observations, the observer is responsible for reporting his/her exact *geodetic co-ordinates*. These are the latitude, the longitude, and the height above mean sea level of the location of the observer's telescope. A trip to the library may be sufficient to unearth a large-scale ordinance survey map and so deduce the required information.

You may wonder if you should make any attempt to allow for the inevitable delay from seeing an occultation event and actually pressing the stopwatch button. The answer is no. The 'raw' timings you obtain are the ones you should record. When your observations are processed at IOTA or ILOC your results will be compared with others and a *personal equation* deduced for you. This is the average delay that occurs between the actual time of the event and when you stop the stopwatch. The only possible exception to this is if you are a particularly experienced observer and you have an accurate value for your own personal equation. Your report must state whether or not a personal equation has been applied to the figures and, if it has, the magnitude of the correction. An observer's personal equation for emersions will be rather greater than that for immersions.

So much for our very brief survey of the Moon as a chunk of rock in orbit about the Earth. Aside from occultations work and eclipse observations, most practical amateur astronomers will be more concerned with the nature and topography of the Moon's surface. As this is a book for practical amateur astronomers, most of the rest of it will be devoted to that field of study.

CHAPTER 2

The moon through the looking glass

Who first looked at the Moon through a telescope? The honest answer is that we do not know. We cannot even be sure as to when the telescope was invented, let alone who was first to look at the Moon through one.

Until a few years ago most historians had settled upon 1608 as the probable year of invention of the telescope and a Dutch spectacle maker, Hans Lippershey, as its probable inventor. Recently, however, evidence for an earlier invention has come to light. For instance, an Englishman, Thomas Digges, is thought to have produced a form of telescope sometime around 1555.

What we can be certain of is that Galileo heard of the Dutch telescope and, with few clues to help him, he did manage to design and build a small refracting telescope for himself in 1609. Shortly thereafter he built other slightly better and more powerful versions (though still extremely imperfect and lacking in magnification by modern standards) and we know that he used them to observe the celestial bodies, including the Moon.

Galileo made sketches of the lunar surface. An Englishman, Thomas Harriott, had managed to obtain a telescope from Europe and also used it to observe the Moon at about the same time as Galileo. Harriott even produced what was very probably the first complete map of the Moon's Earth-facing side to have been made using optical aid. Despite the imperfections of his telescope, Harriott's map does show features we can recognise today.

You might have expected the coarsest features of the Moon to have been charted before the invention of the telescope. Undoubtedly they were, though the earliest 'map' produced without optical aid that we know of is that by William Gilbert. This was published posthumously in 1651, though it is supposed that he made it in 1600, or at some time close to that date, approximately three years before his death.

Although the very beginnings of lunar study might be shrouded in the mists of time, all that occurred after Galileo's era is quite well documented. The Moon had become a subject for serious scientific study and astronomers set about mapping its surface features. As telescopes improved in their power and quality, so successive observers produced better and better maps.

An essential for any cartographic exercise is the standardisation of nomenclature. Naming systems were devised by Langrenus in 1645 and by Johannes Hevelius in 1647. As an aside, Hevelius's maps were notable because they were the first to take account of, and to represent, the regions of the Moon that were only shown as a result of libration. Despite this advance, Hevelius's system of nomenclature was quickly superseded. Our modern scheme of naming lunar surface features really stems from that devised by Giovanni Riccioli. Riccioli was an Italian Jesuit. A pupil of his, Francesco Grimaldi, had made a telescopic study of the Moon. Riccioli combined Grimaldi's observations into a map, which was published in 1651.

Before taking our story further, it will benefit us to pause to consider the appearance of the Moon through a telescope and to get a brief overview of the modern nomenclature of the main types of surface features revealed by one of these wonderful devices.

2.1 THE MOON IN FOCUS

Even a casual glance made without any form of optical aid reveals that the Moon is not a blank, shining disk. Aside from the phases, the Moon's silvery orb clearly shows patchy dark markings. These give rise to the "Man in the Moon" (and the variety of animals and maidens which feature in other folk lores) effect which is so obvious around the time of the full Moon. Figures 2.1–2.5 show the general appearance of the Moon at successive stages in its lunation, as it is seen through a normal astronomical telescope stationed in the Earth's northern hemisphere – in other words, with south uppermost. Since this book is intended for the amateur telescopist and since most of its readers are expected to reside in the northern hemisphere, all the telescopic views of the Moon in this book are orientated with south at least approximately uppermost.

The large dark areas are known as *maria*, Latin for 'seas'; the singular form is *mare*. Thanks to Riccioli, we have such charming names as Mare Imbrium (Sea of Showers), Mare Serenitatis (Sea of Serenity), and Mare Tranquillitatis (Sea of Tranquillity) to encounter on the Moon.

In Galileo's time it was widely believed that the patches on the Moon actually were seas. Admittedly, a few scholars considered the darker areas to be the land masses and the rest of the Moon's globe to be ocean-covered. Much later the true, arid, nature of the Moon was recognised and the difference in hue was taken to indicate a difference in chemical composition.

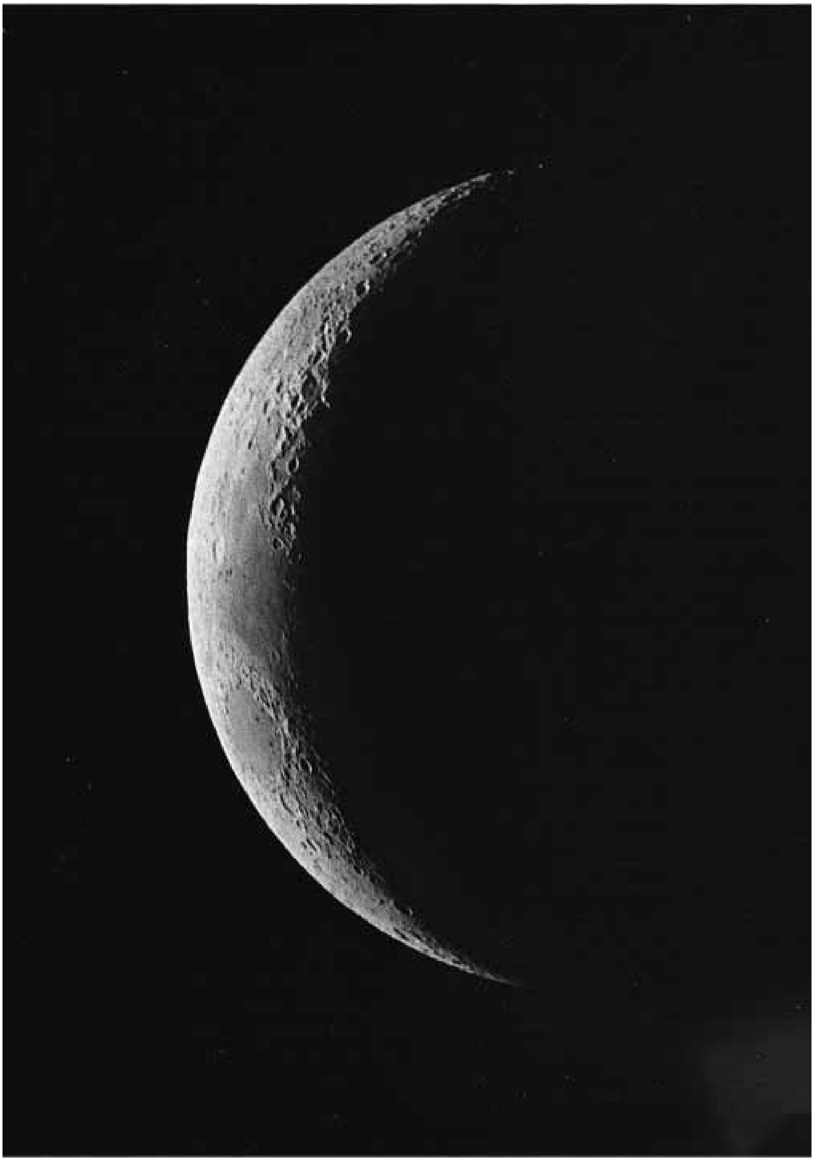


Figure 2.1 The 4-day-old Moon, photographed by Tony Pacey. He used his 10-inch (254 mm) Newtonian reflector at its f/5.5 Newtonian focus to directly image the Moon onto *Ilford* FP4 film, subsequently processed in Aculux developer. The 1/125 second exposure was made on 1991 January 19^{d}. The details of the precise time (from which I could work out the value of the Sun's selenographic colongitude) was not given. However, I estimate the Sun's selenographic colongitude as approximately 307° at the time of the exposure.

In pre-space-age times the dark plains were termed *lunarbase*, while the lighter-hued materials were termed *lunarite*.

As well as the 'seas', we have one 'ocean' (*oceanus*): Oceanus Procellarum (Ocean of Storms) and several 'bays' (*sinus* for the singular case), such as Sinus Iridum (Bay of Rainbows). These are the larger dark areas. In addition there are a number of 'marshes' (*paludes*), such as Palus Somnii (Marsh of Sleep) and 'lakes' (*lacus* for the singular case), for example Lacus Mortis

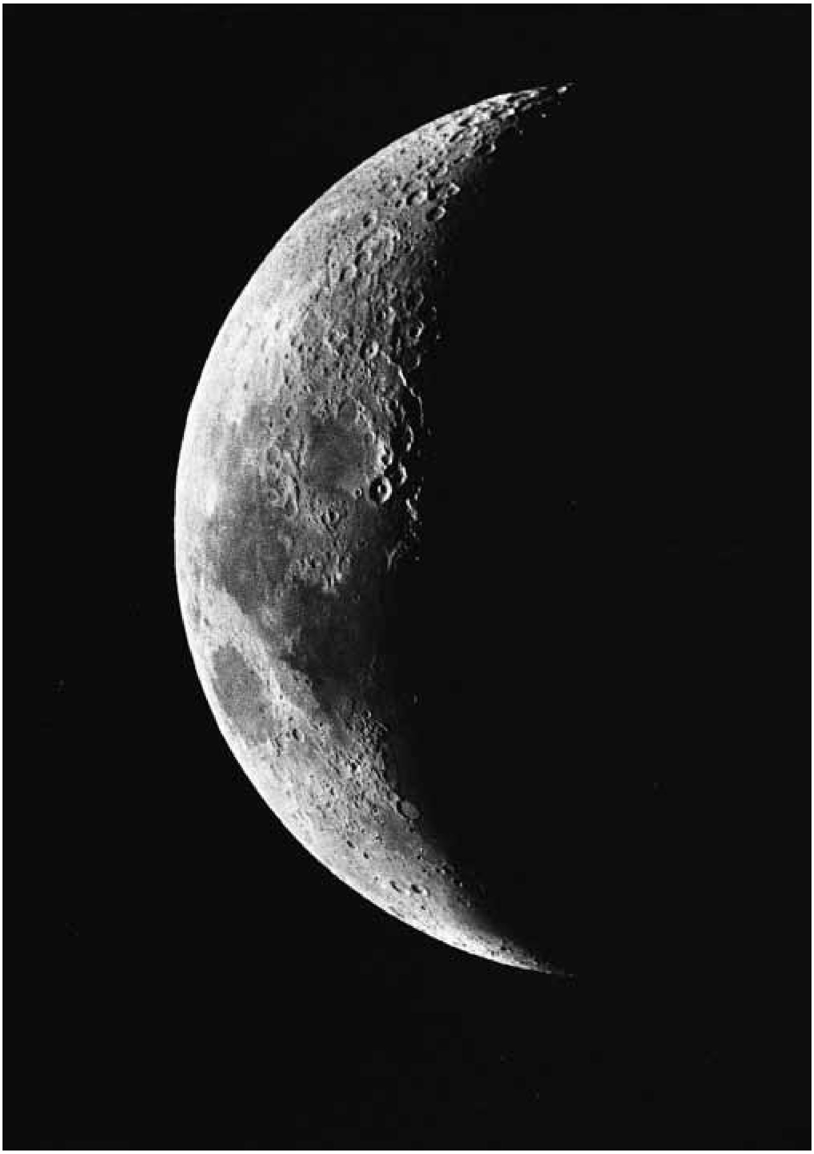


Figure 2.2 The 6-day-old Moon photographed by Tony Pacey. Same arrangement as for Figure 2.1 but he used a 1/60 second exposure on *Ilford* Pan F film, processed in ID11 developer. The photograph was taken on 1992 January 10^{d} 19^{h} 00^{m} UT, when the value of the Sun's selenographic colongitude was 327°.5.

(Lake of Death). These are the smaller mare-type dark plains. They are all easily visible to the user of a pair of binoculars. The lunar equivalent of the Earthly 'cape' is the *promontorium*. An example is the Promontorium Agarum (Cape Agarum) on the south-eastern (IAU co-ordinates) border of the Mare Crisium.

You will find a coarse map of some named lunar features presented in Chapter 7 (p. 152) of this book. In addition, many of the features named in

Figure 2.3 The 11-day-old Moon photographed by Tony Pacey. This time Tony used his 12-inch (305 mm) f/5.4 Newtonian reflector, though with the same technique as he used to obtain the photographs shown in Figures 2.1 and 2.2. The 1/250 second exposure was made on *Ilford* Pan F film on 1992 May 13^{d} 22^{h} 14^{m} UT, when the Sun's selenographic colongitude was 40°.0.

this chapter are discussed in detail in Chapter 8 and images/illustrations of them under differing lighting conditions are included there.

Of course, the view grows more detailed when a proper astronomical telescope is used. Even a small telescope reveals a mass of detail and the sight of the lunar surface in anything larger than a 3- or 4-inch (76 mm or 102 mm) telescope is impressive to say the least. I find that the appearance of the Moon's surface through such a telescope, and using a magnification of the order of ×100, reminds me of plaster of Paris. The waterless 'seas' and other dark plains appear various shades of steely grey and the rougher, crater-strewn, 'highlands' that make up the rest of the surface seem greyish white.

Figure 2.4 The 14.7-day-old Moon photographed by Tony Pacey on 1990 December 31^{d} 20^{h} 15^{m} UT, when the Sun's selenographic colongitude was 78°.7. He used a 1/1000 second exposure. All other details as for Figure 2.1.

When the Moon is close to full (as shown in Figures 2.3, 2.4 and 2.5) its surface seems dazzlingly bright and covered in bright streaks and spots and blotches. At these times it is difficult to imagine that the Moon is made up of relatively dark rock. In fact the Moon's *albedo* is 0.07, meaning that it reflects, on average, 7 per cent of the light falling on it.

Surface features are difficult to make out near full Moon because the sunlight is pouring onto the lunar surface from almost the same direction as we are looking from. This means we cannot see the shadows, so we see very little in the way of the surface relief as a result.

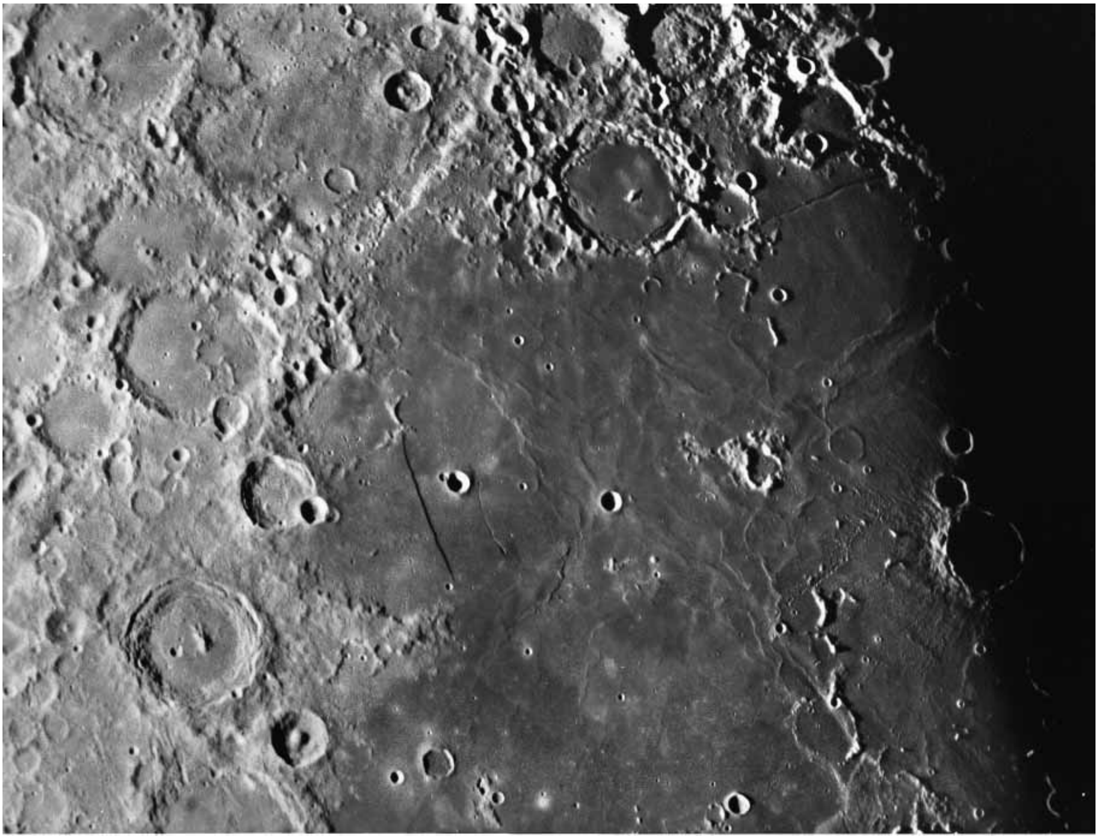
Away from the times when the Moon is full the effect is far less confusing. Shadowing then makes the lunar surface details stand out. This is especially so close to the terminator, where the sunlight is striking the Moon at a very shallow angle. This is evident even by comparing the wide-angle (and hence low-resolution) views shown in Figures 2.1 to 2.5. Notice how the surface relief along the terminator in Figures 2.1 and 2.2 is virtually invisible in the corresponding positions in Figures 2.3, 2.4 and 2.5.

Under low-angle lighting even the lunar maria are shown to be less than perfectly smooth. *Dorsum*, networks of ridges crossing the maria, then become obvious (see Figure 2.6). *Dorsa* are ridges occurring elsewhere than on the lunar maria. They are named after people, for example Dorsa Andrusov and Dorsum Arduino, but the average lunar observer will not have occasion to use these names.

Figure 2.5 The 16-day-old Moon photographed by Tony Pacey on 1992 November 11^d 21^h 45^m UT, when the Sun's selenographic colongitude was 100°.9. The exposure given was 1/500 second. Other details as for Figure 2.3.

If the lunar 'seas' are the easiest features to see with the minimum of optical aid, then the craters must count as the next-most-dominant surface feature on the Moon. These saucer-shaped depressions range in size from the smallest resolvable in telescopes (and smaller, down to just a few metres across, as revealed by the manned landings) to a few that are several hundred kilometres in diameter. The smaller craters vastly outnumber the larger ones.

Following the scheme originated by Riccioli, craters are given the names of famous personalities, most usually astronomers. If it strikes you that this is potentially a rather contentious system then you are correct! Over the years many selenographers had taken it upon themselves to modify the nomenclature assigned by the earlier workers, often putting their own names and the names of their friends onto their maps. The result was that a particular crater might have different names on different maps. Even more confusing, a particular name might refer to different craters on different maps! Fortunately, the system has been overhauled by the International Astronomical Union in modern times. Under the IAU-standardised scheme, craters are still named after famous personalities (with the proviso that the personality is deceased – the only exception to that being the *Apollo* astronauts) and most of the older assigned names have been retained. The IAU nomenclature is most



definitely the one to be adhered to and I would advise caution when using pre-1975 maps.

When seen close to the terminator, craters are largely filled with deep-black shadow and give the impression of being very deep holes. In reality they are rather shallow in comparison to their diameters and can often be quite difficult to identify when they are seen well away from the terminator. Craters saturate the highland areas of the Moon (see Figure 2.7) but there is an obvious paucity of larger craters on the maria. An observer using

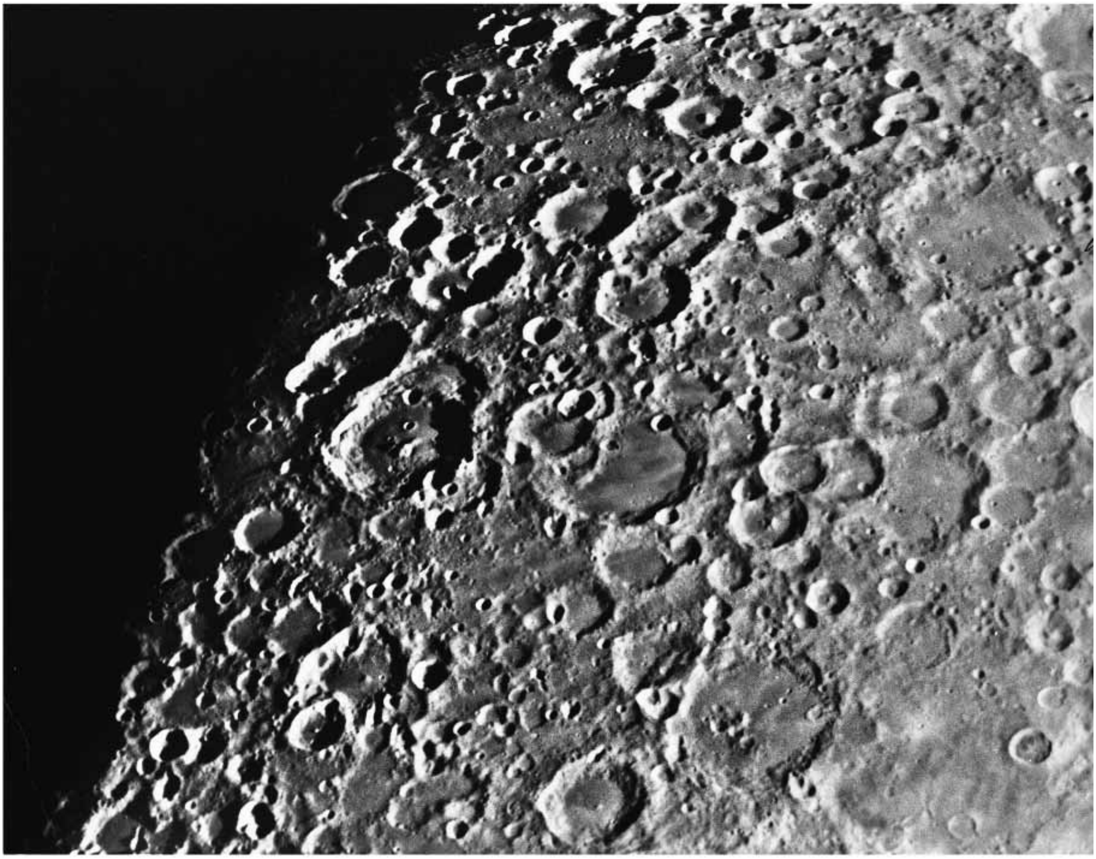
Figure 2.6 With sunlight illuminating the surface at a low angle even the lunar maria appear far from completely smooth. Patterns of ridges cross the part of the Mare Nubium that is shown in this Catalina Observatory photograph. The instrument used was the observatory's 1.5 m reflector and the photograph was taken on 1966 May 29^d 04^h 41^m UT, when the Sun's selenographic colongitude was 22°.6. (Courtesy Professor E. A. Whitaker and the Lunar and Planetary Laboratory, Arizona.)

a typical amateur-sized telescope (around 200 mm aperture) can resolve craters down to about 1–2 km in size and yet many areas of the maria appear craterless. Nonetheless, the photographs sent back by close-range orbiting probes show that even these areas are saturated with small and very small craters. Where there are recognised chains of small craters, these are termed *catena* and are named after the nearest most appropriate named feature. Catena Abulfeda is one example; a 210 km-long chain of small craters near the major crater Abulfeda.

Often the floors of large craters are cluttered with smaller craters and there are many examples of craters breaking into others. In almost all the cases it is the smaller crater which breaks into the larger. Clavius (see Section 8.12), Gassendi (Section 8.22), Posidonius (Section 8.35) and Cavalerius (Section 8.20) are examples of these.

Craters differ in more than their sizes. Some, such as Copernicus, have elaborately terraced walls. Copernicus (Section 8.13) is also an example of one of the many craters to have centrally positioned mountain masses. Other craters, such as Plato (Section 8.33), have their floors flooded with mare material. Some craters have their walls broken down and are almost totally immersed in mare material. Some craters have bright interiors, such as Tycho (see Section 8.46), which is also one of the best examples of craters which are the source of bright streaks of material, termed *rays*, which extend radially from the source crater. Tycho is very easy to see through a pair of binoculars any time close to full Moon, appearing as a bright spot in the Moon's southern highlands. The rays also seem to extend more than half-way around the Moon's globe. Figure 2.5 shows them particularly well. Other craters have relatively dark interiors and no associated *ray systems*. All this tells a story and I will have much more to say about crater morphologies and the evolution of the Moon and its various surface details later in this book. For now, we will continue our extremely brief survey of the main types of lunar surface feature and nomenclature.

After the maria and the craters, mountains (generic name *mons*) and mountain ranges and groups of peaks (*montes*) vie for the attention of the telescope-user. They have been named after their Earthly counterparts, so one can find the Apennine Mountains (Montes Apenninus – see Section 8.5) and Carpathian Mountains (Montes Carpatus – close to the crater Copernicus – see Section 8.13) on the Moon. The lunar highlands are very rough and hummocky, whereas the maria are much smoother. However, mountain ranges often border a mare. Isolated peaks also exist, sometimes actually on a mare. Examples of this type are Mons Piton and Mons Pico (close to the crater Plato – see Section 8.33), situated on the Mare Imbrium. Relatively small blister-like swellings on the lunar surface are termed *domes* but these are not given specific names and are, instead, identified by their



proximity to a known major location in the same way as for the crater chains. The easiest domes to locate are those near the crater Hortensius. These are described in Section 8.21.

The closest match to an Earthly cliff on the Moon's surface is an escarpment (a sudden rise in the ground which continues along an approximately linear, or slowly curved path). The generic name for these features are *rupes*, an example being the Altai Scarp (Rupes Altai – see Sections 8.30 and 8.44) on the Moon's south-eastern quadrant.

As well as the craters and the various raised formations, features sunk

Figure 2.7 The crater-saturated southern highlands of the Moon, photographed using the 1.5 m reflector of the Catalina Observatory, Arizona, on 1966 September 5^{d} 11^{h} 30^{m} UT, when the Sun's selenographic colongitude was 155°.5. (Courtesy Professor E. A. Whitaker and the Lunar and Planetary Laboratory, Arizona.)

below the Moon's surface abound. Gorge-like valleys, called *vallis*, such as the huge Rheita Valley (Vallis Rheita – see Section 8.25) are at one extreme of the size range. Much finer (though often longer) sinuous channels, known as *rilles* (obsolete spelling *rills*; in old books you will also find them often referred to as *clefts*, particularly so the larger examples), also cross the lunar terrain. Several are shown in Figure 2.8. As far as naming them goes, *rima* is used for single examples and *rimae* for networks or groups of rilles. Hence, Rima Hadley and Rimae Arzachel. Many examples are detailed in Chapter 8. All the rilles and most of the lunar escarpments and valleys are named after the closest appropriate major feature. The sole exceptions are: Rupes Altai, Rupes Recta, Vallis Bouvard and Vallis Schröteri.

Figure 2.8 Systems of rilles situated near the centre of the Earth-facing hemisphere of the Moon. Photograph taken using the 74-inch (1.9 m) reflector at Kottamia, Egypt, on 1965 August 4^{d} 20^{h} 43^{m} UT. (Courtesy Dr T. W. Rackham.)

All the foregoing described features can be seen through small telescopes. Even a humble 3-inch (76 mm) refractor is sufficient to show many rilles, despite their being hard to resolve due to their thinness, when they are seen under low-angle illumination from the Sun (and so largely filled with black shadow). They were first noted by Christian Huygens with the primitive telescopes of the seventeenth century.

As I indicated earlier, the Moon appears rather monochrome when seen with a small telescope (aside from the prismatic splitting of light through our atmosphere which causes images seen in a telescope often to be spoiled by colour fringing – discussed later in this book). However, if a sufficient aperture is used then some coloured tints can become visible to the observer. Or at least that is the case for many observers. Sensitivity to colours varies enormously from person to person. Some observers fail to see colour in anything they look at through the telescope. For a few lucky individuals the Universe is a very colourful place. Others can see some colours through the telescope eyepiece, perhaps just the strongest hues on Jupiter and the overall colours of Mars and Saturn.

I am fairly fortunate in that I can easily see colours in many objects through a telescope of sufficient size, though I must say that I have noticed some reduction in my colour-sensitivity as I have got older. I find that I can see subtle coloured tints on the Moon's surface when using a sufficiently low magnification on a reasonably large telescope; for example, ×144 on my 18¼-inch (0.46 m) Newtonian reflector. The overall colour of the rough highlands are still greyish, though perhaps a little 'creamier' in colour than through a smaller telescope, but the large plain of the maria seem tinted with faint blues and greens. In particular, the Mare Tranquillitatis seems especially blue when seen near full Moon. The interiors of some craters, such as Langrenus, appear with a faint brownish or even a golden-yellow tint at these times. Aristarchus appears slightly bluish-white while the raised plateau on which it stands seems particularly brownish to my eyes.

Of course, these colours are very far from accurate. Spectroscopic analysis reveals that the surface of the Moon is really various shades of brown. The human eye has a tendency to normalise the overall colour of the Moon as white. Hence the different shades of brown manifest as the apparent colours seen. A slightly 'redder' brown produces an apparent yellowish or brownish tint, while a 'cooler' shade of brown seems to the observer to be a greenish or bluish tint.

Figure 2.9 shows a specially prepared photograph on which all the usual grey-scale tones have been obliterated. Instead, the shades of grey represent colour differences. Redder tones show up as lighter, and bluer tones show up as darker. Note the relative blueness of the maria and the relative redness of the interiors of many craters. As far as I can ascertain

Figure 2.9 Colour-difference (610 nm – 370 nm). photograph of the Moon The normal grey-scale has been eliminated. Lighter regions are redder and darker regions are bluer.

only a minority of people can perceive these subtle tints through even a large telescope. To most users of small telescopes, the Moon is a world of black and white, and steely greys.

2.2 THE PIONEERING SELENOGRAPHERS

As the seventeenth century progressed so refracting telescope object glasses were made which were a little larger than the first, tiny, examples. However, these lenses were single pieces of glass and so suffered badly from chromatic aberration. The remedy for this aberration (and to an extent the other aberrations that arose mainly from the crudeness of the methods of lens manufacture) was to make the lens of larger focal ratio (and hence greater focal length). To reduce the aberrations to a tolerable level, the focal length had to increase out of proportion to the aperture. So, longer and longer refracting telescopes were made. In some cases the focal lengths reached hundreds of feet (several tens of metres). Even then, the sizes of the objective lenses were still less than 9 inches (23 cm)! Despite this handicap, *selenography*, the charting of the Moon's surface features, steadily improved.

Probably the best map of the Moon made in the seventeenth century was that published in 1680 by Cassini. His 54 cm map (54 cm representing the Moon's diameter), is of remarkable quality considering the cumbersome telescopes he had to work with. Not only is it artistically a fine piece of work but also the positional accuracy of the features it depicts is very good for the time (admittedly it is hardly up to modern standards in this respect!). It showed unprecedented fine details, such as the minute craters (which we now know as *secondary craters*) around Copernicus. It is also more comprehensive in its depiction of features than earlier works, for instance showing the ray systems that surround many bright craters (de Rheita was, arguably, the first to comprehensively chart the rays in 1645) and something of the variations of hue of the lunar maria.

The later years of the seventeenth century also saw the invention of the common forms of reflecting telescope (the Newtonian, the Cassegrain and the now obsolete Gregorian) which eventually led to more manageable and yet higher-quality instruments, and ever better lunar observations.

In Germany Tobias Mayer produced a small, though accurate, map, published posthumously in 1775. He was notable in that he was the first to introduce a system of co-ordinates for lunar surface features, having made his measurements with the aid of a primitive eyepiece micrometer.

As far as the 'leading lights' of selenography go, Germans dominated the period from Tobias Mayer's work through to the late nineteenth century. Perhaps the most famous of these was Johann Hieronymous Schröter. Schröter was a magistrate at Lilienthal (near Bremen, in Germany), where he had enough wealth and leisure time to set up his own observatory. He had various telescopes, including two by William Herschel. His largest (not by Herschel) was a 20-inch (0.51 m) Newtonian reflector of about 8 metres focal length. Completed in 1793, it was the largest telescope in Europe at the time and was surpassed only by William Herschel's 48-inch (1.2 m) of 40 feet (12 m) focal length, though it is thought that the optical quality of the 20-inch was not particularly good.

From 1778 to 1813, Schröter devoted considerable amounts of time and energy to observing the Moon and planets. He set himself the task of making the most detailed map of the Moon to date and he made hundreds of lunar drawings to that end. He used a crude eyepiece micrometer to aid his work, including making measurements of the heights of lunar mountains. He was the first to make a really detailed study of the crack-like rilles. In the end he did not complete his proposed lunar map but instead published the completed sections in a book, *Selenotopographische Fragmente*, in 1791 (a second part was completed and a bound two-volume edition published in 1802). Schröter's work attracted much attention and other selenographers undoubtedly were inspired by the (sometimes controversial) results issuing from Lilienthal.

On the downside, Schröter was not a particularly good draughtsman and he certainly made his fair share of mistakes. In particular he thought he had detected changes on the lunar surface over the years during which he carried out his observations and he was convinced that the Moon possessed a dense atmosphere. Of course, neither are true.

A cruel blow was to befall Schröter when, in April 1813, invading French soldiers looted and then burnt Lilienthal to the ground. His observatory was also looted and then destroyed. At that time Schröter was 67 years old and his health was already in decline. It was too late for him to rebuild his observatory and begin again. Undoubtedly the shock and sorrow he suffered hastened his death. He died three years later.

Wilhelm Lohrmann, of Dresden, also attempted to map the entire face of the Moon in great detail. The first sections of his map were published in 1824 but Lohrmann was eventually defeated by failing eyesight. However, he did manage a general map of the surface of 39 cm diameter. The quest was taken up by Wilhelm Beer and his collaborator Johann Mädler. Beer had a 3¾-inch (95 mm) refractor at Berlin and, together, they used this telescope to study the Moon in detail for over a decade. They eventually (1837) produced a highly detailed and very accurate map. On it, the whole Moon had a diameter of just over 0.9 m. It remained unsurpassed for decades to follow, a significant achievement given the diminutive size of the telescope they used. Beer and Mädler's map was supplemented with their book *Der Mond*. They portrayed the Moon as utterly dead and changeless, in complete contrast to the picture of it painted by Schröter.

Whereas the Moon of Schröter, with its supposed changes and active weather tended to excite the interest of others, that portrayed by Beer and Mädler tended to do the opposite. Given, also, the high quality of their map, the general feeling was that 'the last word' had been stated as regards lunar studies. Few others studied the Moon seriously for more than the next quarter-century.

However, one exception was Julius Schmidt. Schmidt had a lifelong interest in the Moon. After posts at various German observatories, he became Director of the Athens Observatory, in Greece, in 1858. He used the 7-inch (178 mm) refracting telescope there to continue his lunar studies. As well as revising the sections of the lunar maps of Lohrmann, and then going on to complete the mapping of the missing sections, Schmidt was eventually to complete one of his own by 1878.

Schmidt's map, 1.9 m to the Moon's diameter (the map was divided into 25 sections) was incredibly detailed as well as being reasonably accurate. It recorded and placed some 32 856 individual features. It took over the torch from Beer and Mädler as the best lunar map. It was to hold this premier position until 1910, when a 1.5 m map of greater positional accuracy was published by Walter Goodacre, the second Director of the Lunar Section of the *British Astronomical Association* (*BAA*).

This was not Schmidt's only contribution to selenography. Owing to an erroneous interpretation of his, and other people's, observations, he re-invigorated lunar research. The whole episode concerns a small crater, called Linné, in the Mare Serenitatis. Lohrmann, Beer and Mädler, and Schmidt himself had often recorded Linné as a deep crater. Then, in 1866, Schmidt announced that the crater had disappeared! In its place Schmidt could only find a small light patch. As one might expect, a statement like that was sure to get astronomers turning their telescopes back to the Moon. Many leading astronomers joined in and a vigorous debate ensued. In fact, many astronomers continued to cite Linné as a prime example of an area of the Moon that had changed significantly within the history of Man's observations of it, even to as late as the middle of the twentieth century!

We now know that Linné is really a small crater surrounded by a light area. Under certain angles of illumination it can, indeed, appear in the guise of a deep, apparently larger, crater. It seems certain that Schmidt was mistaken. There never was any change in this lunar feature within the period when astronomers were looking at it. However, this mistake was just what was needed at the time to counter the view of the Moon as a dead and uninteresting world that pervaded after Beer and Mädler's epic study of it.

As well as the maps, various other studies of the Moon's topography appeared in the form of books. For instance, there was *The Moon* jointly authored by James Nasmyth (a famous engineer and the inventor of the steam hammer) and James Carpenter. First published in 1874, the authors made serious efforts to understand the origins of the Moon and the evolution of its surface features (though their theories bear little relation to our modern ideas). Much of their researches were based on observations made with Nasmyth's home-made 20-inch (0.51 m) reflector of novel design. Incidentally, the optical arrangement Nasmyth originated is often used in today's largest telescopes and is known by his name. Nasmyth and Carpenter's book also contains beautiful drawings and photographs of sculpted models of regions of the lunar surface (at that time, photography had not technically advanced enough to enable good, detailed, photographs to be taken of the Moon's surface direct through the telescope) along with written descriptions.

Other notable books about the Moon included *The Moon* written by the Englishman Edmund Nevill and published two years after Nasmyth and Carpenter's book of the same name. Actually, Nevill wrote under the name Neison. His book contained a map based on that of Beer and Mädler, along with detailed descriptions of the named features.

If, as a result of the necessary brevity of these historical notes,* I have given the impression that selenography was only carried out by a few individuals then I must rectify that impression. For instance in England there was the *Selenographical Society*, formed in the early 1870s specifically for lunar studies. The *British Association for the Advancement of Science* appointed the Secretary of the Society, W. R. Birt, to head a committee to organise the construction of a new and more detailed map of the Moon. It was intended to be 200 inches (5.08 m) to the diameter of the Moon. Birt was an energetic selenographer and a start was made, though Birt's death and the eventual demise of the Selenographical Society in 1882 meant that the scheme did not bear fruit.

Also, many national and provincial astronomical societies had sections devoted to lunar study. One very active group of the period was the *Liverpool Astronomical Society*. It's director was T. G. Elger, who became the first director of the Lunar Section of the British Astronomical Association when it formed in 1890. In those early years many people spent a great many hours at the eyepieces of their telescopes studying the Moon.

The last really substantial Moon map to be made using the old-fashioned methods of eye and drawing board to record its finest details was the 300 inch (7.6 m to the Moon's full diameter) colossus of H. P. Wilkins. He published the first version of it in 1946 and made revisions in subsequent years. At the time he was Director of the Lunar Section of the British Astronomical Association. The only version of Wilkins' map I have seen is that reproduced in reduced scale in twenty-five sections in the book *The Moon* by Wilkins and Patrick Moore, published by Faber and Faber in 1955. I was lucky enough to find a copy of this work in a second-hand bookshop some years ago, though it is now very rare. The complexity of the hand-drawn details in the map is mind-boggling. Though it is now recognised that Wilkins' map contains many inaccuracies in its depictions of details (I have stumbled across several, myself, without making any effort to find them), the scale of his achievement still warrants admiration.

Photography, invented in the early nineteenth century, was sufficiently developed to come to the aid of Moon-mappers in the last decade of the nineteenth century and, particularly, those of the twentieth century – but that is a tale for later in this book. Now, after this 'potted' history of the earliest years of lunar study (admittedly leaving out much detail and not even mentioning many of the more minor participants), it is time to consider how the observer of today can get the best out of his/her telescope and enjoy and study the Moon's starkly beautiful vistas.

* Note added in proof: just published by Cambridge University Press is *Mapping and Naming the Moon* by E. A. Whitaker – a detailed and fascinating account of the history of selenography.

CHAPTER 3

Telescopes and drawing boards

Why bother to observe the Moon at all, let alone go to the trouble of drawing it? Well, the answer to that is likely to be different for different people. I tried to give you the essence of my personal obsession in the introduction to Chapter 1. Given the fact that you are reading this book, I take it that you have some interest in astronomy in general and, maybe, in the Moon in particular. That at least justifies observing the Moon through a telescope.

What about drawing the lunar surface, though? It is a lot more trouble doing that than passively looking through the telescope eyepiece. Are the results of your efforts going to be scientifically useful? A decade, or more, ago and I would have said "Yes", with a few provisos. Now, I have to admit that there is very little new science to be gained through amateur drawings of the lunar surface. If you wish to obtain high-quality topographic data on the Moon then you would be best seeking out the *Clementine* and *Lunar Prospector* space-probe data on the Internet, or on CD ROM. The various lumps, bumps and other features are now mapped with much greater precision than can possibly be exceeded by an amateur's eye, telescope and pencil.

I have to be brutally honest. There is not really anything much the Moon enthusiast can do at the telescope that is scientifically useful, other than to time occultations (see Chapter 1) and to monitor the Moon's surface for transient phenomena and record any suspicious appearances in a variety of media. This highly controversial field is discussed in Chapter 9.

There are a few minor queries and mysteries that the amateur might help to solve (some of these are highlighted in Chapter 8) but, all in all, the day of the amateur lunar cartographer is long past.

So, why draw the Moon? The mountain climber's adage "because it is there" might suffice as a reason. The Moon's beautiful orb is every bit as much a part of nature as the mountains and valleys, fauna and flora here on the Earth. Drawing the Moon's surface details is also a powerful way of communing with it. The process of doing so will also create a kinship between you and the selenographers of yesteryear who **had** to draw the Moon because there was no more sensitive way of doing it. You will certainly get to know the parts of the Moon you sketch with great intimacy. You might never get to travel to the Moon but carefully observing it through your telescope and drawing what you see through the eyepiece surely comes as a good second-best.

Whatever your reasons for observing, and possibly drawing, the Moon, I hope that you, like me, experience the strongest of all motives for doing it – sheer enjoyment!

Of course, now we come to the 'nitty gritty' of actually doing it. First we must consider the observer's telescope. Unfortunately here I am up against the economics of book production. Space is at a premium. So, can I at this point refer you to my book *Advanced Amateur Astronomy* (Cambridge University Press, second edition, 1997) where I provide general and wide-ranging details about the different types of available telescopes and auxiliary equipment. You will also find there details of their setting up and the necessary mechanical and optical adjustments. In the following sections I offer just a few potted notes on matters of particular relevance to the lunar observer.

First of all, please let me say that if you already own a telescope then use that one for your lunar observing. You will be delighted with the details of our neighbouring world that it can reveal. However, if you are planning to build or buy some new equipment then there is scope (no pun intended!) for making an informed choice. Failing that, there might be ways you can improve your existing equipment to make it more useful for Moon observing. The following notes might help.

3.1 WHAT TYPE OF TELESCOPE DO YOU NEED?

In many branches of observational astronomy a telescope's light grasp is crucial. In such cases a large aperture is normally an advantage. The Moon is one of the few celestial objects that provides us with plenty of light. It is the various other imaging characteristics of the telescope which are most important for lunar and planetary observation. These can broadly be grouped as resolving power and contrast, though there is a degree of interrelation between them.

The image a telescope makes of a point source (in practice, a star) defines what we call the *point-spread function*, sometimes known as the *instrument profile*, of it. The typical diffraction pattern of a star produced by an unobstructed aperture is represented in Figure 3.1(a). Larger apertures produce **smaller** diffraction patterns. It is the size of these diffraction pat-

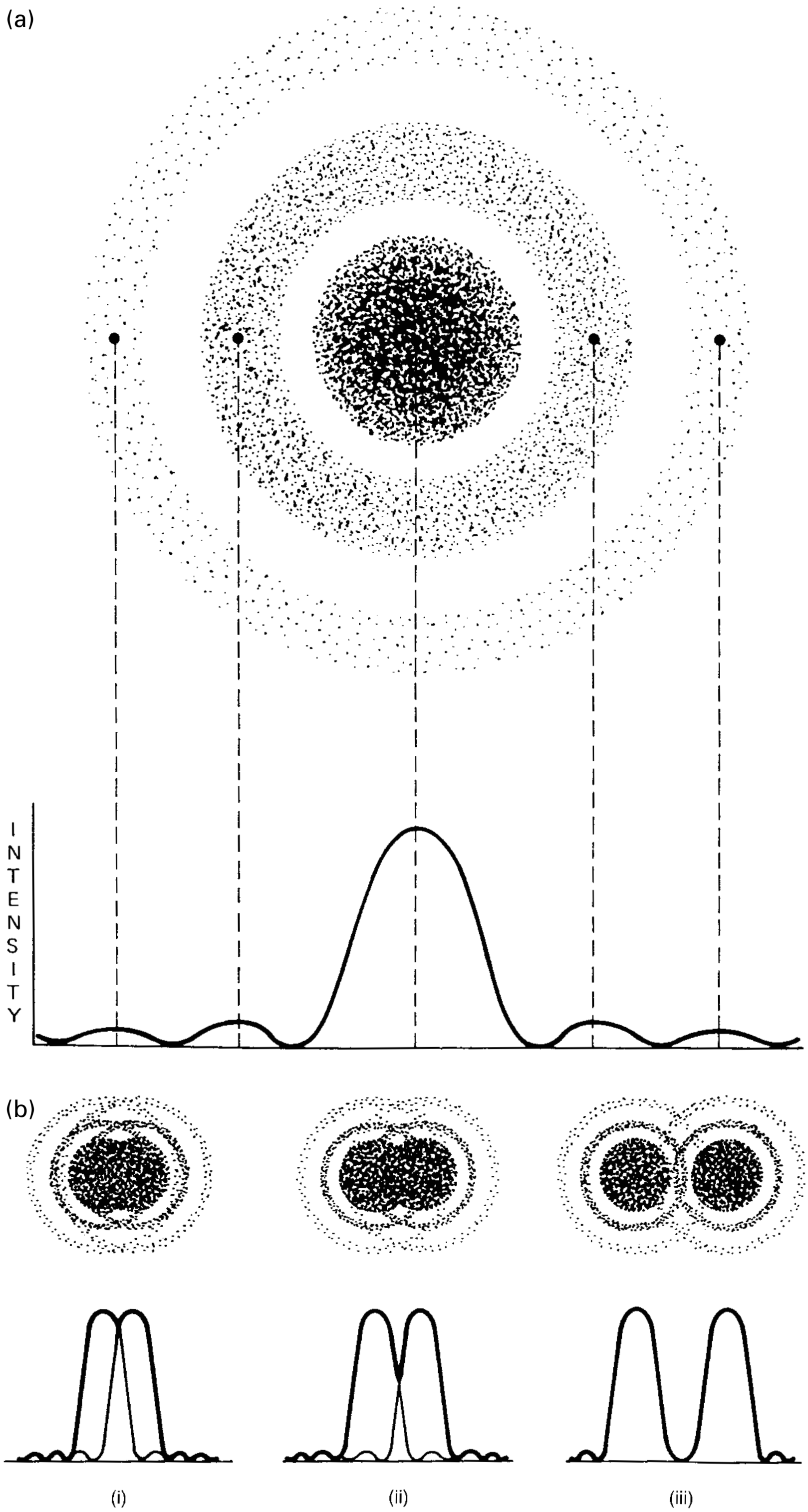


Figure 3.1(a) Idealised representation of the diffraction pattern of a star produced by an unobstructed aperture (for example a refracting telescope). (b) In (i) a pair of stars are too close together for a given telescope to resolve them because the diffraction patterns merge. In (ii) the stars are just resolvable and in (iii) they are easily resolvable. The complex extended image that a telescope forms of the Moon can be, albeit simplistically, thought of as being composed of an array of star-like points in order to understand the principle of resolution of it by a given telescope.

terns that decides whether a telescope has the potential to resolve a close-together pair of stars, or not. This is illustrated in Figure 3.1(b).

So much for stars. We are interested more in resolving details on an extended body – the Moon. The same principle applies. The image the telescope forms of the Moon can be thought of as being composed of a series of overlapping diffraction patterns, each generated by a minute point in the image. A handy way to grasp this is to think of the Moon's image as a mosaic. Obviously the size of the individual tiles determines the fineness of detail that can be represented on the mosaic. If you use a larger telescope the individual diffraction patterns are smaller. This is the same as having the mosaic made up from smaller tiles.

The resolving power, R, of an unobstructed optical aperture is given by

$$R = 137/D, \tag{3.1}$$

where R is in arcseconds and D is the diameter of the aperture in millimetres. This formula is derived from Rayleigh's mathematically derived limit and the numerator (137) is true for the mean visual wavelength (540 nm). Many readers will also be familiar with Dawes Limit. The formula takes the same form but the numerator would be 116 in the above equation. In practice, Rayleigh's Limit gives a truer measure of resolution in images of extended bodies. Note this limit is for details with maximum contrast – in other words, blacks and whites. Low-contrast boundaries are less well delineated.

So, we need a larger telescope to see finer details on the Moon. Is that the end of the matter? Actually, no. There is more to it than that. In practical telescopes the point-spread function is influenced by instrumental design and the accuracy of manufacture of the optical surfaces. We also have to contend with the prevailing atmospheric conditions, but more of that complication later.

On the point about accuracy of manufacture of the optics, again I must refer you to my *Advanced Amateur Astronomy* for a full discussion but I can state here that all the rays collected by the telescope objective from one point on the object ought to be brought to a coincident point in the final-image plane to an accuracy of within ¼-wavelength of yellow-green light. If the ray fronts deviate by more than this amount, about 135 nm, then the diffraction pattern will be noticeably spoilt. The point-spread function will have been changed and both image resolution and contrast will suffer. Even the ¼-wavelength limit is not the ultimate. There would be some improvement in a telescope's performance if it had optics of greater accuracy. However, **most** of the performance can be realised at this universally accepted benchmark of quality.

Of the most common telescope designs (and putting aside any subsequent modifications by the telescope-user), the instrument that comes closest to providing the textbook diffraction pattern structure is the refractor.

Refractors tend to have large focal ratios and this is often cited as a reason why they give good images. Certainly, the relatively gentle curves on optical surfaces with large focal ratios are easier to manufacture with accuracy and this is one reason why refractors make good telescopes for Moon and planet observing. Actually, it is quite possible also to make reflectors with long focal lengths, so this is not an exclusive property of refractors. In addition, large focal ratios allow the simpler designs of eyepieces to function better and this is one real reason for large focal ratios being perceived as delivering better images.

Moreover, refractors generally **have** to have large focal ratios because of a generic problem with them. While the manufacturer designs the refractor to bring the wavelength to which the eye is most sensitive (540 nm) to a minimum focus, inevitably the correct focal positions for the other wavelengths occupy a range of positions extending further from the lens than the minimum focus. This *secondary spectrum* generally shows itself as a softening of contours in the image, together with a reduction in image contrast, and even visible colour-fringing when the problem is severe. Of course, what is tolerable depends upon what one is doing. In any case, the effect of the secondary spectrum diminishes with the square of the focal ratio for the range of sizes and focal ratios normally encountered. Incidentally, the wavefront error (change of focus) for the extreme ends of the spectrum (red and violet light) compared to the yellow-green light can be several times the limit tolerable for the seidal errors (spherical aberration, coma, astigmatism, field curvature and distortion) because of the reduced sensitivity of the eye at wavelengths away from that of yellow-green light.

I have used a number of refractors, both large and small over the years. Based upon my experiences with them I would say that for general lunar work 'old fashioned' two-element achromatic object glasses ought to have a focal ratio of, at the very least, 1.3 times the aperture in inches (0.06 times the aperture in millimetres) in order that the secondary spectrum is not too prominent. Even then the image will not be perfect. As a case in point, I often used the 12.8-inch (325 mm) f/16.4 'Mertz' refractor which was mounted on the 'Thompson' 26-inch (0.66 m) astrographic refractor at Herstmonceux. With it, the Moon's craters were fringed with yellow and the black shadows were filled in with a delicate blue haze! By contrast, the 7-inch (178 mm) f/24 refractor that was mounted on the 36-inch (0.91 m) Cassegrain reflector (the 'Yapp reflector') on the same site gave images of the Moon that were very haze-free and totally free of false colour-fringing.

A few companies, notably Meade, market modern refractors with one component of the two-element objectives made of a special glass. The result is a refractor with a much reduced secondary spectrum compared to one of classical design. These are marketed as 'apochromatic', though that title really belongs to three-element objectives. These have the smallest secondary spectrum (about one-ninth of that of the classical objective of the same focal ratio). The modern two-element 'apochromatic' refractors (they should really be called semi-apochromatic) are much better than the classical ones but not as good as the true triplet apochromatic instruments in terms of the secondary spectra they produce. They are mainly produced with focal ratios of about f/9 and in sizes up to 7-inch (178 mm) aperture. They are expensive for their size but do give superb images.

In the past few years, the Schmidt–Cassegrain (and its close cousin, the Maksutov–Cassegrain) telescopes have become extremely popular. Indeed, they may well be becoming **the** most popular of purchased telescopes. Their compactness, and even portability, lend themselves to the needs of the modern amateur astronomer very well. They are expensive but, for the price, you typically get a computer-controlled instrument that can automatically set and track on any of thousands of celestial objects.

All very well, but how good are they for observing the Moon? Well, if you need computer control to set your telescope to the Moon then something is very wrong! Of course, the portability and compactness aspects are just as much of an advantage to the Moon observer. The downside is that, aperture-for-aperture, they do not give quite as good lunar and planetary images as many other types of telescope.

The reasons are two-fold. One is that the steep curve on the primary mirror (typically about f/2.5 – this is what makes the instruments compact) and the complex curve on the corrector plate (for the Schmidt–Cassegrain, which is the most common type in production; the Maksutov–Cassegrain has a meniscus corrector) are both difficult to manufacture accurately by production-line methods. Inevitably, the optical surfaces will fall just a little short of the ideal accuracy and so the wavefront error will probably be larger than the desired minimum of ¼-wavelength of yellow-green light.

The second reason is common to all telescopes with a central obstruction in the light-path. The central obstruction modifies the diffraction pattern structure. Light is taken from the central disk and given to the rings. This modification of the point-spread function only slightly impairs resolution within an image composed of a pattern of blacks and whites. However, it seriously reduces the visibility and resolution of low-contrast details, especially where those low-contrast markings appear against a bright background. This is usually the case for seeing details on the planets. While it is true that details seen along the Moon's terminator are mostly nearly-blacks and nearly-whites, there are subtle shadings which also form part of the scene. In addition, the reduction of contrast is worst for the smallest details in the image, making things very hard to discern near the diffraction limit. The central obstructions of Schmidt–Cassegrain telescopes are usually at least one-third of the total diameter, the largest for any type of telescope commonly in amateur hands.

The two problems, shortfall in optical accuracy and the central obstruction, each produce additive effects on the point-spread function. The common f/10 Schmidt–Cassegrain telescopes on sale have to have apertures around twice as large as the best refractors in order to show the Moon and planets as well under identical excellent conditions.

The telescope that still gives the observer the best value for money is the Newtonian reflector. Any manufacturer can produce a poor Newtonian telescope but at least it is not too difficult for the manufacturer to produce a good one. The obstruction due to the secondary mirror tends to be about one-quarter of the telescope aperture and providing the mirrors are of high optical quality the resulting Newtonian telescope will produce better Moon and planet images than will the Schmidt–Cassegrain of the same aperture, though still down on what the good refractor can show. However, it will be much cheaper than both.

If you decide to buy or build a Newtonian reflector specifically for observing the Moon and the planets, go for a focal length as large as is practical for your situation (size of garden, size of observatory, etc.), while ensuring that it is firmly mounted. A gangling, spindly affair will flutter in the breeze and shudder with every touch of the focuser – not something that is conducive to good observing!

For purely visual work the telescope need not be driven. Of course, a drive is an advantage as long as it works properly. The requirements for photography and electronic imaging are discussed in later chapters in this book.

Should the telescope have an open framework tube, or one that is solid? The ultimate in baffling against stray light is not essential for Moon and planet work but warm air from the observer can cause problems if it gets into the telescope's light-path. A solid tube prevents this to some extent. However, convective tube currents generated by warm optics and fittings can also degrade the image produced by solid-tubed reflectors. In particular, the thermal lag of the primary mirror can give a lot of trouble. Here, an open tube is an advantage. Vents, and even electric fans installed near the telescope primary mirror, can help matters. My 18¼-inch (0.46 m) reflector has an open-framework tube, while my 8½-inch (216 mm) has a solid tube. On some nights the images produced by the 8½-inch are poor and star images betray the obvious presence of a tube current (sorry, again I must

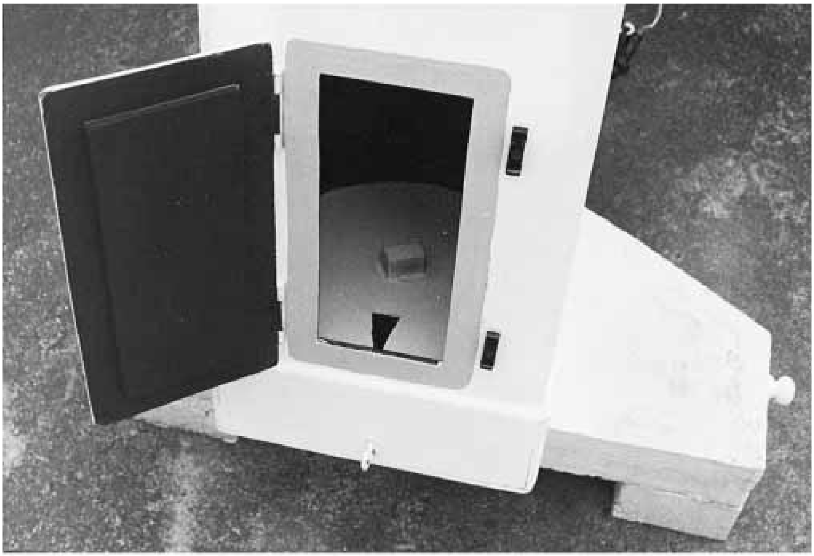


Figure 3.2 The door in the author's solid-tubed 8½-inch (216 mm) Newtonian reflector giving access to the primary mirror cover. It is also useful in ventilating the mirror and cell, so minimising tube currents.

refer you to my *Advanced Amateur Astronomy* for explanations and details). There is a door installed in the tube close to the primary mirror (see Figure 3.2) to gain access to the mirror cover. Opening this door significantly improves the images on those nights, since it lets much of the warm air convected from the primary mirror to escape, rather than passing up the entire length of the tube.

In conclusion, I think the best design is to have the telescope tube partly closed, especially near the eyepiece. It should, though, be open near the primary mirror (or at least well ventilated) to suppress tube currents.

Having the mirrors cool quickly is also desirable to suppress tube currents. A thicker-than-necessary primary mirror and an unventilated cell will work against this. Closed optical systems, such as refractors and Schmidt–Cassegrain telescopes, are less troubled by tube currents, though both need to cool off for a while if brought out from indoors before observing.

Cassegrain telescopes are expensive and tricky to collimate. They are rare among modern amateur astronomers. The secondary obstruction is usually a little larger than that of the Newtonian but they do share the advantage of the Schmidt–Cassegrain in having a long effective focal length in a short tube assembly.

For general (mainly visual) observing of the Moon and planets I would recommend the modern semi-apochromatic refractor if money is of no object. If value for money is sought, I would say go for the Newtonian reflector. It is also the telescope most adaptable for other types of work. Of the other common types, the production Schmidt–Cassegrains would be my third choice because classical Cassegrains would likely cost more, size-for-size, even though they should give better images.

So much for type. What about size?

3.2 HOW BIG A TELESCOPE DO YOU NEED?

If the optical transmission characteristics of the Earth's atmosphere were perfect and the telescope was in a perfectly temperature-stable environment, then it would be a case of 'the bigger the better' as far as the aperture of the telescope goes. The one caveat is that size must never be at the expense of quality.

Of course, the telescope is **not** in a temperature-stable environment and the normal observing conditions are anything but perfect – and that changes matters very considerably.

I still put quality above sheer size when it comes to selecting telescopic equipment. You will have a great deal more satisfaction from working with a telescope of good mechanical and optical quality of moderate, or even small, size than you will from a much larger light-bucket. If your budget can stretch to a first-class 6-inch (152 mm) telescope or a mediocre 8-inch (203 mm) one, or even a tempting but poor-quality 10-inch (254 mm) instrument, put out of your mind any thoughts about impressing your neighbours and friends and go for the 6-inch instead. I guarantee that if you could try all three together one night for Moon observing, it would be the smallest one that would give you the best view and the greatest pleasure as a result.

What if one is rich enough to have quality **and** size? Will a bigger telescope always outperform a smaller one of equal quality? Based on my thirty years of experience of lunar observing with a large variety of telescopes of differing size and design (ranging from a 60 mm refractor to a 0.91 m Cassegrain reflector), my answer to that question is "No". In fact, sometimes even the reverse is true. Understanding why this should be so is not very difficult. There are two main reasons.

Firstly, the column of air through which the telescope is looking is seething with convective pockets, or *cells*, of air of slightly differing temperatures, and hence differing density and *refractive index*. The ones that affect the telescopist to the greatest extend are from 10 to 20 cm in diameter and can occur from just in front of the telescope to many kilometres in height. Each of these cells disturbs the passage of light-rays passing though it. The result is that the telescope cannot produce a sharp and steady image at its focus. The blurred and mobile (we say *turbulent* or *bad seeing*) image that results is well known to all telescope users. However, most do not appreciate just how severe the limitation really is. From most backyard sites the seeing rarely allows details to be resolved that are finer than about 1 arcsecond in extent. For an object situated at the Moon's distance this is a linear dimension of about 1 mile (about 1.6 km).

A good-quality 6-inch telescope will allow you to resolve this level of detail. A bigger instrument will not show you any finer detail on those '1 arcsecond' nights. Of course the image will be brighter when seen through the bigger telescope and the contrast of the image (at least for coarse details) will be greater, the comparison being made at a given, adequate, magnification. In ordinary conditions, the advantage of large apertures in seeing faint planetary markings (and delicate shadings on the Moon) is not as great as one might expect. While I have experienced rare nights where my 18¼-inch (0.46 m) telescope shows views of Jupiter and Saturn reminiscent of *Voyager* space-probe images, I must say that the normal view is much fuzzier and washed-out. On those normal nights I find that my 8½-inch telescope can show these bodies just as well as my 18¼-inch.

Indeed, **sometimes** the bigger telescope will produce significantly poorer images than will the smaller one. If the small-aperture telescope can look through just one convective cell of air at a time, then the image will 'slurp' around its mean position and may distort. However, it will remain quite sharply defined. If the telescope aperture is bigger, then it is looking through a column of air that may include several convective air cells at any one moment. Each cell will produce its own, random, effect and the telescope will combine them. This time, the image will be composed of a number of overlapping components, each one shifting and distorting in a separate way. The end result is a confused and blurred image. It may often be preferable to have the one sharply defined, but admittedly gyrating and distorting, image rather than the confused mess.

The second reason why a bigger telescope is not always better was discussed in the last section – namely thermal effects. The smaller the mass of the telescope, the quicker will it cool to the ambient temperature and so not be troubled by convective currents of air from its optics and fittings. Optical surfaces can also badly distort in steep temperature gradients.

All in all, if you can afford it, I would say go for a Newtonian reflector of 10-inch – 16-inch (254 mm – 406 mm) aperture and as large a focal ratio as you can reasonably accommodate. Bear in mind, though, that the number of nights that you will get full performance, even from a 10-inch, will be very few if your site is anything like mine! If your observing site is consistently poor, as regards atmospheric turbulence, then you may be better off with a 6-inch (152 mm) or 7-inch (178 mm) 'apochromatic' f/9, or f/14–f/20 achromatic, refractor at a similar cost (several thousands of pounds/dollars, plus the cost of housing it).

3.3 EYEPIECES AND MAGNIFICATION

Full descriptions of the types of eyepieces and their imaging characteristics are given in, you guessed it, *Advanced Amateur Astronomy*. In general, if the effective focal ratio of the telescope is f/10 or more, then any of the simpler types will be suitable for lunar observing. Ramsden, Achromatic Ramsden and Kellner eyepieces are commonly available and the modern ones invariably have *bloomed* (anti-reflection coated) lenses. Blooming is highly desirable in order to avoid annoying inter-glass reflections and a general reduction of image contrast. They differ in field size. Ramsdens have apparent fields of about 35°, while the other two generally have apparent fields of about 40° and will give good images in f/6 telescopes with focal lengths longer than 12 mm. (Actual field = Apparent field/Magnification, so a Kellner eyepiece might give a field of ¼° if it produces a magnification of ×160 with a given telescope). Ramsdens will not work well with telescopes of ratios lower than f/10. A general softening of the image and even colour-fringing will be visible when used on lower focal ratios.

Classical Huygenian eyepieces should not be used with focal ratios of less than about f/10 but the modern continental ones generally have a modified design and can work well with focal ratios down to about f/8. They have apparent fields of view around 30°.

The best type of eyepiece for lunar and planetary observation, the Monocentric, seems to be incredibly rare these days. This cemented triplet gives crisp and false-colour-free images even with f/5 telescopes, the disadvantage being a smallish field of view (apparent field about 30°). I wish they were still available. The Tolles eyepiece is really a solid (one piece of glass) version of the Huygenian eyepiece. The field of view is small (25–30°). Now obsolete, it also used to be a favourite of planetary observers, producing crisp and false-colour-free images with focal ratios down to about f/7.

If you have a telescope of focal ratio f/10 or less and want modern eyepieces for lunar and planetary observation then you will be best served by the easily available Plössyl type. They typically have fields of view of around 50–55° and produce high-quality images with any telescope of focal ratio above f/5. They have largely superseded Orthoscopics as the choice four-element eyepiece, even though the finest examples of the Orthoscopics are slightly superior in imaging characteristics (except size of the field of view – apparent field diameter 40–45°) to the Plössyl type.

Apart from the possible exception of Nagler eyepieces (which can also work well with focal ratios down to f/4.5, maybe even f/4), I would not recommend using any of the wide-field eyepieces for lunar and planetary observation, as most lack critical definition and some are troubled by scattered light and ghost images, despite blooming.

Barlow lenses can be useful. The most common form of this accessory consists of a diverging (convex or plano–convex) doublet lens set into one end of a tube, or series of tubes. This end is plugged into the telescope draw-tube while the eyepiece is plugged into the other. The reduction of the convergence of the rays from the telescope objective has the consequence of multiplying the effective focal length of the telescope by a given factor. This is usually ×2 but can be anything the manufacturer desires. All this will be common knowledge to most readers. However, not all may realise that the **effective focal ratio** (**EFR**) of the telescope is multiplied by the same factor. Thus an f/5 telescope is converted to an f/10 one, using a ×2 Barlow. As well as the obvious multiplication of the magnification of the telescope by a given eyepiece, using the Barlow lens allows the simpler (and cheaper!) eyepieces to be used if so desired.

One note of caution, though; adding more lens elements into the optical path will increase the amount of light absorbed and scattered. Of course, blooming, and ensuring the lenses are scrupulously clean (not always easy to do) will go a long way to negating this. Also the Barlow lens must be of high optical quality if it is not to degrade the view produced by the telescope. Regrettably, this is not always the case.

In particular, if your telescope has a focal ratio of less than f/6 I would caution that a common two-element Barlow lens will introduce enough chromatic aberration to produce noticeable colour-fringing when used with powerful (focal length less than a centimetre) eyepieces. Some manufacturers supply triplet (apochromatic) Barlow lenses and I would recommend you obtain one of these if you want to use it with a reflecting telescope of low focal ratio. By easing the load on your eyepieces, a first-rate apochromatic Barlow lens may actually upgrade the quality of the images your low focal ratio telescope can produce, despite any slight negation due to scattered light. In addition, a few well-chosen eyepieces are sufficient, if used in conjunction with one or more Barlow lenses, to deliver a large range of magnifications with a given telescope.

What about the actual values of magnification? Here I must stress that personal preference must rule the day. Having one eyepiece in which you can view the entire Moon in one go is highly desirable, especially for occasions such as eclipses. The actual field imaged must therefore not be less than about 0°.6. This means a magnification of no more than about ×66 (for an eyepiece with a 40° apparent field) to ×86 (52° apparent field eyepiece). Having a set of eyepieces that can deliver a series of higher magnifications (and perhaps a Barlow lens to help fill in the steps) is also desirable. If the observing conditions were perfect (and the telescope were of good quality) then I would normally prefer a magnification roughly equal to the aperture of the telescope measured in millimetres. However, ‘fussy’ detail, such as the individual peaks in a lunar mountain range, might be better appreciated with higher powers, perhaps up to ×2 per millimetre of aperture. Poorer conditions demand lower powers, of course, as do broad features of low contrast.

Most of my lunar observing is done with powers of ×144 and ×207 with my 18¼-inch (0.46 m) reflector because of the usual, 1 arcsecond, seeing conditions at my observing site. Even then, the 1 arcsecond figure refers to the brief glimpses of fine detail, not the average amount of blurring and distortion which amounts to several times this value. I seldom see any real advantage to using higher powers, though on a few outstanding nights I have had incredible views at ×432. Sadly, those instances have been very few and far between – how I wish it were otherwise!.

3.4 MAKING THE BEST OF WHAT YOU HAVE

Let us say that you have a great big 'light-bucket' of a Newtonian reflector with a low focal ratio, mediocre optics, and a large secondary mirror. Perhaps it is one of the cheaply produced large Dobsonian-mounted telescopes. It will come supplied with one or more low-cost eyepieces. You find it gives very bright but disappointingly blurred images of the Moon. Can you improve matters without having to buy another telescope? I am glad to say that the answer is "Yes".

Let us consider the eyepieces. The set that the light-bucket has will undoubtedly work better with a telescope of higher effective focal ratio (EFR). If your telescope has a focal ratio lower than f/5 or f/6, then you might be advised to obtain a triplet (truly apochromatic) Barlow lens in order to raise its effective focal ratio, as described in the foregoing section. A more expensive alternative is, of course, to buy a higher-quality set of eyepieces. The foregoing notes should help you make the choice.

What about that big secondary mirror? You might like to consider replacing it with a smaller one. However, you can't make it too small or you will effectively stop-down your telescope (unless that is a deliberate choice – large cheap primary mirrors are often of poorest accuracy in their outer zones, so blanking off these zones may actually improve the image quality!). If the distance from the telescope focal plane to the secondary mirror, measured along the optical axis, is A and the focal ratio of the telescope is f, then the minimum diameter d of the minor axis of the secondary mirror, A, has to be:

$$d = A/f, \tag{3.2}$$

where d, A and f are all measured in the same units. This bare-minimum diameter **just** allows the very centre of the field of view to be fully illuminated by the rays from the entire primary mirror surface. There will be some vignetting of the rays away from the centre of the field of view.

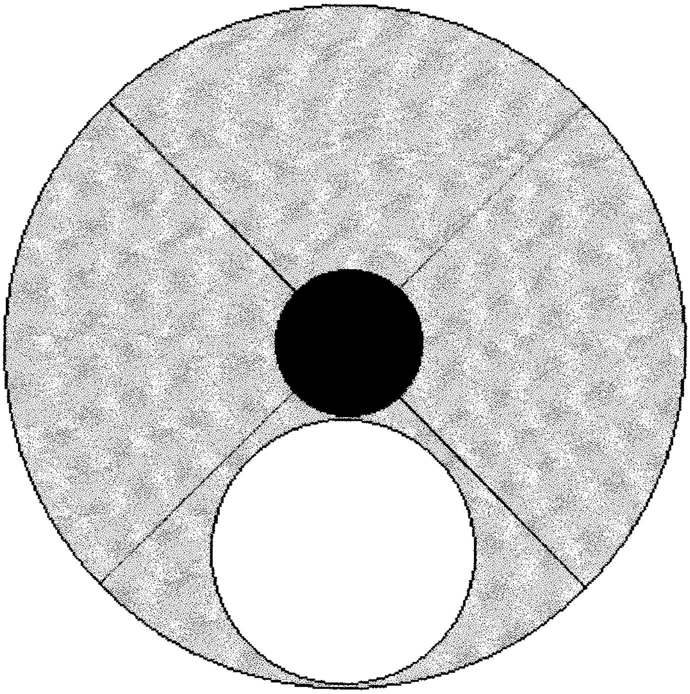


Figure 3.3 An off-axis stop for a reflecting telescope. Unless the mirror is thin enough to distort along its lower edge (unlikely in amateur-sized telescopes) positioning the aperture to expose the lower part of the mirror will normally provide the best images. This is because all of the mirror surface will normally produce upwardly moving convective warm air currents. Positioning the aperture over the lower regions minimises the amount of convecting air the light rays have to pass through.

However, you will find that for purely visual work you will not notice the slight dimming of the image towards the edge of the field of view. Of course, if the telescope had a larger focal ratio to start with, it could already have a secondary mirror that is very small. Despite the outfield vignetting, the image contrast will be at a maximum when the size of the secondary obstruction is at a minimum, as outlined earlier.

The advantages of using off-axis stops over the telescope aperture is hotly disputed. My own experience is that stopping my 18¼-inch (0.46 m) telescope down to 6 inches (152 mm) with a cardboard diaphragm **sometimes** improves the images the telescope delivers. When the seeing is particularly rough and the images of details tend to be multiple and confused the stop sometimes 'cleans up' the view, as described earlier.

Certainly if the optics of the telescope are of poor quality, then stopping the instrument down will usually imporve matters, whatever the seeing. Also the diffraction pattern produced, using the stop, is more refractor-like, even if it is broader because the aperture generating it is smaller. Obviously, the hole in the diaphragm is made and positioned to avoid the secondary mirror and its support vanes (see Figure 3.3). A 16-inch to 20-inch 'light-bucket' may be made to perform like a high-quality 5-inch to 7-inch refractor in this way. Try this for yourself. All it takes is a few minutes to mark and cut out a piece of cardboard to suit your telescope. However, I would caution you to only use the diaphragm if you see a definite improvement in the image. Otherwise the diffraction limit imposed by the reduced aperture might mean that you miss the occasional flashes of fine detail that one usually gets on even poor nights.

If your telescope is deficient in its mechanical construction then perhaps you can make or purchase some replacement parts to improve matters. If the optics are good you might even think about rebuilding the instrument and just salvaging some of the parts of the original. At the same time you can make any changes that will improve its thermal characteristics. However, that is taking us into matters which are beyond the remit for this book. Let us now, at long last, get down to some actual observing and drawing of the Moon's beautiful vistas . . . .

3.5 DRAWING THE MOON

Given the telescope, the basic equipment consists of some sort of clipboard with a source of attached illumination. A small piece of hardboard, or a large dinner mat, a switch, a torch bulb and holder, a small square cardboard or metal box (to mount the bulb in its holder at the head of the board), a switch, some wire, a battery (perhaps mounted on the board by means of a Terry-clip) and terminal connections (or soldered joints), or alternative materials, can easily be fashioned into something appropriate. Adding direct shielding from the bulb is also desirable and a small rheostat is also useful for brightness control. However, keep it simple and, above all, keep it lightweight.

Your drawing can be a simple line-diagram. At the other extreme it can be a photographic quality work of art showing all the half-tones. What is possible depends on your abilities. This will, of course, improve with practice. Even if your work is not to be used for cutting-edge research, astronomy is still a science. **Therefore your drawing must be accurate**. Your fellow astronomers will think little of the most picturesque representation that you can produce if it is inaccurate in its proportions and positions. Even the simplest representation that is accurate is always vastly preferable.

I ought to emphasise that there are many ways of achieving good representations of the Moon's surface. There is a large array of materials – pencil, pen, ink, charcoal, paint, etc. – to be used on an equally large array of papers, canvases, etc. Each will demand its own techniques. Moreover, each individual will undoubtedly find various ways of working that suit him/her best. Consequently, all I will do here is to offer a few guidelines, based on my experience, which is very limited when it comes to drawing the Moon, and that of others who are more experienced.

Andrew Johnson is one of a number of amateur astronomers producing superb representations of the lunar surface. He has written an article outlining his own methods, and giving good general advice for the tyro, in the *Association of Lunar and Planetary Observers* (*ALPO*) publication *The Strolling Astronomer (Volume 37, Number 1, May 1993, pages 18–23).* Andrew has generously let me reproduce some of the illustrations from that article here. The good advice he gives is pretty universal and much is the same as that given herewith. Even so, if you are seriously interested in making high-quality drawings of the Moon then I recommend you seek out his article. I am most definitely not one of the 'grand masters' of lunar drawing. He is.

When you first go to your telescope try not to spend too much time deciding what to draw. At least having an outline plan for the evening will save you a lot of time and effort when you should be actively observing, even though unpredictable weather and observing conditions will demand some flexibility on your part.

Having decided on your chosen target, spend a while scrutinising it with different magnifications before committing anything to paper. **Do not attempt to take in a large area in one go**. The area you should cover in your drawing should certainly not be greater than about 200 km square on the lunar surface. Better still if it is smaller. When you are about ready to begin drawing, aim for a scale of at least 2 km per millimetre.

Considering just the simplest line drawings, you might generate the sketch entirely from the view through the telescope straight on to a blank sheet of paper. If so, you will achieve the best accuracy by starting with a set of faint pencil guidelines to help you with the proportions. This is illustrated in Figure 3.4(a), which shows the first stage of a drawing of the crater Mairan by Andrew Johnson. Keeping the guidelines very light allows them to be erased easily once the major details are blocked in, as they have been in Figure 3.4(b).

Alternatively, you could base your sketch on a pre-prepared outline of the major features. Your work at the telescope would then consist of filling in the fine details and the shadows. You might make an outline by tracing over a suitable photograph. This technique ought to produce a greater positional accuracy in the drawing, though you must not ignore the effects of libration, especially for features near the lunar limb. The libration value at the time of your drawing is unlikely to be similar to that when the photograph was taken.

The real Moon has shades of grey on it, as well as blacks and whites. There are a number of ways you can represent these on your drawing. One is to add numbers to the areas, representing brightness gradations. Figure 3.4(c) shows the next stage in Andrew Johnson's drawing of Mairan. On the scale Andrew has used 0 represents black and 10 represents brilliant white. This can be the finished product.

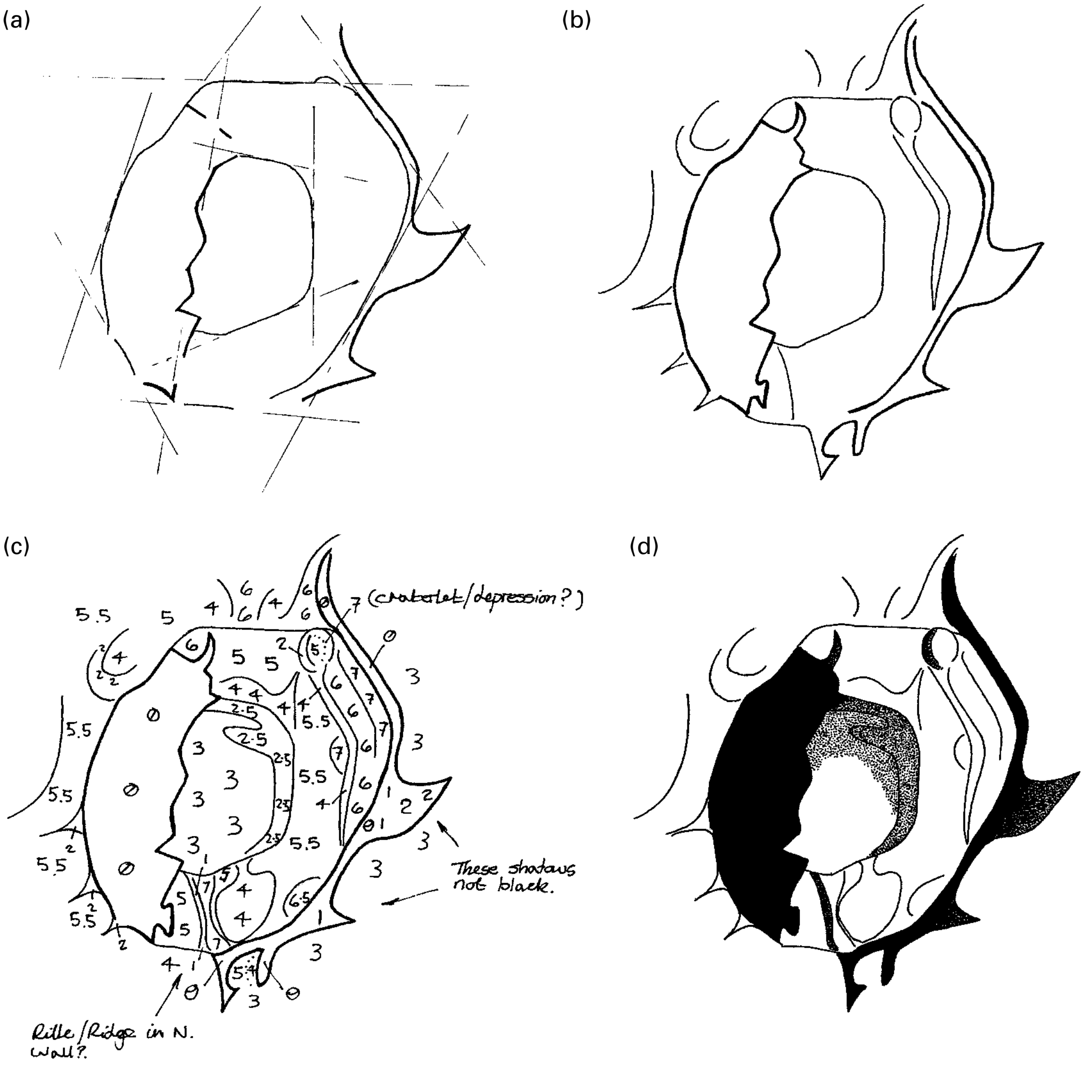
Alternatively, the outline sketch can be carefully traced and, using the numbered original, the shades of grey can be built on in pencil, or what other medium is chosen on the copy. Most of the really first-rate lunar artists use this approach. Obviously, the finished version of the drawing is made after the observing session. This demands that everything is meticulously noted during the observation. Never rely on your memory of what you think you saw through the eyepiece of the telescope. Get it right at the telescope and you will have no temptation to make subsequent alterations to your drawing.

When you have finished your initial sketch, spend a little time comparing it with the scene through the eyepiece. Any perceived inadequacies of your drawing that you do not feel able to correct can always be noted along with it, e.g. ‘small crater should be drawn 20 per cent larger’, etc. Do not forget to include all the usual details of date, time, instrumental details, magnifications, seeing conditions.

You might prefer to make your final version at the telescope, complete with all shades of grey and the black shadows filled in. I have found that this is only possible if you work with very small, and hence simple, areas of the lunar surface. Close to the terminator the shadows change noticeably in just a few minutes. While it is certainly true that you can lay the outline down and then note the time, subsequently spending time doing the shadings, you will find that there is simply not enough time to do a complicated drawing before the lighting over the scene changes too much. Ideally you ought to complete your sketch within half-an-hour.

If you do want to do the whole thing, and produce the finished drawing at the telescope, it is highly desirable you take steps to save time and so work with maximum efficiency during the observation period. Having a pre-prepared outline is particularly useful, as is greying the picture area of your paper before hand. You could use pencil shading for this, or even sprinkling on a little charcoal powder, in either case then smoothing with the finger. At the telescope, a clean rubber can be used for creating the lighter areas and a sharply pointed rubber effectively doubles as a ‘white pencil’. Darker shadings can be built up with pencil, and black felt-tip pens, with fine and broad tips as appropriate, can be used to create the black shadows.

If you decide to produce the final version of your drawing after the observing session then, as already stated, the ways you can do it are almost unlimited. However, not all methods will be conducive to subsequent copying. Having back-up copies and copies to send to observing groups, etc., is often desirable. The cheapest, simplest, and most widely available method of copying, these days, is by way of a *Xerox* or other photocopying



machine. These can reproduce any image composed of lines and dots very accurately. Unfortunately, photocopy machines often do not reproduce half-tone images very well. Consequently, many lunar artists use stippling as a way of representing half-tone shadings in their finished drawings. In his *The Strolling Astronomer* article, Andrew Johnson suggests using a pen (the choice ranging from the expensive professional drafting pens, to the cheap but less durable felt-tips) with a point diameter of 0.3 mm. With great patience the shadings are built up, dot by dot. Andrew uses a desk-mounted magnifying glass, and provides good illumination to ease eye strain. The greater the density of the dots, the darker the shading when

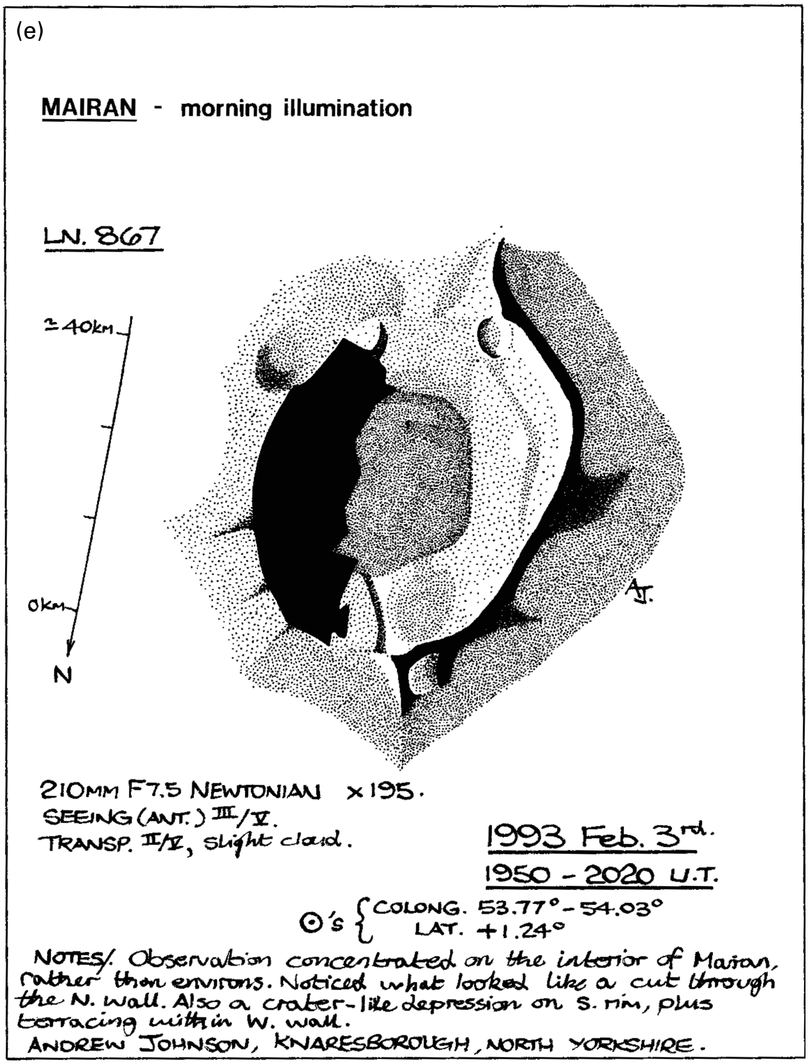


Figure 3.4(a)–(e) Stages in the drawing of the lunar crater Mairan by Andrew Johnson. See text for details.

the drawing is viewed from the normal distance. Andrew typically takes around 2 hours to produce the finished version of one of his drawings. Figure 3.4(d) shows the process underway for his Mairan observation and Figure 3.4(e) shows the final result.

Personally, the whole stippling process makes me exhausted just thinking about it! Nonetheless Andrew's output is very high, as is that of his co-workers, including Nigel Longshaw and Roy Bridge. Many examples of their fine work are shown in the 'A to Z' section of this book, Chapter 8. You will find there many examples of how they represent different types of formations and lighting aspects.

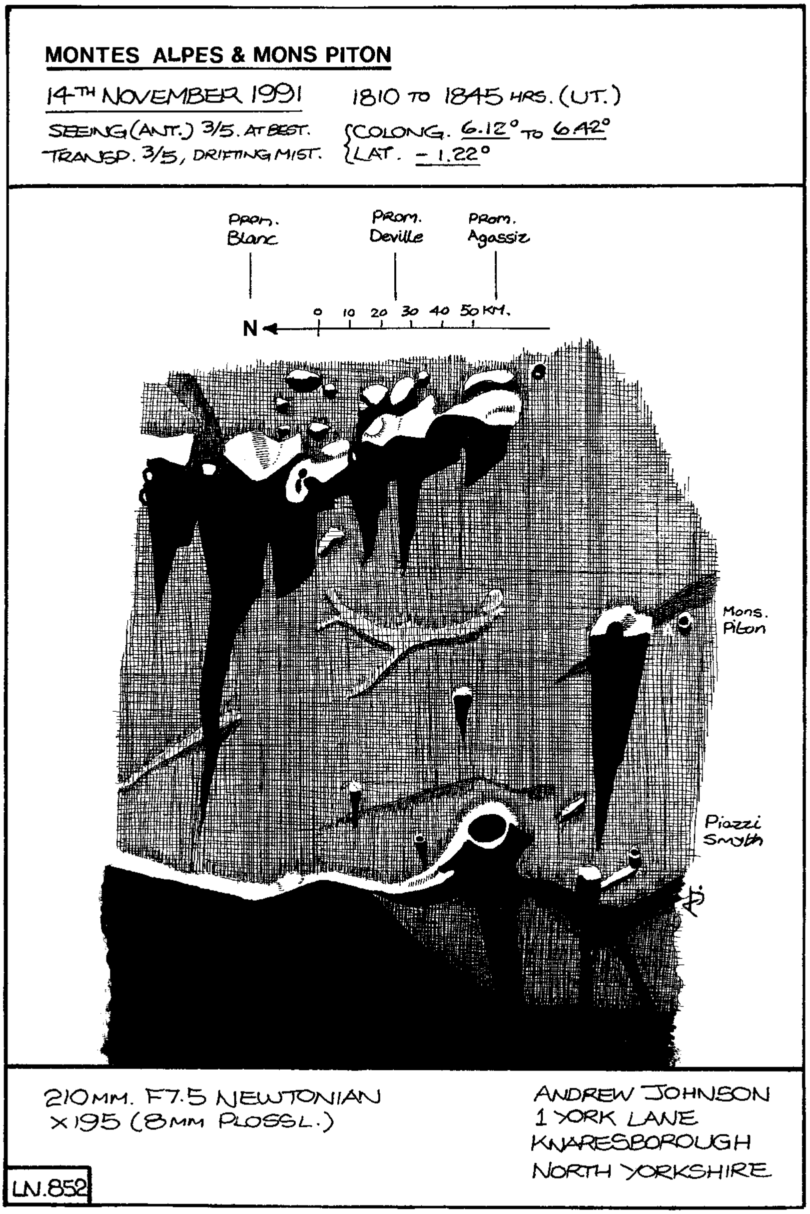


Figure 3.5 One alternative to the stippling technique is cross-hatching, here illustrated in a drawing of Montes Alpes and Mons Piton by Andrew Johnson.

In addition, all three acknowledge the legendary Harold Hill as the supreme master of lunar drawing and the stippling process. He has been studying and drawing the Moon's vistas for over five decades and many of his superlative drawings are shown in his *A Portfolio of Lunar Drawings*, published by Cambridge University Press, 1991.

If the sheer labour of the stippling process puts you off, you might try normal pencil shadings but on stippled paper (obtainable from an art shop), or with normal paper placed over coarse sandpaper. This will create ‘pseudo-stippling’ which will photocopy much better than plain shading alone. Varying the pressure of the pencil creates larger or smaller dots, producing the required shading variations when viewed from the normal distance. Nonetheless, the best result will come from true stippling.

An alternative to stippling that will still photocopy well is cross-hatching. Figure 3.5 shows a striking example of this method produced by Andrew Johnson. Of course, if appropriate copying methods (laser copier, computer-scanner with ‘photo-quality’ output, etc.) are used, then less-arduous methods can be used to make the final drawing.

One rung up the technological ladder from making drawings of the Moon is to photograph it. That is the subject of the next chapter.

CHAPTER 4

The Moon in camera

The first years of the nineteenth century saw the invention and development of photography. The early processes and photographic materials were clumsy and insensitive but a few determined individuals tried their best to record images of astronomical bodies. J. W. Draper, of New York, is usually credited as the first to achieve significant success in photographing the Moon. In the *Scientific Memoirs* of 1840 he writes:

> There is no difficulty in procuring impressions of the Moon by the Daguerreotype. By the aid of a lens and a heliostat, I caused the moonbeams to converge on the plate, the lens being three inches in diameter. In half an hour a very strong impression was obtained. With another arrangement of lenses I obtained a stain nearly an inch in diameter, and of the general figure of the Moon, in which the places of the dark spots might be indistinctly traced.

A decade later J. A. Whipple, also in the USA, succeeded in producing a series of Daguerreotypes of the Moon at various lunar phases. The English amateur Warren de la Rue achieved better results shortly after, as did Lewis Rutherfurd in America. By the close of the nineteenth century the quality of the photographs obtained had improved to the point that the first photographic atlases of the Moon could be compiled.

For example, W. H. Pickering published a complete photographic atlas of the Moon in 1904. The plates were taken at the focus of a specially constructed 12-inch (305 mm) objective. Each region of the Moon was photographed under five different lighting angles, though the scale was not large enough to show the smallest details on the lunar surface. The best lunar photographic atlas of the period was that produced by M. Loewy and P. Puiseux of the Paris Observatory. They employed the 23.6-inch (0.6 m) coudé refractor there between 1896 and 1909 to take the plates for their *Atlas de la Lune*.

As the years rolled on the prospect of space probes, and even manned missions, to the Moon spurred on further efforts. G. P. Kuiper and his colleagues published the *Photographic Lunar Atlas* in 1960. This was a boxed set of large photographs of the Moon, the best examples of images from Mount Wilson, Lick, Pic du Midi, MacDonald and Yerkes Observatories.

Under the auspices of the United States Air Force (USAF), Zdeněk Kopal headed the 'Manchester Group' (based at England's Manchester University), carrying out photography from Pic du Midi Observatory from 1959 to the 1970s. Situated high in the French Pyrenees the seeing at the Pic was (and is!) superb. Initially the chief instrument used was a 23.6-inch refractor, the object glass of which was the very same as that previously installed in the instrument used by Loewy and Puiseux at the Paris Observatory. One member of the Manchester Group, Dr Thomas W. Rackham, had special responsibility for the work with this refractor, though other group members also took part.

Well over sixty thousand photographs were eventually obtained, from which the *Lunar Air Force Charts* were constructed. The photographs were good enough to enable relative heights on the lunar surface to be determined (by means of measurements of the cast shadows) with an accuracy of a few metres in many cases.

The sub-arcsecond seeing typical at the Pic prompted the 'Manchester Group' to procure for the observatory a 43-inch (1.07 m) Cassegrain reflector of design and optical quality especially suited to lunar and planetary imaging. The various members of the 'Manchester Group', Patrick Sudbury having special responsibility for the use of this instrument, began photographic work with it in 1964. Meanwhile they also collaborated with Professor S. Miyamoto and his colleagues in Japan, (again under the auspices of the USAF and NASA) in further photographic lunar cartography, adding the 74-inch (1.9 m) reflector at Kottamia in Egypt to their arsenal. Dr Rackham has very kindly let me reproduce a number of the photographs taken at Kottamia in this book.

The enormously productive 'Manchester Group' were not the only major players in the lunar mapping game. Gerard P. Kuiper, Ewen A. Whitaker, along with Messrs Strom, Fountain and Larson of the Lunar and Planetary Laboratory, based at the University of Arizona, in America, were also active. They produced their superb *Consolidated Lunar Atlas*, consisting of the best 227 photographs of the Moon taken with the 61-inch (1.54 m) Naval Observatory astrometric reflector and the 61-inch reflector on Catalina Mountain, in Arizona. Most of the work (over 8000 negatives actually exposed) was done with the Catalina telescope between 1965 and 1967. You will find sectional enlargements made from many of the Catalina photographs in this book, thanks to the kindness of Professor Whitaker and the University of Arizona.

The professional programmes of Moon-mapping were essential to the up-and-coming space missions. Amateur astronomers also tried their hand at photographing the Moon. Many were very successful, even if the typical backyard observing conditions rarely allowed sub-arcsecond resolution to be achieved in their photographs.

During the 1960s one individual even emulated the professionals and produced a photographic atlas that was commercially published. I refer to the very useful *Amateur Astronomer's Photographic Lunar Atlas* by Commander H. R. Hatfield. In it the Moon is divided into 25 sections, for each there being a detailed key map and several photographs taken under different lighting conditions. Commander Hatfield even built the 12-inch (305 mm) Newtonian reflector and the observatory that housed it himself, as well as much of his photographic equipment. Although the first edition is now long out of print (it was published by Lutterworth Press in 1968) second-hand copies of it are still to be found. I often refer to mine. There is good news in that Commander Hatfield's Atlas is to be revised and re-published by Springer–Verlag. At the time I write these words it is still in production but should be available by the time this book is. It is now called *The Hatfield Photographic Lunar Atlas* and the new edition has been edited by Jeremy Cook.

Georges Viscardy must rank as the premier amateur lunar photographer of recent years because of his very high output of lunar photographs rivalling the professional efforts in their quality and resolution. He has a 20½-inch (0.52 m) Cassegrain reflector set up in the French Alps at a site of superb seeing. His *Atlas–Guide Photographique de la Lune,* published in 1986, contains over 200 plates, with technical details and some descriptions of the surface features.

Most of us have to live with seeing conditions which seldom allow for sub-arcsecond resolution. Nonetheless, photographically recording images of the Moon is still a personally rewarding exercise. Attempts to record any suspected transient phenomena are most certainly of the utmost scientific value. I hope that you will try your own hand at lunar photography and I offer the following notes by way of an introduction.

4.1 FILMS FOR LUNAR PHOTOGRAPHY

Of all the film formats on the market, the most common these days is the 35 mm, or 135, as it is properly known. There is a vast array of colour negative, colour positive and black and white negative films easily available in the 135 format. Most cameras, particularly most of the highly desirable single-lens reflex (SLR) cameras, use this film format. So, my recommendation is to select a camera that uses 35 mm films.

Having settled that, what type of film should we select for our lunar photography? It is always nice to have colour photographs but that is hardly essential in the case of the Moon. Even better if we can give slide shows of our photographs, though colour prints are sometimes more convenient. Certainly they are more portable than a slide projector and screen. However, it is now easy and fairly inexpensive to get prints run off from colour positive (= 'transparency', also known as 'slide') films.

Films come in different sensitivities, or *speed* ratings. Surely light is almost always at a premium in astronomical photography, so a 'fast' (= sensitive) film is desirable?

Is that it, then? We need a fast colour transparency film, from which we can order a set of prints if desired as well as having them mounted as slides? Unfortunately, things are not that straightforward if we wish to get the best possible results. Take a look at Figure 4.1, first viewing it from a distance and then up close. It is a print I made from a fast colour transparency film. The horrible 'pebbledash' effect is known as *photographic grain*. Obviously it limits the amount of detail that can be shown. Prominent grain is an unfortunate characteristic of fast films. 'Slower' (= less sensitive) films have a much finer grain structure and allow finer details to be resolved (grain size is not the only factor which determines a film's resolution of detail but it is an important one).

The film speed is quoted as an ISO (International Standards Organisation) number. The number is in two parts, the first corresponding to the arithmetic ASA number that most modern photographers are familiar with and the second a logarithmic value, equivalent to the old DIN number. For instance *Ilford*'s FP4 black and white negative film has a speed of ISO 125/22°. In this book I propose only referring to the arithmetic part of the ISO number. Hence a film of ISO 250 is twice as sensitive (twice as 'fast') as a film of ISO 125. The ISO 250 film would record an image of half the brightness in the same exposure time as would the ISO 125 film. Alternatively, it could record an image of the same brightness in half the exposure time.

As an aside, I ought to mention that there is an effect called *reciprocity failure*, whereby halving the brightness necessitates using more than double the exposure time. However, this effect only becomes really significant for light levels low enough such that exposures of more than several seconds are needed. We photographers of the Moon need not concern ourselves too much with reciprocity failure.

Of course, we must not forget that the ISO 250 film will have a poorer resolution and noticeably larger grain structure in the final photograph. As far as photographic emulsions are concerned, resolution is expressed in 'lines per millimetre'. If a grid of fine black lines with white spaces between were imaged onto the film, then when the film was processed it could only show the grid if the spacing of the lines were greater than a certain figure. For instance FP4 film, if processed according to the manufacturer's instruc-

Figure 4.1 The deleterious effects of photographic grain.

tions, has a resolving power of 145 lines per millimetre (this is the manufacturer's quoted value). In other words, if the spacing of the lines were less than 1/145 millimetre the film could not resolve them as separate and a grey area would be seen instead of the grid of separate black and white lines. A fast (ISO 1000, or more) film might only resolve about 40 lines per millimetre. We might not be terribly interested in photographing grids of black and white lines but we **are** certainly concerned to record the finest possible details on the Moon.

Another factor we should consider is the levels of contrast we can expect in our final photographs but I defer a discussion of this until Section 4.6. If we are using a colour film, the accuracy of the colour reproduction is also of some concern. Not all colour films will give natural looking reproductions of the Moon's subtle tones. In fact, do we need a colour film at all, since most people see the Moon as stark blacks, greys and whites, anyway?

After the foregoing generalities it is now time to settle on some specifics. There are a number of techniques you might employ to image the Moon. You might be wishing to take the most detailed possible photographs of the Moon through your telescope. At the other extreme, you might just want to photograph the phases of the Moon, and possibly eclipses, with a simple camera mounted on a tripod. In the following notes I detail how you might go about it and in each case I make suggestions of the specific film types you might first like to try. My intention, though, is for you to treat my recommendations as only the first step; merely enough to get you started. Once you gain some practical experience my only advice, then, is that you experiment for yourself and refine your own techniques. Good luck!

4.2 TRIPODS AND TELEPHOTO LENSES, FOCAL RATIOS AND EXPOSURES

If you want to picture the Moon against a particular asterism, or perhaps a grouping of planets, then you will need a larger field of view than you will get by imaging through your telescope. Setting the camera on a tripod and taking photographs using its standard lens, or a telephoto lens, would be best. Of course, the rub is that the image scale will be such as to reproduce the Moon at rather small size on the final photograph.

The image scale, I, measured in arcseconds per millimetre, produced by an optical system of effective focal length F is given by:

$$I = 206\,265/F, \tag{4.1}$$

where F is measured in millimetres. F is the **effective** focal length because this takes into account any additional optics, such as teleconverter lenses, etc. The Moon's apparent diameter is approximately 2000 arcseconds. This provides a useful 'rule of thumb' in that the diameter of the focused full Moon is approximately 1/100 of the effective focal length of the optical system. If we are imaging the Moon at the 2 m focus of a large telescope then the Moon will appear approximately 20 mm across on the film. If we use a 200 mm telephoto lens then the Moon will appear just 2 mm across. With the standard photographic lens of 50 mm focus the Moon's image will span only 0.5 mm.

Of course, this is just the size of the Moon on the film. If, for instance, a print is made from the film, it will be enlarged when printing. However, the

Table 4.1. *Image scales and corresponding angular sizes of field covered by a 135 format film frame for lenses of various focal lengths.*

Focal length (mm)	Image scale (arcseconds/mm)	Angular field of film frame (degrees)
50	4125	27.5 × 41.3
135	1528	10.2 × 15.3
200	1031	6.9 × 10.3
300	688	4.6 × 6.9
400	516	3.4 × 5.2
500	413	2.8 × 4.1
1000	206	1.4 × 2.1
1500	138	0.92 × 1.38
2000	103	0.69 × 1.03
2500	83	0.55 × 0.83
3000	69	0.46 × 0.69

Moon's image photographed using a standard lens and made into a postcard-sized print is still going to be less than a couple of millimetres across.

A film frame in the 135 format covers 24 mm × 36 mm. Most optical systems produce images with a degree of geometric distortion. In the case of camera lenses the image scale almost always gets a little larger (fewer arcseconds per millimetre) away from the centre of the field of view. However, the effect is not usually too severe except in the case of wide-angle (= short focal length) lenses, so it is easy to work out the approximate sky coverage and size of Moon you can expect. Table 4.1 gives the results for some standard lens sizes.

The Moon, at least approximately, shares in the diurnal motion of the stars. True, it lags slightly but it still takes a month to reverse through the constellations of the zodiac. It can also stray up to 28½° north or south of the Celestial Equator (where the stars appear to move the fastest) but this makes only a small difference to its rate of travel across the sky. Unless we are guiding our camera to follow the Moon we must limit our exposure times to avoid its image being smeared across the photograph by its motion. My experience leads me to propose the following formulae for fast (= low-resolution) and slow (= high-resolution) films:

$$\text{FAST FILM:} \quad \text{Maximum exposure (seconds)} = 550/F, \tag{4.2}$$

$$\text{SLOW FILM:} \quad \text{Maximum exposure (seconds)} = 300/F, \tag{4.3}$$

where F is the effective focal length of the optical system, measured in millimetres. Hence with a fast (e.g. ISO 400) film in the camera you could

Table 4.2. *Recommended maximum exposure time for unguided exposures when photographing the Moon with lenses of various focal lengths, using 'fast' (low-resolution) and 'slow' (high-resolution) films. Of course, the shortest exposures recommended will, in practice, necessitate using the closest standard shutter speed setting on the camera (preferably rounding down).*

	Recommended exposure time (seconds)	
Focal length (mm)	Fast film	Slow film
50	11.0	6.0
135	4.1	2.2
200	2.8	1.5
300	1.8	1.0
400	1.4	0.75
500	1.1	0.60
1000	0.55	0.30

use an exposure time of up to 11 seconds with a 50 mm focus lens but would be limited to no more than 1.1 seconds if you were using a 500 mm telephoto lens. I summarise some results for various focal lengths in Table 4.2. Some people would argue that I have been too severe and slightly longer exposures could be given. I am sure that others would say I have been too lax. What you will find tolerable in practice will be determined by the quality of your lens, the resolution characteristics of the film you use and the enlargement to which you subject your photographs.

So much for the length of the longest exposure we **can** give with a fixed camera but how long an exposure do we **need** to give? The answer to that depends on four main factors: the apparent brightness of the Moon, the optical transmission efficiency of the optical system, the sensitivity ('speed') of the film, and the effective focal ratio of the imaging system.

The brightness of the Moon varies considerably with its phase, so we need to worry about the phase of the Moon when deciding on the exposure. As for the transmission efficiency of the system, that is a factor which is best allowed for by actually attempting lunar photography. If you get lunar images dimmer than you expect, well, just increase the length of the exposure! It is, though, unlikely that the efficiency of the system would fall outside the range 50 per cent to 95 per cent, in which case the end results ought to be fairly predictable.

A much more important factor is the speed of the film. The manufacturer will quote a value but this may be altered by the processing. Often the manufacturer quotes a range of ISO values with some indication of the options available for processing. 'DIY-ers' can process a photographic film to a widely different speed rating than that intended by the manufacturer. More about this in Section 4.6.

The last of the main factors is the effective focal ratio of the system. Effective focal ratio, f, is given by:

$$f = F/D, \tag{4.4}$$

where F = effective focal length and D = aperture. Both quantities must be expressed in the same units, for example both in millimetres, etc. This ratio is the same as the 'f/number' so familiar to photographers. In the case of the camera lens, the focal ratio is usually altered by changing the effective aperture of it by means of an internal iris. *Teleconverters* inserted between the camera body and the chosen camera lens are useful in that they provide different effective focal lengths, and so different image scales. As an example, a $\times 2$ teleconverter doubles the effective focal length of the lens. Do remember, though, that the doubling of the focal length is achieved with the same iris opening (= effective aperture), so the effective focal ratio of the lens is now doubled.

You might think that since the effective aperture of the lens remains the same it should intercept the same amount of moonlight and so the exposure we should give should not be altered when we insert the teleconverter. Instead, the effective focal ratio is crucial in determining the correct exposure.

To understand why consider three lenses, each of 25 mm aperture. One of them has a focal length of 50 mm, and so has a focal ratio of f/2. Another has a focal length of 100 mm, and so is an f/4 lens. The last has a focal length of 150 mm, and so is an f/6 lens. The first one produces an image of the Moon that is approximately 0.5 mm across. The second lens intercepts the same amount of light as the first but the image of the Moon it produces is 1.0 mm in diameter, twice the diameter and four times the area of the first. Thus, the surface brightness of the image of the Moon produced by the f/4 lens is only one-quarter of that produced by the f/2 lens. The f/6 lens again intercepts the same amount of light as either of the other two lenses but it produces an image of the Moon that is spread to three times the diameter, and so nine times the area, of that produced by the f/2 lens. The f/6 lens produces an image of the Moon that is only one-ninth as bright, in terms of the light per unit area in the image, as that produced by the f/2 lens. It is the brightness per unit area of the image on the film that is important in determining the correct exposure.

Table 4.3. *Recommended exposure times for photographing the Moon at various stages of the lunar cycle using various effective focal ratios. These figures have been standardised for recording onto film of speed ISO 125. These figures can be used to calculate exposure times for other focal ratios and film speeds. Interpolating will allow the exposure times needed for other lunar phases to be estimated.*

Lunar phase	Exposure times (seconds) for each of the focal ratios indicated								
(days)	f/5	f/7	f/10	f/14	f/20	f/28	f/40	f/56	f/80
3 days, 25 days	1/30	1/15	1/8	¼	½	1	2	4	8
7 days, 21 days	1/125	1/60	1/30	1/15	1/8	¼	½	1	2
10 days, 19 days	1/250	1/125	1/60	1/30	1/15	1/8	¼	½	1
15 days (full Moon)	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	¼

In general for extended (non-point) objects:

$$\text{required exposure} \propto f^2. \tag{4.5}$$

Objects which produce point images, such as stars, are not (within limits) diluted by increasing focal lengths. Consequently, the limiting stellar magnitude obtainable in your photographs is a function of aperture (and, of course, length of exposure and film sensitivity) but not of effective focal ratio.

Bearing all the foregoing in mind, I can proffer a table of recommended exposures at various effective focal ratios (see Table 4.3). To simplify the table I have standardised the film speed at ISO 125. If you wish to use a film of higher speed then simply reduce the exposure time in proportion. Use of a slower film necessitates increasing the exposure time in proportion, of course.

The figures in the table are based upon my own experiences in lunar photography using my own equipment. In time you will undoubtedly replace my figures with your own and I offer them here merely to get you started. Actually, I recommend that you go one stage further and bracket your chosen exposure with one of half the value and one of twice the value. Do this even after you have gained enough experience to be fairly confident that your chosen exposure should produce acceptable results and you will guarantee a high success rate in your lunar photography.

Enough of the theorising. Let us now do some photography. We set up our camera on a firm tripod and decide to use a 200 mm telephoto lens to photograph the phases of the Moon. We hope to also capture some of the coarsest of the markings on the Moon's illuminated disk, particularly the major 'seas'. What film should we have in the camera? Of all the black and white films available I have no hesitation in recommending one above all others; and that is *Kodak*'s TP2415. Depending how it is processed, it can have a speed rating of between ISO 25 and ISO 200 with normal development techniques (*hypersensitisation*, by which technique TP2415 can be uprated to ISO 1200, is only of interest to 'deep sky' astrophotographers) and a resolution of between 125 and 400 lines per millimetre. This is roughly double the resolving power of other films of comparable speed. It also produces good strong contrast but it is the potential resolving power of the film which really sets it apart from the other black and white films. As far as colour negative and colour positive (=transparency) films go, they are much more evenly matched speed for speed.

One thing I would urge is to go for films of fairly low speed ratings, certainly less than ISO 200. For most telephoto shots you will be using a fairly low focal ratio, almost certainly less than f/22 even if you include a ×2 converter, and so you are best off using a slow (and hence high-resolution) film. Even then, the exposures will likely be shorter than a second – an exposure length permissible for an effective focal length of up to 550 mm. You certainly will not need a fast film to achieve this and since the slower films have the better resolution characteristics, why use a fast one, anyway?

For colour photography, you might like to try films such as *Kodak* Gold 100 (a colour negative film with a speed rating of ISO 100) or Kodachrome 64 (a colour transparency film of speed ISO 64), though the market place is replete with competing films by other makers.

Colour renditions do vary. Some films tend to make the Moon look greenish. Others tend to make it look brown. I will leave you to do your own experimenting and find the colour films that produce results you like best.

As with any conventional photography of earthly subjects, the tripod and camera must not shake during the exposure. Investing in a good, sturdy tripod is very important. Another good investment is a cable release for the camera. It is very difficult to avoid jarring the camera when pressing the exposure button. Even so, before loading the camera with film it is wise to check that the mirror-slap inherent in single-lens reflex cameras produces no visible vibration of the camera perched on its tripod. If you see a visible twitch then you need to make or buy something very much better. Non-SLR cameras, or ones which have a lock-up reflex mirror, are naturally much less troubled by shake during the exposure. Talk to your photographic dealer and study the current magazines to find out what is available in the market place at the time you are ready to make the purchase. The *Olympus* OM1 was always a firm favourite of astrophotographers of recent years.

As well as recording the phases and the coarsest of the surface details of the Moon, telephoto shots are particularly suitable for capturing the

Table 4.4. *Recommended exposure times for lunar eclipse photography. These are the times for ISO 100–125 film at f/5, ISO 200–250 film at f/7, ISO 400–500 film at f/10, or ISO 800–1000 film at f/14. The tabulated figures can be used as the basis for calculating exposure lengths at other focal ratios and film speeds.*

Stage of eclipse	Exposure time (seconds)
First umbral contact	1/250
Umbra half covering Moon	1/125
Umbra three-quarters covering Moon	1/30
Just before totality	1/15
Just after onset of totality	5
Mid totality (for an average eclipse)	15

beauty of lunar eclipses. Eclipse photography is made complicated by the vast change in the brightness of the Moon during the event, as the brilliant full Moon gives way to a coppery-red umbra. Even worse, the darkness of the umbra can vary from eclipse to eclipse. With a largely cloud-covered Earth and a patch of good transparency through which you can see the Moon, the umbra can be a bright golden colour. At the other extreme the umbra can be dark enough to be invisible to the naked eye. In Table 4.4 I offer some recommended exposure times for eclipse photography. However, these must be treated as a very rough guide at best. Certainly bracket your chosen exposures by ones of double and half the values. If your resources allow, having one camera loaded with slow (ISO 50–100) film for photographing the partial phase and another loaded with a fast film (ISO 400–1000) for capturing details in the umbra would be the ideal.

For the same reason that the brightness of the umbra of the eclipsed Moon is hard to predict, so is the brilliance of Earthshine. Something around five seconds exposure at f/5 and with an ISO 400 film in the camera ought to be right. Of course, if you are using a relatively short focal length camera lens to capture the image, you might be better off with a longer exposure on a slower film to get the best possible resolution.

The difficulties in photographing the eclipsed Moon and the Earthshine are both lessened if you are able to photograph at the principal focus of your telescope (provided its focal length is not too long). This topic is discussed in the next section.

4.3 LUNAR PHOTOGRAPHY THROUGH THE TELESCOPE – AT THE PRINCIPAL FOCUS

Some people mean ‘principal focus’ when they incorrectly say ‘prime focus’. I am willing to wager that amateur reflecting telescopes with no secondary mirror and equipment mounted at the true prime focus position are extremely rare. In most cases the 'principal focus' will be the Newtonian focus, though the first focal plane of the refractor, the Cassegrain reflector, or the catadioptric telescope also counts. The photographic emulsion is positioned at the principal focus in each case with no additional optics to further enlarge the image. The basic principles already set out in this chapter apply here, equally as well as for conventional photographic lenses. In effect the telescope becomes the telephoto lens.

Image scale, and so the size of the Moon's image on the film, are calculated just as before. Obviously the Moon's image diameter is likely to be larger because your telescope's focal length is probably larger than that of any of your photographic lenses. If your telescope's effective focal length is longer than about 2.4 m, you will find that you will not be able to fit the entire Moon within the film frame.

As before, the exposure required for a given lunar phase and effective focal ratio can be derived from Table 4.3. Most telescopes used by amateurs have ratios somewhere in the range of f/4.5 (for the 'fastest' Newtonian reflectors) to f/20 (for some Cassegrain reflectors), with the greatest number having ratios in the range f/6–f/15.

The problems encountered with photography at the telescope's principal focus are usually ones of pure mechanics. Just mounting the camera at the correct position can be a headache. Many telescope suppliers provide a wide range of accessories you can purchase, including 'T-ring' adapters that can fit your lensless camera body into the telescope drawtube. However, the film-plane within the camera will normally be about 5 cm back from the T-ring. You might find that the focuser will not rack inwards far enough to allow the film to reach the focal plane. Making or buying a low-profile focuser might solve the problem. If not, then you might have to take the drastic action of altering the positions of the optics of your telescope (for instance with a Newtonian reflector moving both the secondary mirror and the focuser a little down towards the primary mirror) within its tube.

Sorry, but I must say it: **Do not even think of doing this unless you are sure you are competent to undertake this task, that you can make all of your measurements and alterations accurately, and can safely store the telescope's optics while carrying out the work.** I would hate to think of any enthusiast ruining their expensive telescope because of anything I have written, so please forgive me including this elementary warning.

Remember that if you move a reflecting telescope's secondary mirror a little towards the primary it will intercept a larger area of the cone of rays from the primary. Make sure that the secondary mirror is large enough to still intercept all the rays (see Equation (3.2), Section 3.4). It might work fine in its original position but could easily *vignette* the field of view (prevent all the rays from the primary reaching the outer parts of the field of view) if you move it too close to the primary mirror. Vignetting might also be caused by the telescope drawtube or even the camera's T-ring for telescopes of ratio lower than about f/5.

One quick method of checking for obstructions in the light-path is to set the camera, with no film loaded in it, in the telescope and adjust to produce a focused image through the viewfinder (assuming here an SLR camera) as if you were about to make an exposure. Lock open the shutter on the 'B' setting. Then open the back of the camera and let your eye search the rectangular aperture that defines the film frame. Can you see the primary mirror/objective of the telescope unobstructed, even with your eye positioned to correspond with the corners of the film frame? If not, then the image will be vignetted. You should be able to see what is causing the vignetting. You might decide to put up with it, especially if the image of the Moon is small enough on the film frame not to be significantly affected and only the corners of the film frame are significantly darkened. At least you will be able to see what component(s) of your telescope is/are causing the obstruction and so you can make an informed decision whether or not it is worth making the necessary changes to your telescope.

Does your telescope need to be driven (at least at the sidereal rate, if not actually at the lunar rate) in order to get sharp photographs? In general, the answer will be "No" for most of your lunar photography at the principal focus. The rule of thumb formulae I have given for the longest exposure times permissible when using a photographic lens are a little too lax to apply when using your telescope to do the imaging. The reason for this is that your telescope should have the potential to produce nearly diffraction-limited images. Most photographic lenses, even good-quality telephoto lenses, are not this good. Telescopes larger than about 5-inch (127 mm) in aperture could potentially image details down to about an arcsecond in extent (this is about 1.7 km at the Moon's distance). Another limiting factor comes into play for apertures larger than this: atmospheric turbulence. This might limit the attainable resolution to 1 or 2 arcseconds on many nights, however large an aperture you use. Consequently, for 'principal focus' imaging using a 75 mm or larger aperture telescope, of greater than about 1 metre effective focal length, I would impose a blanket ban on unguided exposures of longer than 1/15 second duration. Diurnal motion will smear the Moon's image by about an arcsecond in 1/15 second. Keeping the exposure time less than this is usually possible except when using a slow film with a 'slow' telescope to photograph a thin crescent Moon. Trying to capture the Earthshine or a lunar eclipse almost certainly will require exposures of several seconds, even with a low focal ratio and a fairly fast film. This necessitates driving the telescope during the exposure.

An often overlooked difficulty is that telescope shake is much more likely than diurnal motion to dominate as the cause of blurred pictures for exposure times in excess of 1/60 second. The mirror-slap of an SLR camera can cause significant problems, the opto–mechanical system of the telescope being a wonderfully sensitive detector of vibrations! Some SLR cameras are on the market with lock-up reflex mirrors. After focusing through the viewfinder in the normal way, the mirror is manually locked into its 'up' position and the exposure is made after a few seconds have passed in order to allow any vibrations to die down. The camera's shutter mechanism can produce some vibration, though not as much as the mirror-slap. I would say that using a cable release is mandatory for this type of photography. Fumbling to press a button on the camera while it quivers on the telescope is hardly conducive to getting sharp photographs!

Another way of avoiding camera–telescope shake is to install a separate shutter before the camera. Making sure this shutter is first closed, the camera shutter is locked open on its 'B' setting. After allowing a few seconds to pass for the inevitable vibrations to die down, the secondary shutter is then opened for the required exposure time. Finally the camera shutter is, of course, closed. If the foregoing is a little off-putting, it might well be the case that your telescope is sufficiently rigid not to be troubled by camera shake for any of the exposure lengths you need to use. You might get very good lunar photos without having to worry about shake. Why not try things out first? If you do get smeared images then you will know why and then can devise ways around the problem.

For photographing details on the sunlit portion of the Moon I recommend *Kodak*'s TP2415 if you can make your own black and white prints (currently in the UK it is expensive to have prints made from black and white films). Colour films, such as Ektachrome 200 (for transparencies) or *Kodak* Gold 200 (for prints) will normally be fast enough for the sunlit portion of the Moon photographed at the principal focus. Personally, I would always go for a slower film when the Moon's brightness and the telescope's focal ratio allow the exposure to still be less than 1/60 second.

The beauty of lunar eclipses is well brought out by colour films, though for recording details in the umbra a faster film may be desirable to keep the exposure length down to a few seconds. There are plenty of ISO 400 films available in black and white, colour transparency and colour print types.

My general advice about photographing eclipses and the Earthshine through a telephoto lens (see the last section) is the same when using a telescope for photography at the principal focus. Figure 4.2 shows a splendid photograph of the Earthshine by Martin Mobberley using his

Figure 4.2 Earthshine on the Moon, photographed by Martin Mobberley at the f/5 Newtonian focus of his 14-inch (356 mm) reflecting telescope on 1989 August 28^d 03^h 20^m UT. The 5 second exposure was made on T-Max 400 film.

14-inch (356 mm) reflector at its f/5 Newtonian focus (the instrument is a Newtonian–Cassegrain convertible). The details are given in the caption accompanying the photograph.

There are further examples of principal-focus photography, for eclipses, Earthshine, and other whole-Moon shots in Chapter 1 (Figures 1.3 and 1.7), Chapter 2 (Figures 2.1–2.5) and Chapter 8 (Figures 8.24(b) and 8.46(d)).

4.4 HIGH-RESOLUTION PHOTOGRAPHY

The image scale at the 2.59 m Newtonian focus of my 18¼-inch (0.46 m) telescope is 80 arcseconds per millimetre. In perfect seeing the telescope should allow details as fine as 0.3 arcsecond to be seen. In order to photographically record details this small by imaging the principal focus directly onto the film, the film would have to have a resolution of 260 lines per millimetre. Of the films commonly available only *Kodak*'s TP2415 potentially has this resolution if processed in the correct way. Even so, how does one focus the image to the necessary degree of precision? The camera viewfinder (here assuming an SLR camera) will not be good enough. Granted, the chances of getting seeing that good are remote on any given night, anyway, but that is no reason to forego trying to get the best resolution possible in your lunar photographs. The inescapable conclusion is that to have the best chance of recording lunar images of the highest resolution possible on the greatest number of nights possible one must enlarge the primary image. There are four main methods of doing this: projection using a Barlow lens, projection using an eyepiece, relay lens projection, and infinity-to-infinity (∞ to ∞) focusing using the eyepiece and camera lens. The following notes detail each of these methods.

Barlow projection

Figure 4.3 shows the arrangement, together with the formulae for working out the enlargement factor. The lens must be mounted into a tube with the appropriate bayonet or screw-fitting attachment to your camera. The only real problem with Barlow lenses is that they are usually designed for one specific value of amplification (commonly ×2). Using them to provide any other value of amplification necessarily increases the aberrations produced by the lens. This lowly amplification may not be enough to match the potential resolution of the telescope to that of the film. At the time of writing (summer 1998) there is one high-quality Barlow lens commercially available, *Tele Vue's '5x Powermate'*, which you

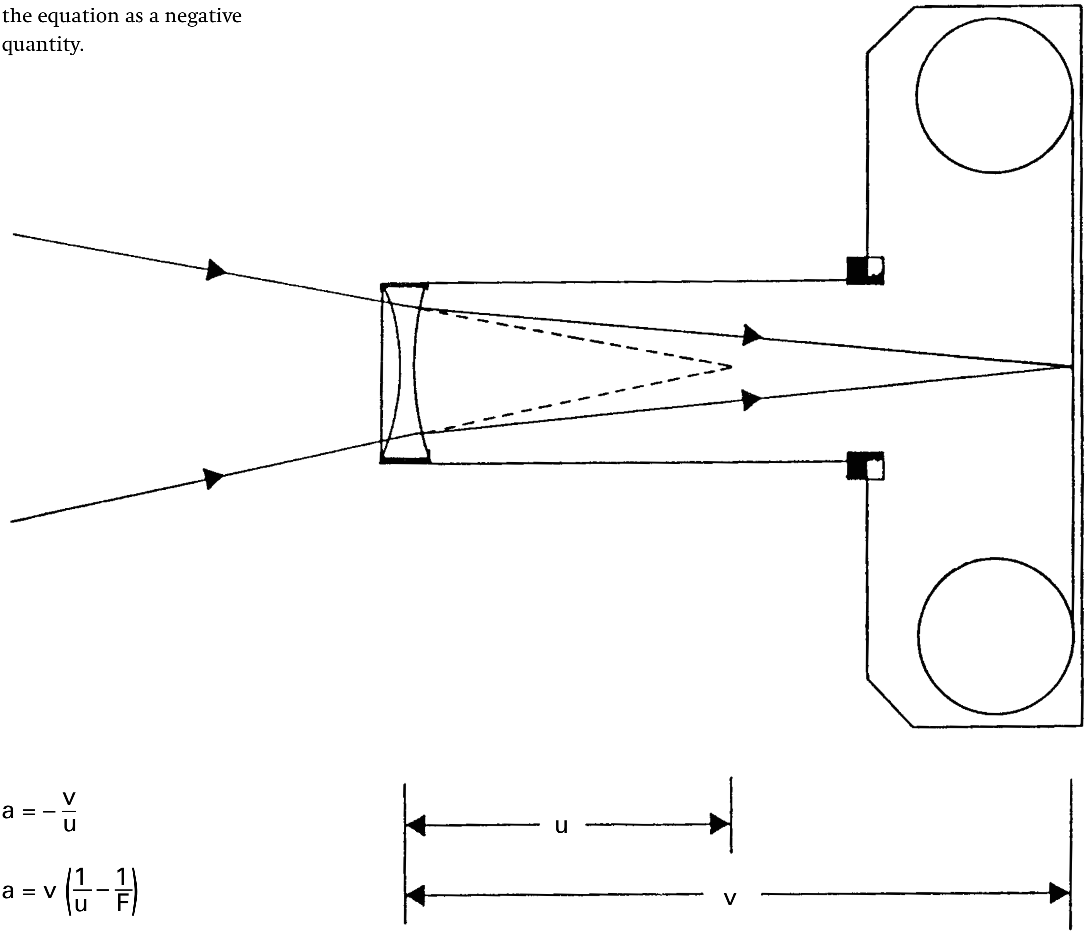


Figure 4.3 The optical configuration for projecting (and enlarging) the primary image by means of a Barlow lens. Alternative formulae are given for calculating the amplification factor, *a*. The focal length of the Barlow lens is *F*. It is entered in the equation as a negative quantity.

$$a = -\frac{v}{u}$$

$$a = v\left(\frac{1}{u} - \frac{1}{F}\right)$$

could use for your photographic work. Unscrewing the lower section of the unit, containing the four-element lens itself, (and remounting it in your own tube with an adapter to your camera) would work but make sure that the lens–film distance is pretty much the same as the manufacturer's intended lens–eyepiece distance. The amplification will then be close to the manufacturer's intended ×5 and the performance of the lens will be good. **Let me emphasise one important point: Unscrew the barrel containing the lens in its cell by all means but do not even think of disturbing the lens assembly in its mounting unless you are an optical specialist – you could so easily ruin the performance of this expensive accessory it is just not worth taking the risk.**

Another reason for keeping to the manufacturer's intended amplification factor when using a Barlow lens is the possibility of introducing some vignetting if you do not. In the severest case you might be unknowingly stopping the telescope down to a small aperture! The minimum diameter, *D*, the Barlow lens should be in order to fully illuminate the projected image out to a diameter, *d*, centred on the optical axis is given by:

$$D=\frac{1}{a}\left(\frac{v}{f}+d\right), \tag{4.6}$$

where a is the amplification factor, v is the distance the lens is set inside the telescope's focus, and f is the focal ratio of the telescope without the Barlow in position.

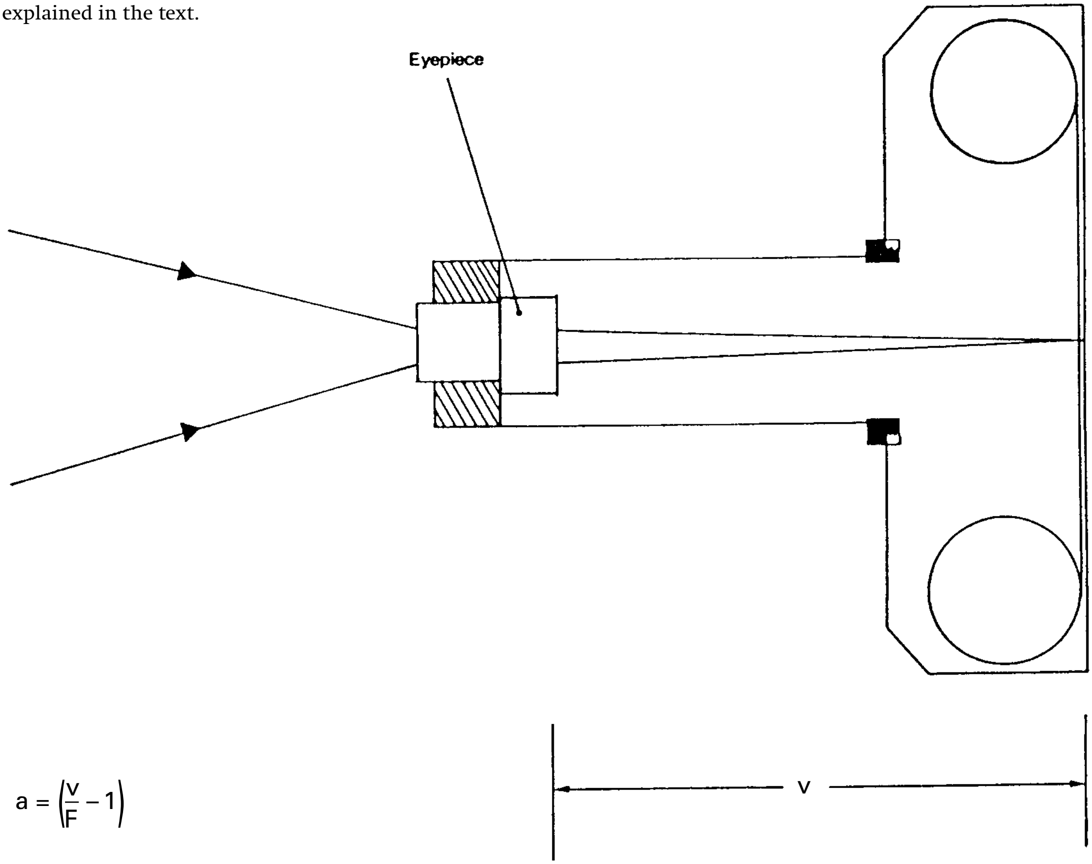
As an example of Barlow amplification in action, using the *5x Powermate* to project the image from a 12-inch (305 mm) f/5 Newtonian reflector onto the film, at the manufacturer's intended amplification factor, produces an effective focal length of 7625 mm, an effective focal ratio of f/25 and an image scale of 27 arcseconds per millimetre. The potential, diffraction-limited, resolution of the telescope is 0.45 arcsecond. To realise this would require a film resolution of at the very least 60 lines per millimetre. This scale will produce a Moon of about 7.6 cm diameter, only a portion of which will fit within the film frame in one go.

Eyepiece projection

As Figure 4.4 shows, the eyepiece is mounted so that the rays emerging from the eyelens converge to form a focused image on the film. Unfortunately, this is not what the eyepiece was designed to do. Sets of parallel rays emerge from the eyelens and enter the observer's eye when the eyepiece is used as the manufacturer intended. Using it as a projection lens involves setting it slightly further out from its normal focused position in the telescope, which is usually not a problem. Unfortunately, the result is an increase in the optical aberrations produced by it. Good eyepieces will still produce sharp images within a small area of the centre of the film frame but the outer zones can be very blurred.

Figure 4.5 shows one of my early attempts at eyepiece projection photography. Notice the horrendous outfield blurring I got using an 18 mm Orthoscopic eyepiece to enlarge the f/5.6 Newtonian focus of my 18¼-inch reflector to f/17. This problem is greatly reduced when using the eyepiece to create larger amplification factors. The reasons for this are two-fold. Firstly, the rays emerging from the eyelens are less convergent (and so the paths of rays through the eyepiece are nearer to what the manufacturer intended). Also, the 'sweet spot' of a sharply focused image on the film is increased in size by virtue of the greater magnification, anyway.

For lower amplification factors a high-quality Barlow lens may serve best. Eyepiece projection would be the best choice for large amplification factors. Figure 4.6 shows a good example of the results obtainable by this



$$a = \left(\frac{v}{F} - 1\right)$$

Figure 4.4 The optical arrangement for enlarging the primary image by eyepiece projection. The amplification factor, *a*, is found from the equation given. The focal length of the eyepiece is *F*. The equation is approximate as explained in the text.

Figure 4.5 The horrendous blurring of the outer zones of this photograph is a severe disadvantage of the method of eyepiece projection when used to provide low amplification factors to image the Moon. This photograph was taken by the author on 1977 September 2^{d} 23^{h} 57^{m} UT. He used an 18 mm Orthoscopic eyepiece to enlarge the f/5.6 primary image of his 18¼-inch (0.46 m) Newtonian reflector to f/17. The exposure was 1/30 second, made on *Ilford* Pan F black and white film.

technique. You will find others in Chapter 8 (Figures 8.5(c), 8.13(a), 8.13(f), 8.14(a), 8.17(a), 8.17(b), 8.24(a), 8.26(a), 8.26(b), 8.30(a), 8.34(a), 8.35(a), 8.42(a), and 8.44(a). All details are given in the accompanying captions. You will gather that eyepiece projection is the most popular method of primary image enlargement!

Relay-lens projection

The aberrations, particularly outfield blurring, inherent in using eyepieces to project the primary image are avoided if one can use a relay lens, or other type of compound lens specifically designed for projection. The lens from a photographic enlarger would be a good choice. Some camera lenses might also be suitable. The principle is easy. As always, the difficulty is actually constructing the mechanical supports/adapters/tubework/etc. to do the job. There are as many solutions as there are different telescopes. What you can do really depends upon your own constructional skills and the materials and tools you have available. Remember, some or all of the parts you need might be obtainable ready-made from telescope manufacturers/dealers and/or photographic dealers/manufacturers. While always urging great care with your expensive camera and

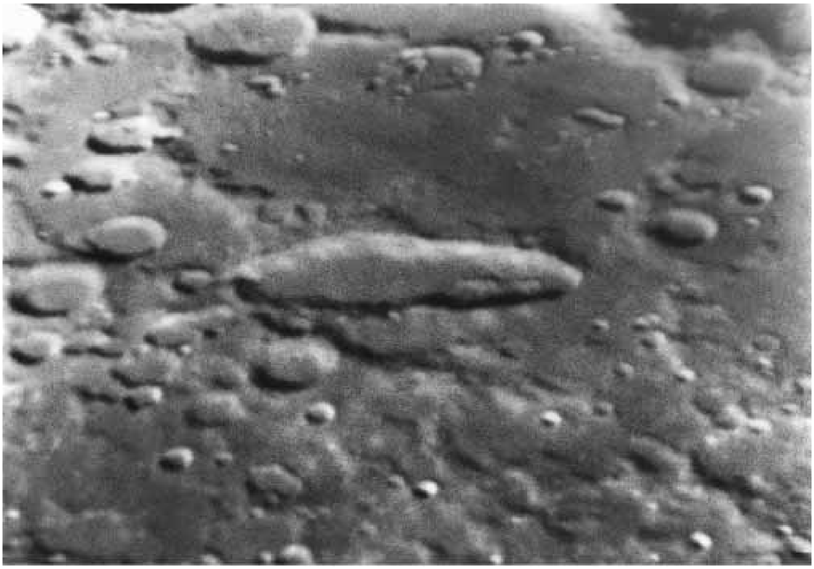


Figure 4.6 The intriguing lunar crater Schiller, photographed by Martin Mobberley on 1984 March 14^d 20^h 55^m UT. He used eyepiece projection to amplify the f/20 Cassegrain focus of his 14-inch (356 mm) reflector to f/60. The ½-second exposure was made on *Ilford* XP1 black and white negative film. Schiller is orientated with its long axis roughly north–south on the Moon, though in the telescope field south lies approximately to the upper left (Schiller lies close to the Moon's south-east limb).

telescope, I certainly advocate an experimental approach to your practical astronomy.

To avoid effectively stopping-down the telescope, the focal ratio of your relay lens should be no more that one-half that of your telescope. At least that is the case for fully illuminating the centre of the field of view with the amplification factor being unity. The equation for predicting the amplification factor is the same as that for eyepiece projection. Though the focal ratio of the lens can be a little higher when used to produce greater amplification factors, this might still only fully illuminate the very centre of the field. Keeping the focal ratio to no more than one-half that of your telescope for higher amplification factors would then increase the size of the unvignetted area on the film.

Under this heading I include the commercially produced *teleconverters* and *tele-extenders*, which can work excellently with telescopes, even if they are designed to be used between a camera body and a conventional photographic lens.

Infinity-to-infinity focusing, using the camera lens and the eyepiece

Though the purist might shudder at the thought of eight or more separate lens elements between the principal focus and the film, and have nightmares about multiple reflections and a 'fog' of light swamping the dim image, keeping both the telescope eyepiece and the camera's lens in place can actually work really well. With today's multicoated eyepieces and camera lenses the amounts of light scattered, reflected, and absorbed by them are very much more reduced than was the case for the products of yesteryear.

In this arrangement the eyepiece is focused in the normal way and then the camera, complete with its lens set to ∞ (infinity) focus, is brought up to the eyepiece. The camera is carefully positioned such that it looks squarely, and on-axis, into the eyepiece. In effect, the camera has replaced the observer's eye.

This technique can work with a non-SLR camera, though having the facility to see what the camera is seeing is certainly an aid. Also, some tweaking of the focusing can be made if you use an SLR camera. Given that there might be some uncertainty in the precise 'infinity' focus of your eye caused by the natural accommodation of focus and/or any long- or short-sightedness, one can expect better and more consistent results by directly viewing through the camera's focusing screen.

However, the modern low-cost 'point and shoot' cameras are unlikely to produce any worthwhile results. They are set up for photographing subjects such as Aunt Matilda patting your pet Rottweiler in your garden; and the flash gun is certainly not powerful enough to be of any use in your lunar photography! By all means do try but be prepared for disappointment.

The amplification factor, a, is given simply by the ratio of the focal lengths of the camera lens, F_c, and eyepiece, F_e:

$$a = F_c / F_e. \tag{4.7}$$

Figure 4.7 shows a photograph of the Moon I took using this method.

One advantage of this method is that both eyepiece and camera lens are being used well within their intended parameters and so can deliver images of the highest quality. You might notice that Figures 4.5 and 4.7 are both taken at the same effective focal ratio. Also, they are both virtually full-frame reproductions from the negative. The much more even focus of Figure 4.7 is obvious.

While it is always best to firmly attach the camera to the telescope, another advantage of the infinity-to-infinity method is that tolerable results, though certainly not the best results, can be obtained by **hand-holding** the camera to the eyepiece and taking a 'snapshot'! I took Figure 4.7 exactly that way. I often use this method when I want to take quick photographs without going to the trouble of setting up the equipment to attach the camera to the telescope. Figures 8.20(a) and (b), also 8.34(b), further on in this book, were taken by the same method. Details of the film used, effective focal ratio in each case, etc., are given in the accompanying captions.

Of course, hand-holding the camera demands that the exposures

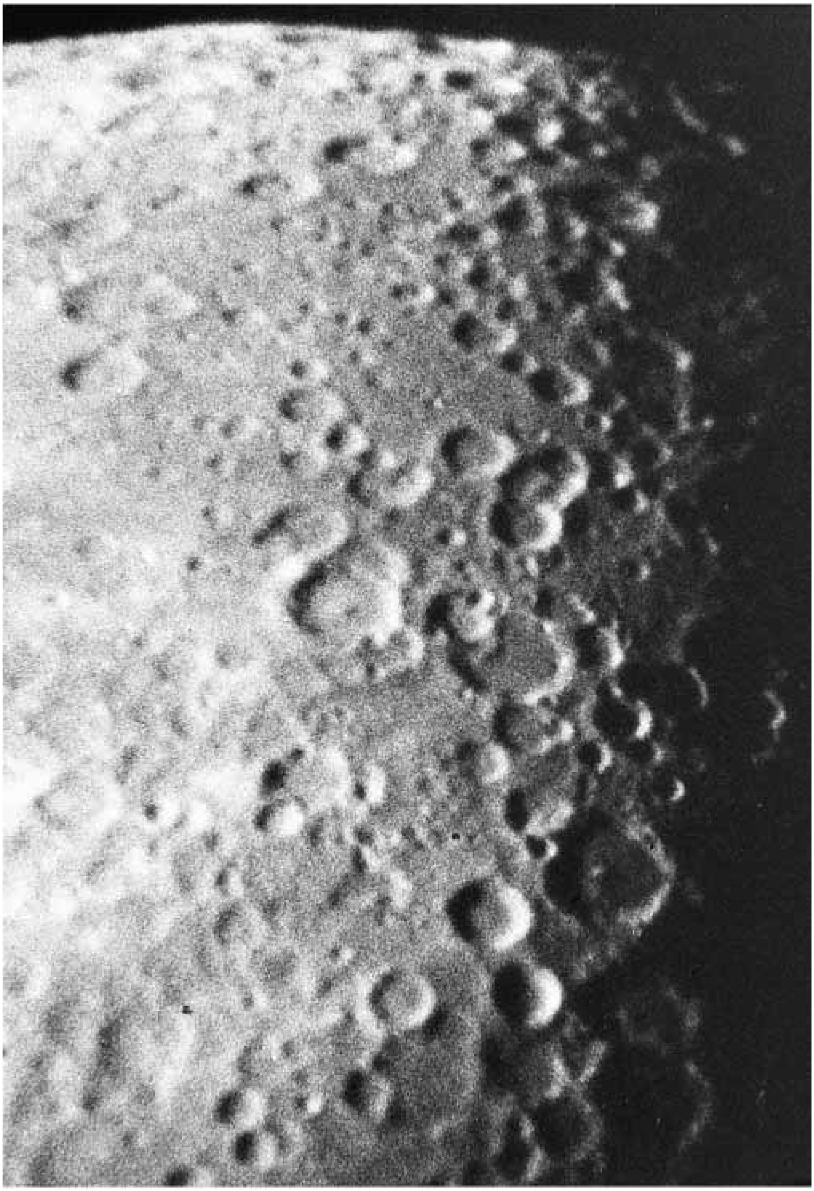


Figure 4.7 The author used the 'infinity-to-infinity' method to obtain this view of the southern highlands of the Moon on 1987 January 7^d 19^h 20^m UT. The camera, fitted with a standard lens of 58 mm focal length, was hand-held to an 18 mm Orthoscopic eyepiece plugged into his 18¼-inch (0.46 m) Newtonian reflector. The EFR of this arrangement is f/17, the same as that for the photograph shown in Figure 4.5. Notice the much more even focus achieved by the 'infinity-to-infinity' method. The film used was *3M* Colourslide 1000 and was commercially processed, though the author subsequently copied the transparency onto black and white negative film so that he could make his own print.

should certainly be shorter than 1/30 second, better 1/60 second or less, if consistently sharp photographs are to be obtained.

The 'rub' is that exposures that short demand a fast (and hence grainy and low-resolution) film in the camera. Even then the amplification factor cannot be too high. However, using this technique it is possible to photograph terminator details in the first or the last quarter Moon with an exposure of 1/60 second on ISO 1000 film at an effective focal ratio of no higher than about f/20. A typical ISO 1000 transparency film, such as *3M*'s Colourslide 1000, will likely have a resolution of about 40 lines per millimetre. With a 12-inch (305 mm) telescope you might just be able to capture details at the arcsecond level of resolution at f/20 using Colourslide 1000 (the image scale being 34 arcseconds per millimetre on the film). Obviously, the chances of recording fine details get much better nearer full Moon (when a slower film and/or a shorter exposure and/or a greater amplification factor) can be used.

If you feel that attaching your camera to your telescope and arranging to project the image onto the film is just too much like hard work, then I urge you to try some hand-held 'snapshots' using the infinity to infinity technique. Your results will be much inferior to the best that could be obtained but provided you use a fast film in the camera you may be surprised at just how good your lunar photos will turn out. Go on – have a go! You might even be spurred on to more serious efforts afterwards.

4.5 SLOW FILMS AND LARGE EFFECTIVE FOCAL RATIOS

The simple sums detailed in the foregoing sections predict that one should be able to achieve arcsecond, perhaps even sub-arcsecond, imaging in your photography with focal ratios of no higher than f/20, even with a fast film in the camera. At least this should be the case for the large-aperture end of the amateur size range of telescopes. However, the best photographs I have seen of the Moon have all been made using relatively slow films (under ISO 200) with telescopes working at high effective focal ratios (f/40, or more) and relatively long (circa ½ second) exposure times.

Problems with camera–telescope shake can become acute with these long exposure times, even if your set-up is good enough to produce smear-free pictures at 1/30 second exposure, or less. Failing a commercially made second shutter inserted before the camera, as mentioned earlier, you might be able to make something for yourself. A spring-, or motor-driven rotating blade is a feasible solution. Absolute accuracy in the timing is not essential but the exposure times produced by your arrangement must at least be reasonably consistent. One 'low-tech' approach is to hold a large black-painted piece of cardboard, shaped like a large paddle, in front of the telescope as the second shutter. A 'slicing' action will reduce the amount of air turbulence generated in the light-path. Obviously, short exposures are a problem for this method but ½ second should be achievable.

Driving the telescope is mandatory when using longer exposure times. Even if the drive works smoothly, one should be aware that the Moon moves across the sky about 4 per cent more slowly than the diurnal motion. The telescope drive will probably work at the sidereal rate. It also changes its declination particularly rapidly when close to the Celestial Equator (the rate of change then being 0.3 arcsecond per second). At these times the total differential motion is nearly 1 arcsecond per second. Unless your telescope has a 'lunar rate' drive you will be advised to keep your exposures to no longer than ½ second.

Another difficulty is that the cyclic distortions of the image produced by atmospheric turbulence may smear the details in image while the exposure is being made. Keeping the length of the exposure down at least provides the chance of securing a sharp image. Longer exposures are the preserve of the very best nights. Even then, I would urge taking several repeated exposures (at each of your chosen bracketed exposure values) in order to have a fighting chance of getting that one good photograph.

4.6 PROCESSING THE FILM AND TECHNIQUES TO BRING OUT DETAIL IN PRINTING

Doing the processing/printing yourself is advantageous in that you can control all that goes on. Tailoring what you do to the subject matter in hand will potentially give the best results. On the downside, photographic darkroom work is a hobby all on its own. Setting up a darkroom is expensive, and can be problematical in many homes. Some practice will be required to master the basics, let alone the more advanced techniques. I was lucky in that I began photography as a hobby, along with the sciences – particularly chemistry and astronomy, at a very young age. As the years progressed I was able to use photography in my astronomical work and even the chemistry helped in the concocting of various processing solutions with specialised characteristics.

In writing these words, I recognise that very few readers will have any experience of darkroom techniques. Neither will they have any inclination to go to the expense and trouble required to set up a darkroom and process their own photographs. I would go even further and say that the number of youngsters taking up darkroom work as a hobby is declining – and it is the young who form the chief intake of hobbyists. This is also true of many other practical/constructional hobbies. For instance, in the field of astronomy there are now very few young people who are even the slightest bit interested in building their own telescopes and/or auxiliary equipment. I find this sad but have to recognise this fact in writing this book for the modern amateur astronomer.

Consequently, later in this section I offer a few brief notes that may help those who already have some darkroom experience and wish to produce their own lunar photographs. Most readers will be in the hands of commercial processors and so a few words on that score may first be in order.

Commercial processing of your photographs

The golden rule when having your astronomical photographs commercially processed is to include a note with the film, briefly explaining what the subject of the film is. If you have any specific instructions (for instance, "I know these negatives will come out thin, so please up-rate the film to increase the contrast. Also, when printing please try to avoid the prints being too dark") these can be included in your note, though production-line methods will not allow the processing operative much leeway.

If your photographs include a lot of blank sky (for instance, a sequence of eclipse photographs taken with a telephoto lens) then include at least one ordinary (Aunt Matilda in the garden) photograph so that the operator has something to set the film cutter by. It would be a great shame if you get your photographs back only to find that your Moon images have all been sliced in two!

Having your films/photographs processed by a professional photographic studio/laboratory will allow you to specify a wider range of controls (second only to doing the processing yourself) but will be **very** much more expensive.

Processing your photographs yourself

Basic knowledge and experience of darkroom techniques is assumed here. If you do not have this experience but wish to know what is involved (with a view to deciding if you do wish to undertake your own processing) please refer to one of the many books currently available on this subject.

As referred to earlier, the graininess, contrast, and actual photographic 'speed' of a film is dependent on how it is processed. The choice of developer, the chosen solution strength used, the temperature, and the development time are all variables that will have a bearing on the final results.

Generally, extending the development time and increasing the temperature of the solution from the manufacturer's recommended values will, up to a point, increase the speed, contrast and graininess of the images on the film. Go too far, though, and your images will begin to suffer from dichroic (chemical) fog. Keeping the other variables the same, reducing the strength of the developer will reduce the effective speed of the film and the contrast level in the image.

By experimenting with the dilution and temperature of the developer along with increasing the development time you may well suppress the grain. I advocate experimentation. However, I must say that you will probably get the best results by sticking fairly close to the manufacturer's guidelines. When processing my own Moon photographs I tend to process them at the recommended temperature and solution strength and choose the development time that corresponds to the high-contrast end of the range.

As far as printing goes, the Moon does present one difficulty. Whereas the dynamic range (range of brightness values recordable) of the film might be of the order of 1000:1, that of the print will be only about 50:1. Consequently, getting details in the region of the Moon's terminator while avoiding the areas away from the terminator being bleached out white is not easy. Printing onto a low-contrast paper (and/or using a low-contrast print developer) would certainly compress the tonal values and show a greater brightness range on the final photograph. However the individual details will be less well seen and the print will look very 'flat'. Figure 4.8(a) shows an example. Figure 4.8(b) shows the result of printing the same negative onto a high-contrast paper. Note the loss of detail in the regions away from the terminator.

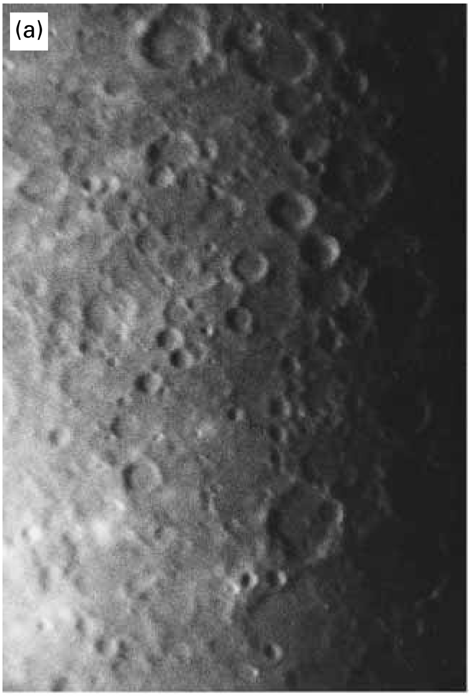
There is one solution to this problem: use a high-contrast paper (and/or print developer) but expose different parts of the photographic paper by different amounts in order to even out the differences in brightness. If you are experienced in the darkroom you will probably already be aware of this technique, termed *dodging*. Figure 4.8(c) shows the result. A piece of cardboard was used as a mask to cover all of the photographic paper, above the easel, just before the enlarger was switched on. Then the cardboard mask was slowly withdrawn, uncovering the darkest (on the negative) part of the image first. The mask was continuously withdrawn over the next few seconds, until all the photographic paper was exposed to the image. A few more seconds to complete the exposure and then the enlarger was switched off. The paper was then developed in the normal way. As always, a little experimentation will prove invaluable but the improvement in the results certainly make it worth the effort.

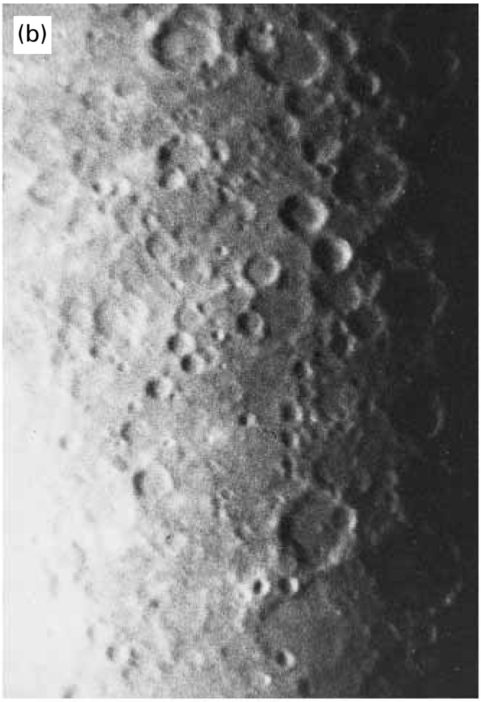
4.7 PHOTOGRAPHY THROUGH COLOURED FILTERS

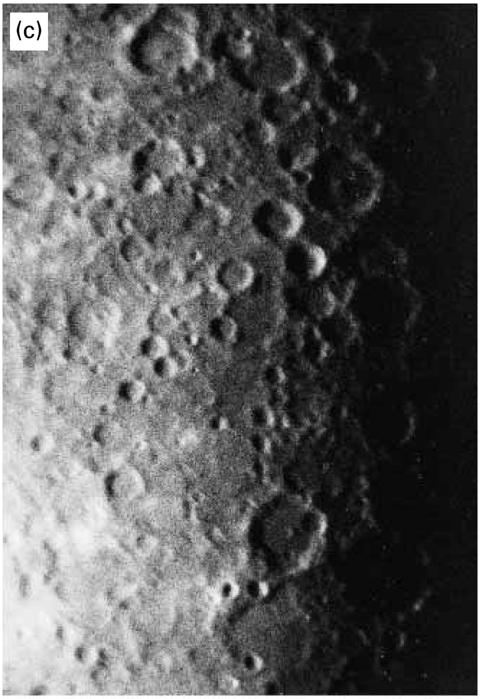
Though coloured filters can be used in combination with coloured films, you would normally wish to use them in conjunction with black and white films. The film that would be the best choice in other respects, *Kodak*'s TP2415, is also the best to choose for filter work, owing to its broad spectral response. TP2415 maintains its sensitivity well into the red part of the spectrum. Most other films have poor responses to red light. As it is, using coloured filters necessitates increasing the lengths of exposures.

The Moon may look monochrome to you but you will be surprised at the result if you take comparative photographs through red and through blue filters. A yellow or an orange filter may help improve the contrast of the image when the sky is hazy. Any residual secondary spectrum produced by your telescope's optical system (including the auxiliary optics)

Figure 4.8 One problem peculiar to photographing the Moon is coping with the large brightness variation in the vicinity of the lunar terminator. Each of these prints are from the same negative obtained in the same way (date, film and method) as the photograph shown in Figure 4.7. (a) Normal print onto Grade 2 (normal contrast) paper. Most of the details are visible but the result is rather 'washed out'. (b) Print made on Grade 4 (hard contrast) paper. Though some details are much better seen, details in the brightest and the darkest regions are lost. (c) Print made in the same way as (b) but using a moving mask while the photographic paper was being exposed under the enlarger to even out the large-scale image density.







can be suppressed by using a strongly coloured filter. A deep-yellow filter may well be mandatory when using a refractor for Moon photography for this reason.

4.8 FURTHER READING

My intention in this chapter is to provide enough information to enable you, the reader, to decide whether or not you would like to try your hand at photographing the Moon. The notes I have given here should be enough to get you started if you do decide to have a go. I realise that I have only scratched the surface, so to speak. I have provided a fuller account of the methods, techniques and equipment needed for amateur astrophotography in my book *Advanced Amateur Astronomy*. Going beyond that, there are a few specialist books you might like to consult. I especially recommend: *Astrophotography for the Amateur*, by M. Covington (Cambridge University Press, revised edition, 1991); *A Manual of Advanced Celestial Photography*, by B. Wallis, and R. Provin (Cambridge University Press, 1988); and *High Resolution Astrophotography*, by J. Dragesco (Cambridge University Press, 1995).

CHAPTER 5

Moonshine and chips

Growing numbers of amateur astronomers are following the lead of the professionals and are now recording images of astronomical bodies in electronic media. However, not everybody is able to afford the cost of the equipment needed. There will also be many who do not wish to get involved in the complicated technical matters that are a necessary part of the imaging process. There is no shame attached to either case. At least I hope not, as my own astronomy has always had to be done on a shoestring budget and I do not yet own a 'proper' CCD astrocamera. You might lack a large and expensive telescope, fitted with an expensive CCD astrocamera, linked to an expensive computer but you are certainly not barred from enjoying the Moon's spectacular vistas and studying its physical and topographic features!

You can still do some useful research (the opportunities for which are limited, anyway) using 'old-fashioned' methods with modest equipment. However, it is folly to deny that electronic imaging, particularly when allied to computer processing, permits a significant improvement in the level of detail attainable. If you can afford it, and if you are happy with dealing with the technology (particularly computers) involved, then I strongly recommend that you pursue this field. In the same way as I intended for the previous chapter on 'old-fashioned' photography. I hope the notes I give in this one should be of help in getting you started if you do decide to undertake electronic recording of the Moon's image.

Actually, there is one way of getting very high quality images of the Moon for a much smaller budget than that needed to set up for 'full-blown' CCD astrophotography: use a domestic video camera to do the recording. This method is also technically the simplest – you can get great results without going anywhere near a computer. There are even some advantages to the video technique which are not shared by other methods.

Consequently, I have devoted a large amount of room in this chapter to video techniques. First, though, let us consider the more usual form of CCD camera and its operation.

5.1 SOME BASIC PRINCIPLES OF CCD ASTROCAMERAS

A *CCD*, or *Charge-Coupled Device*, consists of an array of light-collecting units, called *pixels*. Each pixel is usually of a size ranging from 10 μm to 25 μm (10 micrometres to 25 micrometres). Professional astronomers mostly use large CCDs, typically having 2048 × 2048 pixels. These are very expensive and, moreover, make heavy demands on the computer used for the recording and subsequent image processing. Currently, amateurs use smaller versions. A typical amateur's CCD might be composed of an array of something like 500 × 360 pixels, each pixel being about 15 μm square. The recordable picture area would be 7.5 mm × 5.4 mm in that case.

These figures are only intended to give you an idea of what is typical at the time of writing (1998). As I write these words, personal computers are coming onto the market with ever-increasing speed and memory capacity and sophistication of software. This potentially allows the images generated by larger CCDs to be processed. I imagine that affordable astrocameras with larger CCDs will appear in the amateur marketplace in the next few years. It is inevitable that much of the information I provide in this chapter will be out of date by the time this book appears in print, such is the current rate of progress in this field. You should bear this in mind and seek out the latest information if you choose to enter the arena of electronic imaging yourself. The basic principles will, though, remain standard for years to come and it is these I offer herewith.

Whatever the size of CCD, the array of pixels are mounted on an 'integrated circuit' or 'silicon chip' type base which has about 20 individual electrical connections to its supporting electronics. The way it works is that photons of light falling on particular pixels liberate electrical charges within each of them (the energy of the incoming photons causes electron–hole pairs to be created within the semiconductor lattice). The more light (and so more photons) falling on a given pixel, the more electrical charge is created within it. If an image is focused on the picture-receiving area of the CCD the pixels corresponding to the brightest parts of the image have the greatest amounts of charge liberated in them. The dimmest parts of the image generate the smallest amount of charges in the corresponding pixels.

Of course, charges would continue to build up all the while the light is falling, until each pixels is full, or *saturated*. Well before this stage is reached, the process, known as *integration*, has to be stopped. Ideally an *integration time* (equivalent to the photographic 'exposure length') is selected so that at the end of it the pixels associated with the dimmest parts of the image have only a small charge while those associated with the brightest parts of the image have lots of charge, though less than the amount necessary for saturation.

When the integration is completed the array of charges are sequentially read off the chip and sent as a representative data stream to a computer, or other electronics, to deal with in order to recreate the image on a monitor/TV screen, or to download it into a computer's memory, or onto a computer disk, etc.

Photographic emulsions generally have values of *detector quantum efficiency* (DQE) of about 1 or 2 per cent. In other words, about one in a hundred to two in a hundred of the incoming photons are detected and go toward forming the image. The other ninety-eight or ninety-nine of each hundred photons are wasted. Of course, a DQE of 100 per cent is the best that one could possibly have; all the incoming photons then being detected. One of the advantages of the CCDs is that they have DQE values often exceeding 50 per cent. At least that is the case over a limited range of wavelengths.

The earlier examples of CCDs tended to have their maximum sensitivity in the red, or even the near infrared, portion of the spectrum. A typical response might be a DQE of about 40–80 per cent in the 600–950 nm wavelength range falling away steeply at shorter and longer wavelengths to become zero at about 400 nm and again at at about 1100 nm. This is very different to the spectral response of the eye, the maximum response of which occurs at a wavelength of about 550 nm in the yellow-green portion of the spectrum and falls to zero at about 380 nm (violet) and at about 700 nm (deep red).

Many of the latest generation of CCDs have coatings which enhance their response to light at the blue end of the spectrum. As an example, the *Philips* FT 12 has a response which is closer to that of the human eye. It has a peak sensitivity at 530 nm, falling to half that value at about 400 nm and 700 nm. However, it does so at the expense of some of its sensitivity, having a peak value of DQE of only 30 per cent.

Those who wish to image faint comets, nebulae and galaxies will need a high-DQE chip but there is usually plenty of light available from the Moon and so DQE is only of minor importance to the lunar imager.

So much for the basic principles. There are a number of variations in the design of modern CCD detectors. Look at the literature and you will come across the terms *interline transfer* and *frame transfer*. These refer to the way the image is read off the chip. You will also come across *back-illuminated* and *front-illuminated* CCDs. These terms refer to the mechanical structure of the CCD. Each type has its theoretical advantages and disadvantages (mainly in sensitivity, freedom from 'noise', resolution and spectral response), though as better and better CCDs are manufactured the seeming advantages of one type tend to be overtaken by those of the other.

One problem afflicting CCDs of all types is something inaccurately called *dark current*. While an integration is in progress, thermally liberated charges build up in each of the pixels. At room temperature these charges can build up to fully saturate each pixel in just a few seconds. Even before then the charges are reducing the total dynamic range (range of brightness levels) recordable. The effects are negligible for very short integration times, say a small fraction of a second, but integrations longer than that demand the CCD be cooled. Practical CCD astrocameras have built-in thermoelectric coolers. This is essential for astronomers wishing to image faint objects and is desirable, though not essential, for those wishing to image the Moon or the bright planets.

Limiting ourselves to the requirements of the Moon observer, the basic characteristics we need to worry about in selecting a suitable CCD astrocamera are: cost, the size of the **imaging** area of the CCD (one-half of the area of the frame-transfer CCD is for imaging, the other acting as a storage area of the charges before they read off) and resolution in the image (number of pixels height × number of pixels width comprising the image).

When you are buying a motor car you will be interested in the performance figures of the engine. Unless you have a particular interest in car mechanics you will not trouble yourself with the details of how the manufacturer has achieved that stated performance. I expect most readers of this book will only be interested in the performance figures of the CCD camera, so I will not waste space and bog things down with further technical theory here. I have provided details of the more general uses of CCD cameras in my book *Advanced Amateur Astronomy*. Here I will concentrate on the matters of most relevance to the lunar observer.

5.2 CCD ASTROCAMERAS IN PRACTICE

Figure 5.1(a) shows the camera head of the *Starlight Xpress* SXL8 unit. Notice the cooling fins projecting from the back of it. The major part of the mass of the camera head (about 1 kilogram) is associated with the cooling unit. The small grey square that lies within the head is the actual CCD. It is the *Philips* FT12, referred to earlier.

Figure 5.1(b) shows the rest of the *Starlight Xpress* SX system. It is fairly typical of commercial units. The plug at the end of the ribbon cable is for attaching to the user port of the computer. Notice that the camera head has a short barrel fitted into the front of it. This is so the camera head can be plugged into the telescope drawtube (or adapter tube if one is using a Barlow lens, a relay lens, or an eyepiece to enlarge the primary image) in the same manner as one would plug in an eyepiece. In practice, the weight of the camera head necessitates re-balancing the telescope tube, perhaps using counterweights.

Another *Starlight Xpress* system is shown in Figure 5.2. This one, the SFX camera system, is unusual in that it is a 'stand alone' unit that does not require the addition of a computer. The box of electronics will capture and display the images on a monitor direct, though a computer is needed to save and to process them.

The SXL8 unit is more typical of commercial CCD astrocamera systems. As well as the *Starlight Xpress* units manufactured by *FDE Ltd*, there are many others. I recommend searching them out in advertisements in astronomy magazines current at the time you decide to purchase the camera. Get further information direct from the manufacturers and take the time to make your choice carefully. To get you started I have included a limited list of CCD equipment suppliers in Section 5.6 – but beware; there are many others and the list only covers some of the main companies trading at the time of writing.

When you have made your purchase read the manufacturer's instructions very carefully. The time and effort spent will be more than repaid by how quickly you will be able to achieve first-class results. Here I confine myself to offering a few general comments on matters relating to operating the camera with your telescope.

In use, you can expect the temperature of the CCD to stabilise in about 10–15 minutes after switching on the cooling unit. The temperature will be monitored and displayed by the supporting electronics unit as shown in Figures 5.1(b) and 5.2. After plugging the camera head into your telescope (with any necessary auxiliary optics in place) the next task is to point the

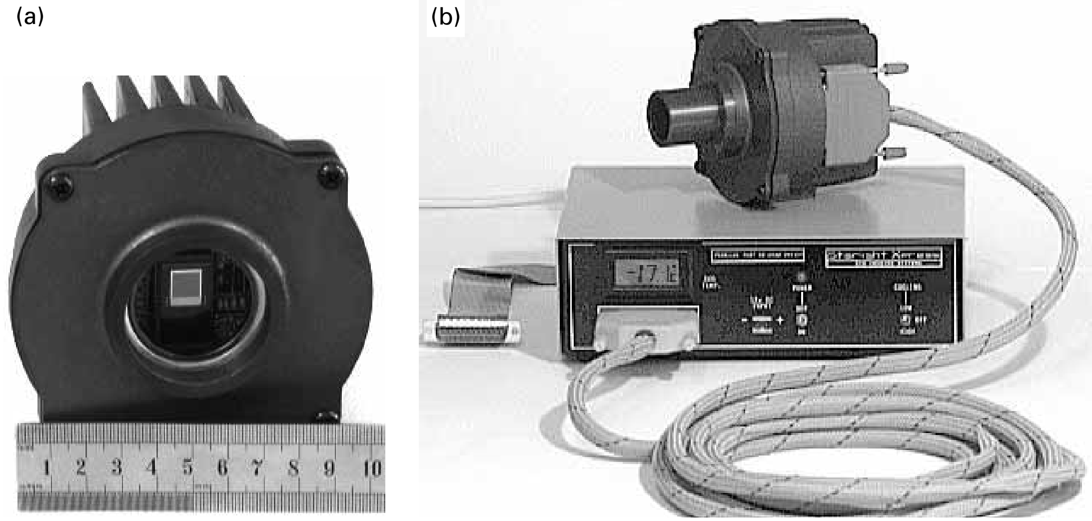


Figure 5.1 (a) The *Starlight Xpress* SXL8 camera head. The CCD can be seen within it. (The scale is in cms.)
(b) The complete *Starlight Xpress* SX camera system, typical of commercial units.

Figure 5.2 *The Starlight Xpress* SFX system is unusual in that it can capture and display images without the need for a computer. Saving and processing images does, though, require a computer.

telescope to the Moon. The small area of the CCD makes this a little difficult, especially when the primary image is enlarged.

Obviously a finderscope is of help here, especially one fitted with crosswires. However, a finderscope is certainly not an essential. Sighting up the telescope tube will get you pretty close to start with. You will find that on peering into the telescope tube you can see the patch of moonlight on the tube wall, the optics, or the internal fittings, and simply move the telescope until the light drops into the drawtube. Fine adjustment of the telescope's aim is achieved by operating the camera and seeing the results displayed on the monitor.

With the camera plugged into the telescope and it trained on the target the next task is to focus the image. This is achieved by tweaking the focuser between exposures and monitoring the results. (Hint – After doing this for the first time, a mark made using a felt-tip pen, etc. could be put on the drawtube, or focuser wheel, etc. to speed things up in future.) A motorised focuser would make life very much easier, allowing all the adjustments to be done by remote control while you are seated in front of the monitor. If you cannot afford one, perhaps you can make your own, or even motorise the existing one?

Of course, tweaking the focus, then performing an integration, waiting for the image to appear, then tweaking the focus again, etc. could certainly be time-consuming. However, many astrocamera systems have a special 'focusing mode' whereby only a small area near the middle of the frame is imaged to speed up downloading the images. It produces a rapid sequence of images, allowing one to quickly achieve the sharpest possible focus.

The procedures for making *dark frame* and *flat field* exposures will be described in the manufacturer's instructions. These will improve the cosmetic appearance of the recorded images. Suffice it to say here, for exposures of less than a second you will probably not need to subtract a dark frame provided you have the cooling unit switched on. Whether you will have to make a flat field exposure will depend upon the quality of the CCD. Recourse to the manufacturer's explanations and instructions, together with the results of your own experimentation, will soon settle this point.

I do realise that the set-up procedure I have given here is idealised. At least for your first attempts the sequence may be rather more muddled. For instance, you won't be able to focus properly until the exposure is at least approximately correct to start with. However, a little practise will soon work wonders and will make setting up a streamlined and swift affair.

After making some further trial exposures of differing lengths in order to get the best-looking image you can begin the serious process of imaging the Moon. You could perhaps store the images as files (*TIF* or *GIF* format files are normally preferred among amateur astronomers) on disk or in the computer's memory.

Maximising the resolution

In the same way as for imaging onto photographic film, the image will normally have to be enlarged from that at the principal focus in order that the limiting resolution of the CCD does not restrict the achieved resolution of the image. The theory and practice of enlarging the primary image is covered in Section 4.4.

The fact that the imaging area of the CCD is physically much smaller than that of the normal photographic film frame will mean that it is much less afflicted with outfield blurring if you decide to use eyepiece projection as the method of primary-image amplification.

What enlargement factor do you need? Here the Nyquist theorem is a useful guide. As it applies in our case it means that the smallest details resolved in the image ought to be sampled with at least two CCD pixels. Less than that and the image will be under-sampled and some of the resolution will be lost. Also, spurious details may be generated by the undue prominence of the 'blocky' nature of the CCD matrix. For imaging with a good-quality telescope of up to about 12 inches (305 mm) in aperture one might set the desired resolution as that imposed by the diffraction limit (discussed, with formulae, in Section 3.1).

By Rayleigh's formula, a 12-inch aperture should resolve down to 0.45 arcsecond. Of course this is better than the seeing prevalent at most sites will normally allow but it is better to 'aim high'. However, it would be as much of a mistake to aim too high. For a given CCD, the area of the Moon imaged will also be at a premium. Filling the available picture area with a very blurry view of a single small crater is hardly desirable!

If we were using a CCD with 15 μm (1.5×10^{-5} m, or 1.5×10^{-2} mm) sized pixels, then we should arrange that the smallest details resolvable should cover two adjacent pixels (a linear distance of $2 \times 1.5 \times 10^{-2}$ mm, which is equal to 3×10^{-2} mm). As an example, let us say that we are using a 12-inch telescope and hope to capture details at the diffraction limit. Hence the image scale we need is $0.45/3 \times 10^{-2}$, or 15 arcseconds/mm. To get that image scale we need an effective focal length of 206 265/15, or 13 551 mm (Equation (4.1), relating image scale to effective focal length, is given in Section 4.2). This is an effective focal ratio of f/44.

It might be useful to realise that this 'diffraction-limited – Nyquist limit' is attained for a 15 μm CCD in use with **any** optical system of this effective focal ratio (because the image scale is proportional to the aperture for a given focal ratio, and the resolving power is also proportional to the aperture). The same limit is reached with an effective focal ratio of f/30 when using a CCD with 10 μm sized pixels, and f/60 (in round figures) for one with 20 μm pixels.

Given normal seeing conditions, I would advise against further proportional increases in focal length for apertures larger than 12 inches. Instead, use the extra aperture of the telescope to deliver images to the CCD at a lower effective f/number. The extra brightness will allow shorter exposures to be given and so increase the chances of getting that elusive sharp image amid the usual turbulence. At any rate, that is what I would do. I recommend experimenting to find out what best suits your own equipment and the conditions at your own observing site.

Once you have your images stored on disk or in the computer memory you can take advantage of one of the major bonuses that comes with this technology: enhancing them by the use of image-processing software. More of this in Section 5.4.

5.3 VIDEOING THE MOON

Take a look at Figure 5.3. It shows the great crater Plato and part of the Montes Alpes. I took this photograph using my own telescope, though not by means of conventional film photography, nor by the use of a proper CCD astrocamera. In fact, I used my own domestic video 'palmcorder'.

The seeing was very ordinary that night and yet the resolution of the image approaches the 1 arcsecond level. It is, you will have to take my word for it, depressingly rare for the seeing to allow details any finer than that to be seen (or even just glimpsed) from the garden of my home in Sussex, England.

Using conventional photography, I would have had to take more than one hundred exposures in order to have a fair chance of getting just one that shows details as fine as this on the same night. Yet this picture is not a fluke. Take a look at Figures 5.4, 5.5 and 5.6, also made in the same videoing session, showing other parts of the Moon that night.

The telescope I used was my 18¼-inch (0.46 m) reflector but the seeing was the limiting factor in the resolution of the images, not the size of the telescope. You could have done just as well as I have with a telescope of less than half the aperture of mine. In better seeing conditions you could easily improve on my results. In the following notes I explain how.

The video camera

If you already own a video camera, then put that one into service with your telescope. I am sure that you will be delighted with the results. However, if you are wishing to buy one with the express purpose of using it with your telescope (and all the other uses for it are a mere bonus) then I recommend considering a few factors before making your choice.

Figure 5.3 Video image of the Moon taken by the author, using his 18¼-inch (0.46 m) reflecting telescope on the date and time shown. The large crater at the lower right is Plato and the mountain range extending from the upper left to Plato is part of the Montes Alpes. Further details in text.

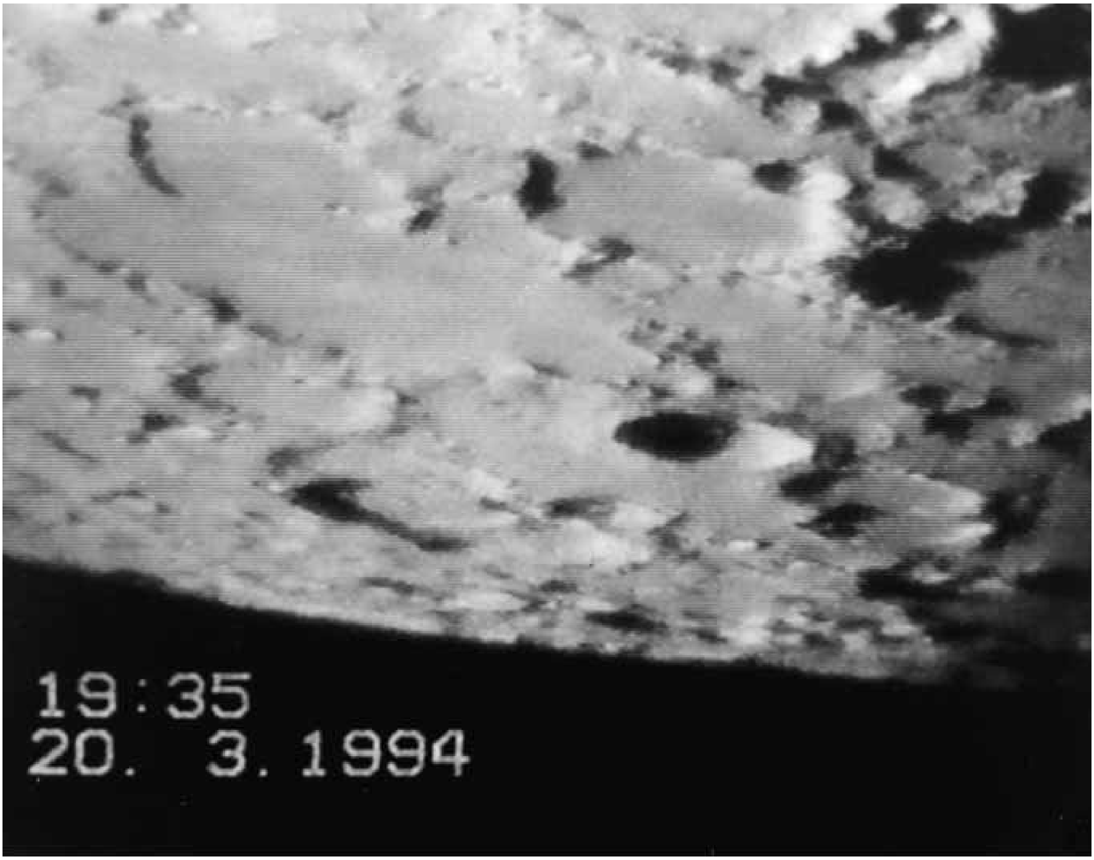


Figure 5.4 The north polar region of the Moon. A video image taken by the author at the date and time shown. Further details in text.

After its cost, one important consideration is the camera's size and weight. Though it is sometimes possible to successfully arrange the camera on a separate tripod and have it peering into your telescope, you will normally have to have the camera riding on the telescope. I have achieved some success in hand-holding the camera to the eyepiece but the results are decidedly hit and miss, especially as holding the camera still for long periods is difficult.

Even a 'palmcorder' type of camera will have a mass of about a kilogram. You also will have to construct something to do the job of firmly attaching the camera to the telescope. The heavier the camera is, the firmer – and this usually means heavier – this contraption will have to be. Will your telescope remain shake-free with all this weight hanging close to the eyepiece? Do not forget that you will also need to add counter-weighting to re-balance the tube and/or the mounting!

Consequently, unless you own a telescope which is constructed like a battleship, I recommend selecting a video camera which is as lightweight as possible.

The next thing to worry about is the resolution of the camera. Obviously it should be as great as possible. All modern video cameras have CCDs as their image detectors. A low/medium-quality camera will have a '⅓-inch CCD image sensor', more expensive models having a '½-inch' version. You will normally find the figures for picture resolution, and size of CCD in the technical specifications section of the instruction manual. I recommend that you insist the storekeeper opens the box so that you can examine the manual prior to purchase. The stated picture resolution is often that in the horizontal direction. The vertical resolution is usually slightly better. A '⅓-inch CCD' camera ought to have a horizontal resolution of more than 200 lines across the full width of the TV frame.

Unlike the older video cameras which used vidicon tubes as their sensors, all modern cameras are very light sensitive. On the low light level

Figure 5.5 Another video still of the Moon obtained by the author using his telescope, this time of the region of the crater Regiomontanus (the large formation just below centre, containing the volcano-like structure on its floor). The date and time the image was taken is displayed at the lower left.

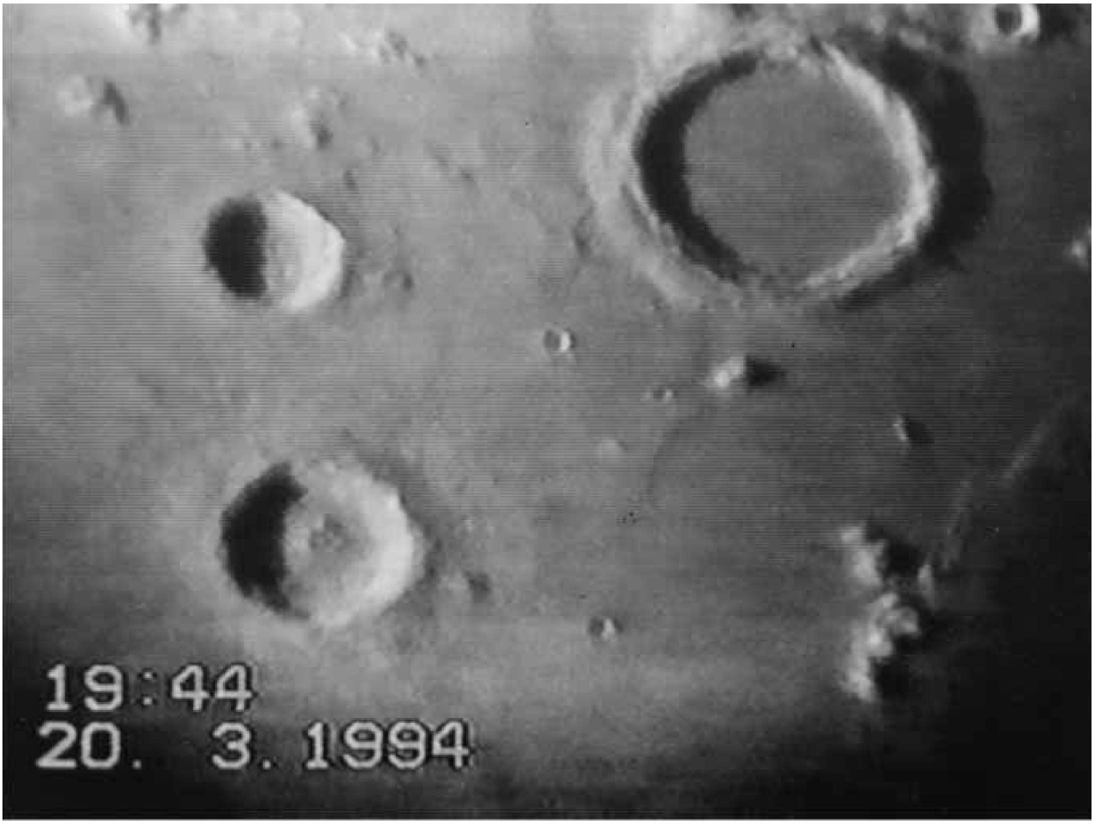


Figure 5.6 Part of the Mare Imbrium, the largest crater being Archimedes, imaged by the author at the date and time shown. Other details as for Figures 5.3, 5.4 and 5.5.

exposure setting mine records in illumination levels as low as 1 lux. Using my camera with my 0.46 m telescope, I was able to successfully record the dust shells around the nucleus of comet Hale–Bopp. You should not have any trouble in recording the Moon's vistas through the camera, even when using a telescope of quite small light-grasp. On the contrary, you might even have to take precautions against too much light if you use a low magnification on a large-aperture telescope!

There is one major pitfall I must warn against: **do not purchase a video camera which has no manual override for focusing**. Using a video camera on 'automatic focus mode' to try and image the Moon through the telescope is doomed to failure. Do so and you will find the camera's electronics will not like the image your telescope delivers one little bit. The camera focusing mechanism will restlessly zoom and jitter about the mean focus setting. Trying to watch the playback will make you feel very queasy! You **must** be able to focus the camera manually.

I purchased my video camera at the beginning of 1994. It is a *National Panasonic* NV-S20B and cost me just under £600 (about $1000). It is a 'palmcorder' having a mass of just under 1 kg without its batteries (it can be powered by a transformer at the end of a long, lightweight, cable if desired). The '⅓-inch CCD sensor' has a horizontal resolution of "more than 230 lines", according to the specifications. The camera has the facility for on-screen recording of the date and time, if desired, as well as a selection of 'shutter speeds' which allow one to optimise the image quality for different lighting conditions. More about the usefulness of this function later. The camera lens can 'zoom' between effective focal lengths of 5 mm (the widest-angled view in normal use) to 40 mm for close-ups. We need the lens set to 'maximum zoom' ('$\times$8', 40 mm effective focal length in the case of my camera) when using it with the telescope.

Mounting and shooting

I certainly do not recommend attempting to remove the lens of your video camera. So, you are forced to leave the telescope eyepiece in place and use the 'infinity-to-infinity' focusing method, as described in Section 4.4.

The camera needs to be mounted so that it looks squarely into the telescope eyepiece. Figure 5.7 shows how I attach my video camera to my 0.46 m telescope. There are as many solutions to the problem of mounting the camera on the telescope, and ways of achieving the necessary re-balancing of the telescope, as there are different telescopes. It is purely a matter of

Figure 5.7 The arrangement the author uses to attach his video camera to his telescope. Counterweights (not shown) attach to the bottom end of the telescope tube to restore the balance.

mechanics. Even if the publisher were to allow me many extra pages in this book so that I could outline several of the possible solutions, the chances are that I would still not cover anything that is suitable for **your** particular telescope and camera, given the tools and materials **you** have at your disposal. So, the mechanics of achieving the mounting of your camera onto your telescope I must leave to you.

At least Figure 5.7 might provide some inspiration. Note how I have provided some adjustment for 'squaring on' the camera to the eyepiece – necessary to get the best-quality images. I have also made some provision for racking the camera back and forth, which is a great convenience when using different eyepieces and for initially setting everything up – particularly changing eyepieces and focusing, when some clearance will be needed in front of the camera lens.

The Moon is in the sky and we have just set the camera into its mounting, fitted to our telescope, and have also attached the counterweighting. The telescope is balanced and ready to turn towards the Moon. We have already made sure that the camera focus is set to 'manual' and that the focus ring is moved all the way to 'infinity' (long distance) focus position, also that the 'zoom' setting is to maximum (more about this shortly) and that the camera is otherwise ready for operation.

With the camera set back as far as possible from the telescope, plug a low-power eyepiece into the telescope drawtube. Adjust the rackmount so that the eyepiece is close to its normal position for infinity focusing. Perhaps a pre-determined felt-pen mark on the drawtube would be a useful guide, since you will not be able to get your eye to the eyepiece with the camera in position.

If the eyepiece is fairly close to its correct infinity focus position, then the camera can be safely brought up so that its lens is a centimetre or two from the eyepiece but do leave room enough for any necessary fine adjustment.

Now it is time to point the telescope towards the Moon. My comments here follow those already given in Section 5.2. At the point where the moonlight is dropping into the telescope drawtube you will probably be able to see it emerging from the eyepiece and illuminating the camera lens.

Powering-up the camera and looking through its viewfinder, you ought to be able to easily find the Moon's image and set the telescope on the part of it that you want to record. At this point you can make any fine adjustment necessary to the telescope focuser **but please do be very careful that you do not drive the eyepiece into collision with the camera lens!** If desired, you can now bring the camera a little closer to the eyepiece, though a gap of a centimetre or so will make no difference; the camera lens is big enough to capture all the emergent rays without it having to be in extremely close contact with the eyelens of the eyepiece.

Having brought the image to as fine a focus as possible, you should now be seeing an impressive view of the Moon's mountains and craters. Try the various camera exposure settings. The shortest on my camera is the so-called 'sports' setting. This produces the best result with my telescope. The image is sharpest at this setting because the effects of turbulence and any tremors of the telescope are virtually 'frozen' on individual frames.

Also, I find that my 0.46 m telescope gathers too much moonlight for the camera to cope with on the other settings. On my first attempt, I found that a black curtain effect (caused by severe overload) descended over the image when the Moon entered the field on all but the 'sports' exposure setting. Even if your telescope is rather smaller than mine, you will probably find that the fastest exposure setting will give the best recorded image.

Of course, the magnification of the image, the transparency of the air, etc., will all determine the correct exposure. At least you can see what is happening through the viewfinder while you select the different exposure settings on the camera – a big advantage over silver halide photography!

You might be satisfied with the view you already have through the camera and can set it recording onto its own tape. Alternatively you might wish to change the eyepiece to give a higher magnification. More on this later, though here is the place to explain why the camera ought to be left on a setting close to full zoom.

The reason is that on lower settings (at which the camera lens has a shorter effective focal length) not all of the rays emerging from the eyepiece can find their way unobstructed through the camera lens assembly. If you experiment with the camera on the telescope you will find that on a low zoom setting the image appears as a small island in a sea of surrounding blackness. Press the zoom button and you will find that this patch expands in size. Nearly full zoom will be needed before the image fills the field.

If you can successfully mount your video camera onto your telescope, and get it balanced properly, you will find this technique very forgiving as regards any other requirements of your telescope. An equatorial mount is a great convenience, while a drive is very much a luxury. You could even get superb results from an undriven altazimuthly mounted telescope. There are other advantages in using a domestic video camera: the images are in full colour and one can record a commentary at the same time as recording the view through the telescope – though you might warn the neighbours, lest they become perturbed on seeing you apparently chatting to yourself while at your telescope!

Field of view and image scale

The effective focal length and effective focal ratios are calculated in the same way as for a conventional camera in the infinity-to-infinity configuration (see Section 4.4). By way of an example, the photographs shown in Figures 5.3, 5.4, 5.5 and 5.6 were all taken with my 0.46 m reflector, which has a focal length of 2.59 m. My camera, with its lens adjusted to 'full zoom' (effective focal length 40 mm) was set looking into an 18 mm focal length Orthoscopic eyepiece. The amplification factor was 40/18, or 2.22. Thus the effective focal length of the combination was 5.76 m, and the effective focal ratio was f/12.4.

Knowing the effective focal length, the image scale can be calculated. In this case it was 206 265/5760, or 35.8 arcseconds per millimetre. However, I do not know the precise size of the CCD so this figure is only useful in making a rough prediction of the area imaged. The "⅓-inch" size of the CCD is only a rough guide. It is a category, rather than a precise figure, and refers to the approximate (and usually exaggerated!) length of the diagonal between corners of the CCD's imaging area. If your video camera has a '⅓-inch' CCD you can expect it to have an imaging area of something like 4.0 mm × 5.3 mm.

The area covered in each of the photographs presented in Figures 5.3, 5.4, 5.5 and 5.6 is approximately 140 arcseconds × 190 arcseconds. The reproductions are virtually the full frames photographed from my TV screen.

Maximising the resolution

You might not know the size of the pixels in your camera but you can still ensure that you do not under-magnify the image and so limit the potential resolution. The manufacturer's specifications sheet will provide you with a figure for the resolution in terms of the size of the full frame. My camera has a resolution in the horizontal direction of "more than 230 lines". With the arrangement of my telescope, camera and eyepiece already described the width of the full frame comes out as 190 arcseconds. Therefore the potential resolution of the image is 190/230, or 0.8 arcseconds.

On most nights I find that I can only glimpse arcsecond-level details, so this choice of amplification is about right. Increasing the magnification would serve only to reduce the field of view and produce a blurrier image. However, on nights of perfect seeing my telescope ought to resolve down to about 0.3 arcsecond. I could match this by exchanging my 18 mm focal length eyepiece for one of 6 mm focal length. The potential resolution would then be 0.28 arcsecond and the size of the field of view would be 48 arcseconds × 63 arcseconds. Unfortunately, the very few instances I have experienced seeing anywhere near that good have all happened before I acquired my video camera!

Playback!

Videoing the Moon is surely the easiest way of getting high-quality images of it if, like me, you have limited facilities and a poor observing site. With more than two-dozen images recorded every second, you can search out the few best ones in each session. Your friends will be wowed by the impressive views of the Moon you will be able to show them on your television screen. More importantly, since these images are 'hard copy' they have real scientific value. The contentious field of TLP research is one where hard-copy evidence of any suspected anomaly is highly desirable. Not only would the evidence be more believable, but also having hard copy enables scientific measurements to be obtained from the images. More about TLP research in Chapter 9.

The video images you can achieve should be much better, in terms of limiting resolution even if not in total area of the Moon imaged to a high quality, than anything you can achieve through old-fashioned silver halide photography. In fact you can make them better still if you can send the images to your computer!

Linking your video to your computer

There is a way of sending the output of your video recorder/camera to your computer. Your computer must be fitted with a piece of circuitry (in computer jargon a *card*) known as a *frame-grabber*. If you are up to the job you could install this hardware (and then install the operating software) yourself. If not, then you will have to have a computer specialist do the job for you. I am quite well practised in electronics. However, I am very much a novice when it comes to computers. All my previous books were written on my old *Amstrad* Word Processor! After it gave eleven years of faithful (if sluggish) service, I decided that it was about time I put it out to grass and get something more modern. As well as my replacement machine performing as a word processor to enable me to write this book and those in the future, I looked forward to the various other clever things it should be able to do.

I ordered a bespoke computer in 1996 (the specifications of which I determined after seeking the advice of knowledgeable friends) and had the supplier fit a frame-grabber card in it. What I got was a *Hauppauge 'VideoMagic' Motion-JPEG video-capture* card fitted into my *Pentium 133* computer. The computer has a 1.6 Gigabyte hard-disk and 32 Megabytes of RAM. If those specifications seem laughable to you, remember in 1996 those values of speed and memory were quite respectable! At the time of writing (1998) the same money (£2000, $3200 – including the *Windows '95* and *Hauppauge 'VideoMagic'* software and a *Hewlett Packard* Deskjet 690C printer) would easily buy a system with twice the memory and processing speed. Those figures will undoubtedly have further increased by the time you are reading these words.

In most respects I am very pleased with the performance of the package, though I am disappointed in the performance of the *frame-grabber* itself. The software for processing individual frames is fine and I have achieved impressive results in manipulating images sent to me on disk by other astronomers. The system can do many impressive things, including sampling sequences of video and processing them with a variety of special effects for re-editing back into one's home-made movies, etc. However, I find the quality of the initially 'grabbed' individual frames is a little lacking compared to the same frame 'frozen' on my VCR and displayed on my TV. I have spent some while checking that all the software and hardware settings are correct. They are. It seems that in doing many clever things, the system does the one thing I particularly want less well! Of course I can still enhance and manipulate my own video images, though the quality of the end result must suffer because of the lower quality of the initial grabbed image.

One very successful and popular frame-grabber/digitiser is the '*Snappy*', manufactured by *Play, Inc.* It plugs into the computer's external user port, so obviating the necessity of internal installation. Ron Dantowitz, a practitioner of video imaging who gets outstandingly good results, uses a '*Snappy*' frame-grabber as part of his system, so it is obviously a good one! Now that I have begun to acquire a little knowledge and experience in computers and image processing I can be sure that when I upgrade I will do so rather more effectively than I did on my first attempt.

Once the raw image is in your computer you can perform various operations on it. Image processing is the subject of Section 5.4.

Other video systems

The problem of fixing a weighty and bulky video camera to your telescope can be avoided if you elect to buy or, if skilled in constructional electronics, make for yourself a video system in which the imaging unit contains just the CCD and the minimum of supporting electronics. This part of the system is attached by lightweight cable to the rest of the imaging and/or recording device. If you are prepared to deal with suppliers other than the high street stores, you can obtain a variety of suitable CCD imaging units. For instance, the major electronics manufacturer *Philips* produced a monochrome CCD camera module as long ago as 1988. Despite its impressive specifications, including a resolution of 450 lines and a sensitivity of 0.02 lux, it retailed at only £400 (about $640).

You will find suitable cameras supplied by security equipment retailers, the major electronics firms, and (usually at higher cost) suppliers of astronomical equipment. In addition, many electronics firms will sell you kits for constructing your own CCD camera equipment.

You might well feel overwhelmed and confused when you start receiving information packages and brochures from the suppliers you seek out but if you focus on six main requirements for your system you should soon be able to settle on the one that meets your needs. I would prioritise the six factors, with the most important first, as follows: compatibility with standard video recording equipment, cost, resolution, the weight and bulk of the unit that attaches to your telescope, and ease of operation. Happy hunting!

David Brewer, in the USA, and Martin Mobberley, in the UK were among the first of the amateur astronomers to use video techniques in their observing. That was back in the 1980s. There are now many others. I got surprisingly good images of the Moon, myself, using a borrowed old vidicon-tubed camera in 1985. Cameras have got very much better and cheaper since then.

Thomas Dobbins, in Ohio, USA, produces superb results with a camera that cost him only $400 (obtained from Hong Kong) in the mid-1990s. He has written an account of his work, ‘Recording the Moon and planets with a video camera’, in the December 1996 *Journal of the British Astronomical Association* (Vol. 106, No. 6) and I recommend seeking this out.

I have already mentioned Ron Dantowitz of Boston, USA. My jaw dropped open when I saw the illustrations in his article, ‘Sharper images through video’, in the August 1998 issue of *Sky & Telescope* magazine. As well as obtaining stunning images of the Moon and planets, Dantowitz even manages to resolve Earth-orbiting satellites and the Space Shuttle *Atlantis*! The details of his technique are too involved for me to include here, and so I recommend adding his article to your reading list. However, the key component of his video system is an off-the-shelf commercial monochrome CCD camera. A version of it, called *Astrovid 2000*, especially modified for astronomical use, is currently (1998) available from *Adirondack Video Astronomy*, who can be contacted at: 35 Stephanie Lane, Queensbury, NY 12804.

5.4 IMAGE PROCESSING

Once the digitised image is in your computer you can perform a wide variety of operations in it. As well as manipulating the brightness levels, colour hue, and saturation, of the image, one can perform various enhancement procedures.

It is possible to combine frames or semi-frames, to stitch frames together in order to build up a large area image from smaller components, to apply various filters to enhance small-scale features, etc. What you might try will, of course, depend upon the time, energy, and resources you have available. Suitable software packages abound. A software package which is particularly popular with astro-imagers at the time of writing is *Adobe PhotoShop*.

This area is large and still growing. As well as keeping a lookout for articles in contemporary astronomy magazines, I recommend you keep an eye out for recent books. Those 'recent-ish' as I write these words include: *Choosing and Using a CCD Camera*, by Richard Berry, Willmann–Bell 1992; *The Art and Science of CCD Astronomy*, edited by David Ratledge, Springer–Verlag 1996; and *A Practical Guide to CCD Astronomy*, by Patrick Martinez and Alain Klotz, Cambridge University Press 1997.

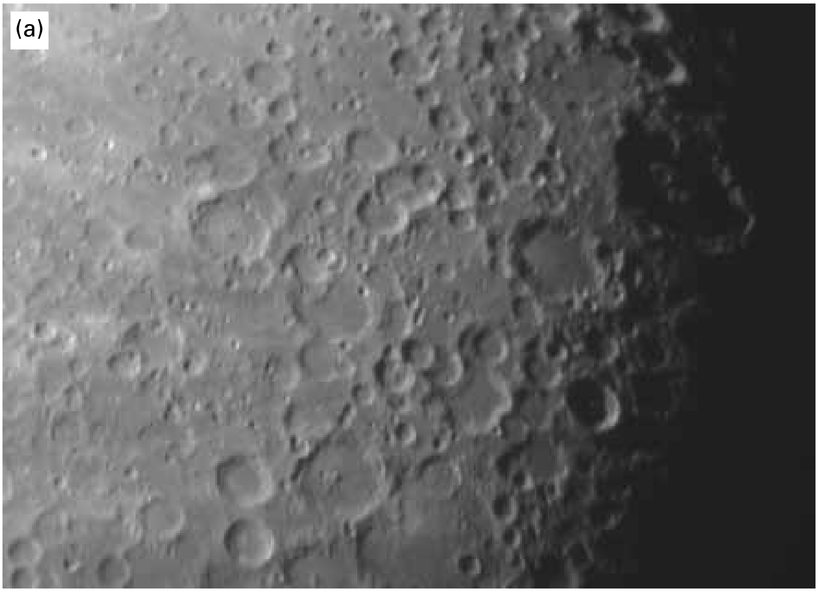
I offer here just a couple of examples of image processing in action. Figure 5.8(a), (b) and (c) shows how Terry Platt has started with a raw image of the Moon and processed it to show fine details. Figure 5.9(a)–(e) shows a sequence where I have applied further image processing to one of Terry Platt's already very good images. The details are given in the accompanying captions. As you will see from Figure 5.9, operating the software is a matter of clicking on icons and dragging slider bars. Fortunately, full instructions are always supplied. Study these well and be prepared for many hours of experimentation if you hope to become a virtuoso of image processing.

Terry Platt began experimenting with CCD imaging in the 1980s, building his own equipment. Since then he has gone on to produce the *Starlight Xpress* range of CCD astrocameras which are now sold world-wide. Terry has kindly let me include a number of his superb images in this book. You will find examples in Chapter 8, Figures 8.4(b) and (c), 8.13(d), 8.17(f), 8.33(c), 8.44(e), 8.46(c), and 8.47(a). CCD images by another enthusiast, Gordon Rogers, are to be found in Figures 8.11(b) and 8.14(e). Details are included with them.

As well as inputting images into your computer direct from the CCD camera system, or from the frame-grabber attached to your video camera, you could also digitise your own photographic transparencies, negatives or prints. Suitable scanners are now becoming more affordable. All the enhancement procedures can be applied to these images just as well as to those originating from CCDs. I recommend seeking out a couple of *Sky & Telescope* magazine articles: 'Digitally enhance your astrophotos' in the July 1997 issue and 'Digital desktop darkroom' in the July 1998 issue. Although both articles concentrate on deep-sky subjects, much of the material is also relevant to the lunar imager.

5.5 GETTING HARD COPY

The printers for home computers available for a given outlay are getting better. Ones that produce print-outs of truly photographic quality are now easily within the financial reach of many people. Alternatively, if you lack



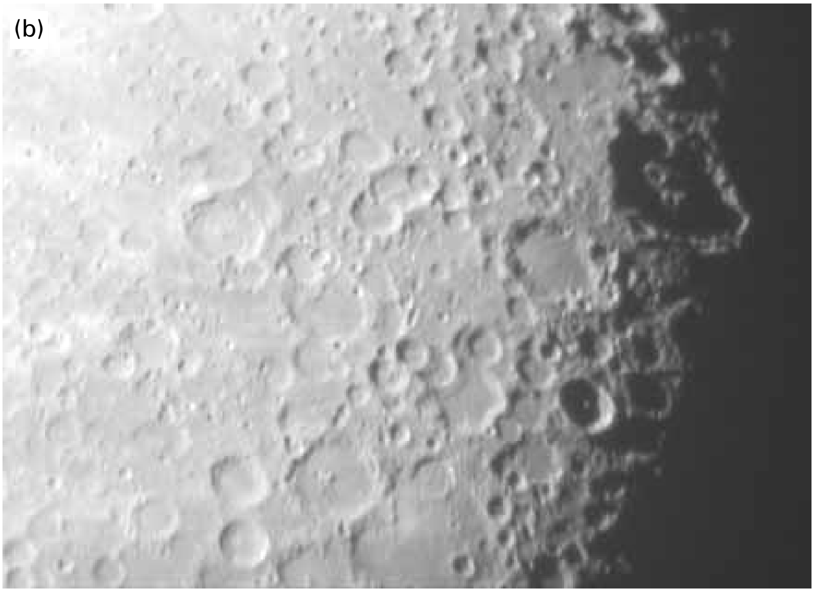


Figure 5.8(a)–(c) Stages in the processing of one of Terry Platt's images of the Moon.
(a) 'Raw' image obtained by imaging the Moon at the f/5 Newtonian focus of an 8-inch (203 mm) reflector (stopped to 3-inch, or 76 mm, off-axis) onto the CCD of a *Starlight Xpress* SFX camera.
(b) Result of a non-linear contrast stretch in order to improve the details in the dark terminator region.

one of these, or if you wish to get hard copy direct from your TV or computer monitor – for instance you may want still photographs from your Moon videos as displayed on your TV – then you can do this as well. However, there is more to it than simply pointing your camera at your TV and snapping away. It **is** relatively easy to get good results but you have to go about the task in the right way.

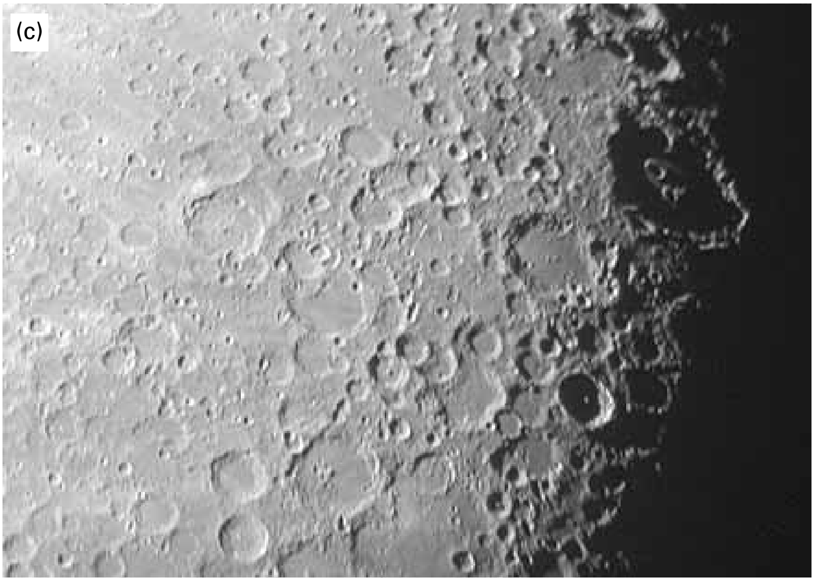


Figure 5.8 (*cont.*)
(c) Final result, after the image sharpness has been improved by using a 'high-pass filter'.

After the obvious basics of setting the camera up on a tripod in front of the TV/monitor and aligning and focusing on the image as carefully as possible through the viewfinder, the room should be made as dark as possible to avoid reflections showing up in the glass screen.

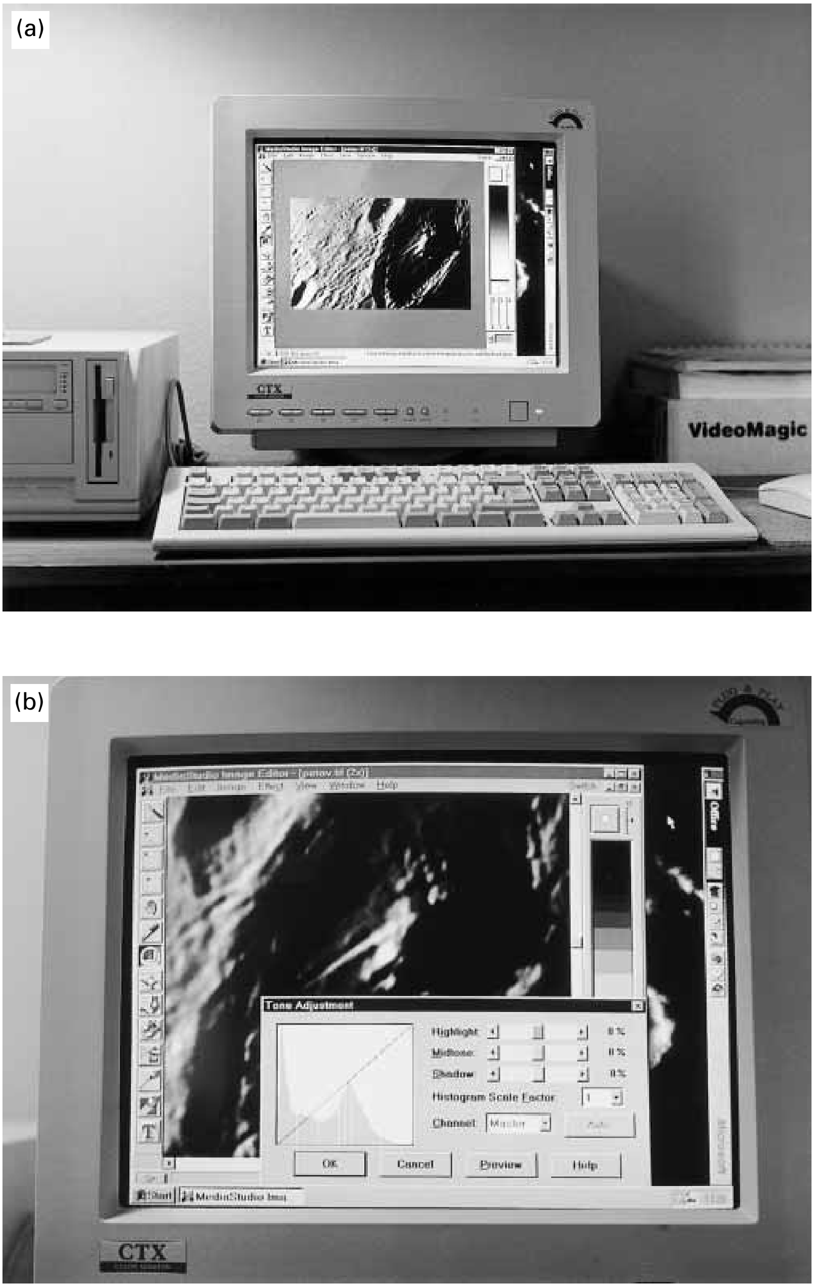
The film in the camera ought to have a speed of around ISO100–125. Using the camera's exposure meter (or a separate one if needed) select the appropriate f/number that corresponds to an exposure of ¼ second. You will still have to use a wide aperture, perhaps f/4, but that is not the main reason for selecting that particular exposure length.

The necessity for the long exposures is due to the way the TV generates the viewing picture on its screen. The picture is synthesised from a small spot of varying brightness that scans over the screen building up a *raster*. This spot starts at the top left of the screen, moving to the right. Then it rapidly starts again at the left of the picture but just a little lower than before. The process continues down the screen.

In 1/50 second after the process started (1/60 second for televisions in the USA) the spot has built up a partial picture composed of a grid of horizontal lines with gaps in-between. In the next 1/50 second (1/60 second for televisions in the USA) the spot starts again near the top left of the screen and fills in all the missing gaps. In this way the interleaved scanning process creates the illusion of a complete and fairly flicker-free picture every 1/25 second for UK televisions and 1/30 second for those in the United States.

The human brain may be fooled but the camera is not if the exposure is too short – either a partial picture or one with light and dark bands on

Figure 5.9(a)–(e) Further manipulation on the author's computer of one of Terry Platt's superlative CCD images.
(a) 'Original' image.
(b) 'Tone adjustment' histogram for the 'original' image (having first 'zoomed-in' on a selected area).



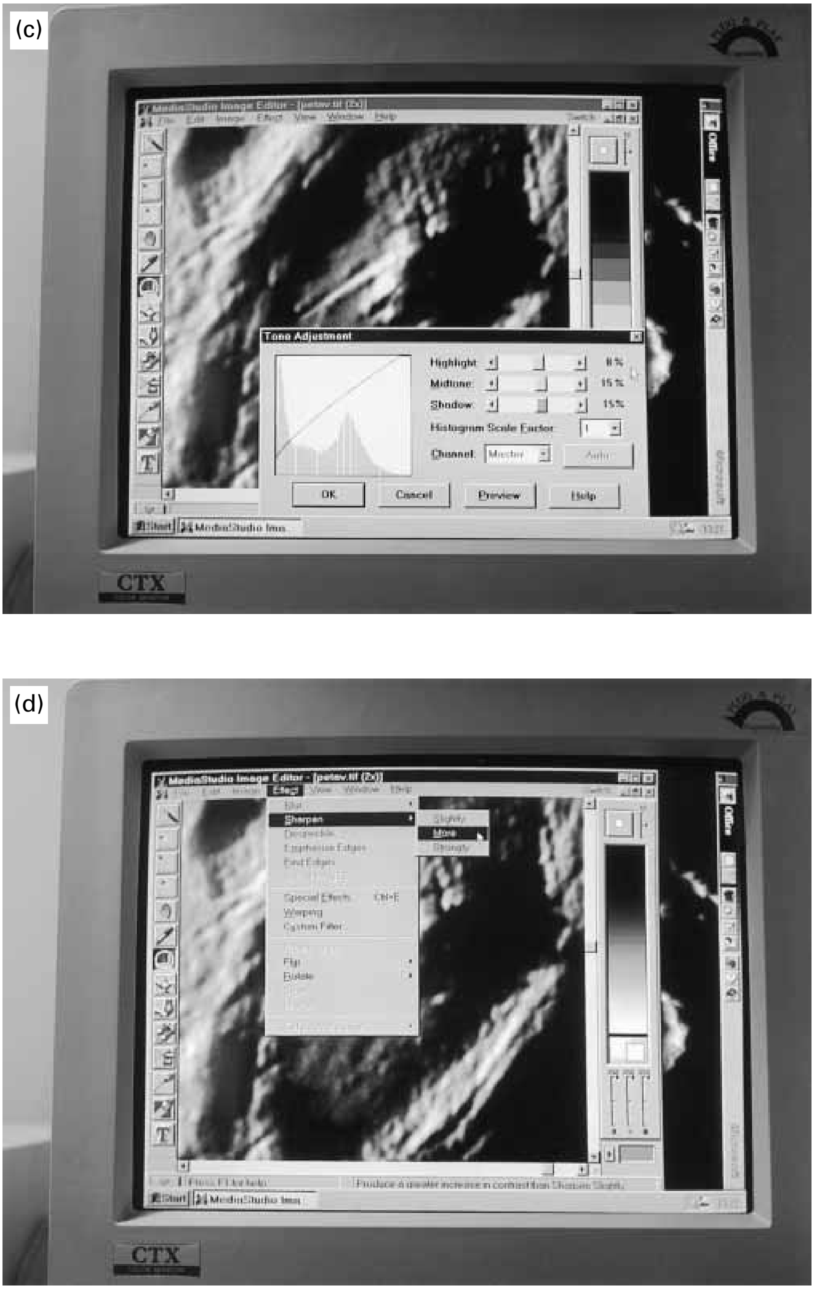


Figure 5.9 (*cont.*)
(c) Effect of altering the parameters (by dragging the slide-bar controls in the window) in order to improve the visibility of the shadow details within the crater. Note the change in the parameters and the new histogram.
(d) Calling up the appropriate window in order to sharpen the image.

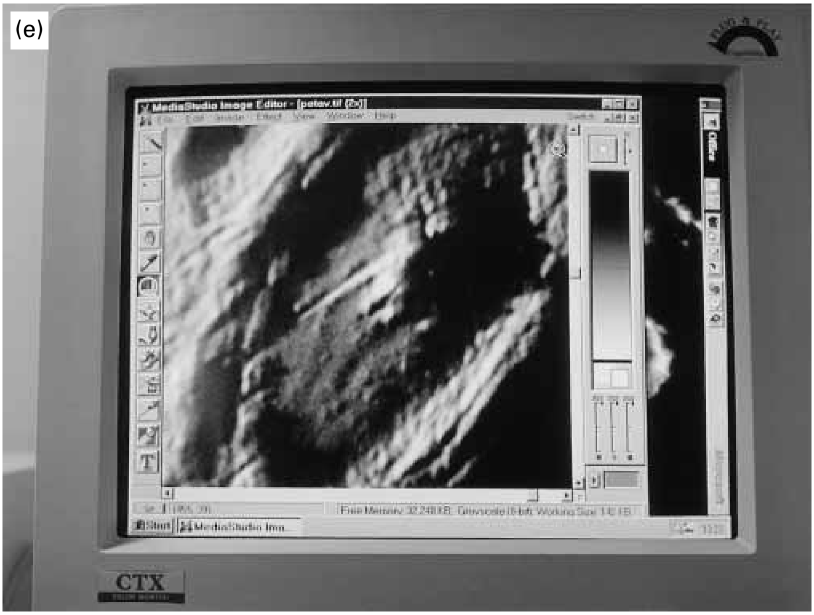


Figure 5.9 (*cont.*)
(e) The final result.

it would be the result. The snag arises from the way the camera's shutter interacts with the image of the moving spot. For my earliest experiments I used an exposure of 1/8 second and this proved to be only just sufficient to avoid significant bands of lighter and darker image appearing. These broad bands are caused by un-synchronised incomplete fields. Figure 5.6 is one of those early results and the banding is slightly in evidence. The extra field-sweeps comprising an image recorded in ¼ second are enough to blend out the banding.

For photographing video stills, the freeze-frame on your VCR must work well. If it doesn't, try adjusting the tracking control. This will usually calm a fluttering image.

In his *Journal of the British Astronomical Association* article, referred to earlier, Thomas Dobbins advocates combining several exposures in order to reduce the 'grain' that often blights still images. He simply leaves the video playing and makes his photographic exposure at the time he judges the image quality to be at its best. However, he does record the Moon from a site where the seeing conditions are much superior to those I have to put up with.

I seldom get even two consecutive good frames, let alone a whole sequence of a dozen or more of them. My best results come from carefully searching out those individual frames where at least the central area of the image reveals the sharpest details. I then photograph just those. Obviously this needs a VCR with a good pause and frame-by-frame advance facility.

Nowadays all but the cheapest (less than four head) models of VCR should be up to the job.

If having your off-screen Moon photographs commercially processed, it is probably advisable to include a brief note explaining what the content of the film is, when handing it over. Of course, doing the processing and printing yourself does allow you to be fully in control. For instance, if the TV screen's phosphors are unduly prominent you can try slightly defocusing the image to soften their appearance. Provided you do not take the defocusing too far you should be able to produce a more aesthetically pleasing result without any significant loss of lunar detail.

5.6 SOME CCD EQUIPMENT SUPPLIERS

This list is intended merely to get you started in your search for suppliers of CCD equipment. It is not complete and, in any case, may well be out of date by the time you read these words. It covers only the main suppliers of dedicated astronomical CCD systems. Neither I, nor the publishers, would wish to endorse one manufacturer's products over those of another, nor can become involved in any disputes between you and any supplier. This list is for information purposes only.

Celestron International, 2835 Columbia Street, Torrance, California 90503, USA (Available in the UK from David Hinds Ltd., Unit 34, The Silk Mill, Brook Street, Tring, Herts., HP23 5EF).

True Technology Ltd, Woodpecker Cottage, Red Lane, Aldermaston, Berks, RG7 4PA, England.

Meade Instruments Corporation, 6001 Oak Canyon, Irvine, California 92620, USA (Available in the UK from Broadhurst, Clarkson and Fuller Ltd., Telescope House, 63 Farringdon Road, London, EC1M 3JB).

Micro Luminetics Inc., 3447 Greenfield Avenue, Los Angeles, California 90034, USA.

Santa Barbara Instruments Group, PO Box 50437, 1482 East Valley Road, Suite #33, Santa Barbara, California 93150, USA.

SpectraSource Instruments, 31324 Via Colinas, #114, Westlake Village, California 91362, USA.

FDE Ltd., Foxley Green Farm, Ascot Road, Holyport, Berkshire, SL6 3LA, England.

CHAPTER 6

The physical Moon

This book is intended to be a 'hands-on' primer for the practical astronomer who wishes to observe the Moon. As such, giving even the briefest outline of lunar science, let alone giving details of how this knowledge was obtained, may seem to be a waste of precious space. On the other hand, while it is true that the Moon's stunning vistas can provide many hours of entertainment of the 'sight-seeing' kind, I would argue that observing the Moon is ultimately a sterile and pointless exercise unless one is attempting to understand and know it better. If you accept that premise then it follows that having some knowledge and understanding of the Moon (including knowing what mysteries still remain to be solved) will expand, and give some meaning and purpose to, your observations of it.

In that spirit I offer this highly abridged account of the space-borne missions to the Moon and some of our modern ideas about the physical nature and evolution of the Moon that arose because of them.

6.1 THE FIRST LUNAR SCOUTS

In 1903 Orville and Wilbur Wright made their first powered flights at Kitty Hawk. Astonishingly, it was only 66 years later that Neil Armstrong and Edwin 'Buzz' Aldrin stepped from their space-going vehicle onto the Moon's alien surface. The pace of progress at that time was breath-taking. Indeed, it was only in 1957, a mere dozen years earlier, that *Sputnik 1*, the Earth's first man-made satellite, was launched into orbit, marking the true beginning of the 'Space Age'. The many elements of progress – such as in launch-vehicle design, probes, satellites, telecommunications, and much, much, more – all form part of a complex story. Here, though, there is room only to mention some of the main highlights of the saga of the space-borne exploration of our neighbouring world.

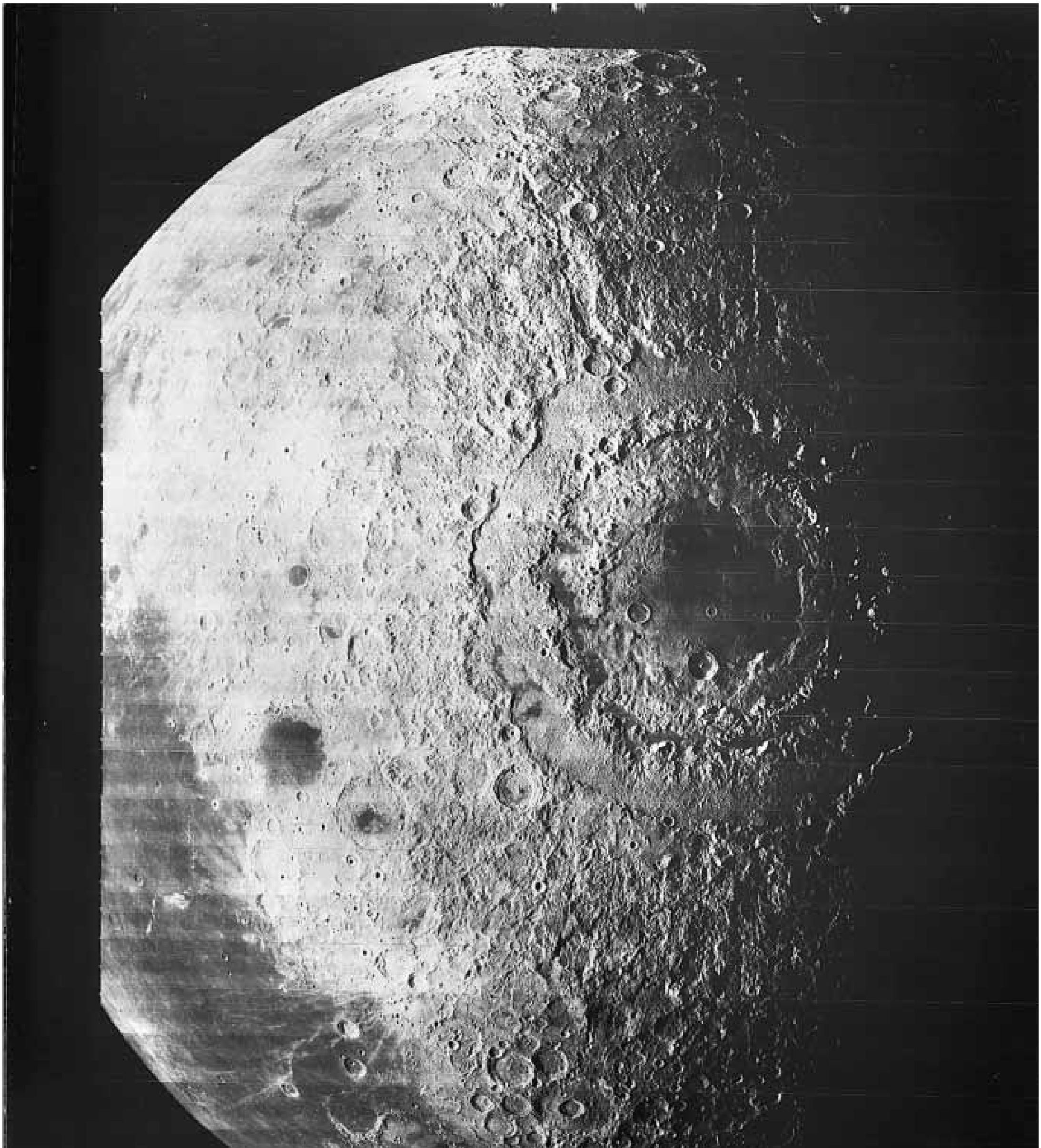
The first Moon mission successes came with three Russian probes in 1959. *Luna 1* (at the time the *Luna* probes were called *Lunik*) was the first to achieve a flyby, passing less than 5000 km from the Moon and revealing that it has no significant global magnetic field. *Luna 2* made further measurements as it headed towards the Moon, eventually impacting with the lunar surface in the Mare Imbrium. It was thus the first man-made object to make physical contact with the Moon. *Luna 3* was much more ambitious. As well as making a full range of scientific measurements, its trajectory carried it about 4600 km beyond the Moon so that it could look back and photograph the Moon's rear side. The images it transmitted to us might have been of poor quality by modern standards but the Earth-averted hemisphere had never before been seen. We learned much from those first blurry photographs.

Figure 6.1 The Moon viewed from an angle impossible from the Earth. This *Orbiter IV* view of the Mare Orientalis, clearly shows the multi-ring structure of this vast impact basin. The inner, basalt-lava-flooded, section has a diameter of about 320 km while the outermost ring spans about 930 km. The south pole of the Moon appears at the top of this photograph and part of the near-side feature of the Oceanus Procellarum appears to the lower left. The small patch of dark mare material between the Mare Orientalis and the Oceanus Procellarum (but closest to the Oceanus Procellarum) is the basalt-flooded crater Grimaldi (see Section 8.20 in Chapter 8). (Courtesy NASA and Professor E. A. Whitaker.)

The next few years brought forth a mixture of successes and failures. The continuing *Luna* series of probes, and a *Zond* probe (*Zond 3* in 1965, another mission to photograph the Moon's averted face while it was on its way to Mars – two objectives for the price of one!) were joined by the American *Ranger* series of probes. *Ranger 7* was the first to photograph the Moon at very close quarters. As it hurtled to destruction in the Mare Nubium in July 1964 (this part of the mare being re-named Mare Cognitum, 'The Known Sea', in commemoration) it took and transmitted back to Earth over four thousand photographs. Altogether, nine probes bit the lunar dust (and seven others either missed the Moon or were not intended to hit the surface) before *Luna 9* became the first soft-lander in February 1966. It touched down in the Oceanus Procellarum, near the great crater Grimaldi.

Luna 10 became the first lunar-orbiting satellite in April 1966 and in the next ten years 38 further lunar satellites and soft-landers were sent to the Moon by the Russian and American space agencies (including the manned missions, described in the next section). Among them the American *Orbiter* series of lunar satellites, in the late 1960s, were particularly valuable in mapping much of the Moon to a finer resolution than was ever possible from the Earth. Of course, the mapping also included areas that were either poorly seen, or totally hidden on the lunar far-side (see Figures 6.1, 6.4 and 6.5; also Figures 8.7(c), 8.13(g), 8.17(e), 8.22(h), 8.28(b), 8.33(e), 8.37(e), 8.41(e), and 8.46(d) in Chapter 8).

The American *Surveyor* craft also produced particularly valuable results, as they were in effect soft-landing laboratories, sending back photographs from their landing sites, as well as testing the mechanical properties and chemical composition of the lunar soil. Meanwhile the Russians continued with their *Luna* probes. *Luna 16*, launched in 1970, was the first robot vehicle to return a lunar soil sample to the Earth. *Luna 17* (better known as *Lunokhod 1*) did even better, in that it was the first robot rover vehicle to explore the



surface of another world. It spent over 10 months exploring the Moon's surface, covering about 10.5 km of the Mare Imbrium in that time. *Luna 20* was another mission to recover lunar soil, this time from the Apollonius highlands, in 1972.

The next year saw another Russian roving vehicle, *Lunokhod 2* (*Luna 21*), put down in the Mare Serenitatis – but of course the main glory in the years 1969–72 belongs to the Americans. For it was in those years that science fantasy became science fact – and men walked upon the surface of another world.

6.2 MEN ON THE MOON

While the unmanned probes were doing their work, preparations were underway to send men into space. Major Yuri Gagarin was the first man sent above the Earth's atmosphere in the Russian *Vostok* capsule on 12 April 1961. Gherman Titov was next but the Americans were not far behind. Colonel John Glenn was launched into space on 20 February 1962 in *Friendship 7*, one of the *Mercury* series of manned capsules. I really wish there was space available here to describe the events of the next few years because the tale is a truly thrilling one. Instead, I must be content merely to relate that the Americans eventually overtook the Russians in what unofficially became known as "The Space Race".

The American *Gemini* missions gave way to the *Apollo* programme. The hardware to enable men to get to the Moon was designed, built and tested in stages. The Christmas of 1968 was memorable because the astronauts Frank Borman, James Lovell and William Anders became the first people to travel beyond the Earth's realm as their *Apollo 8* spacecraft went into orbit around the Moon. Only two more *Apollo* missions were required to further refine and rehearse everything. *Apollo 11* would be the one to achieve the great goal.

On 16 July 1969 the mighty *Saturn 5* three-stage rocket launched from Cape Kennedy (previously known as Cape Canaveral, the name being changed back again after the Apollo missions) with the astronauts Neil Armstrong, Edwin 'Buzz' Aldrin, and Michael Collins riding in the nose-cone capsule of *Apollo 11*. Stages one and two were released to fall away from the rocket when their fuel loads were expended and their work was done. The third stage finally put the astronauts and payload into orbit. The payload consisted of the Service Module, at the top of which was the nose-cone capsule (Command Module), and the Lunar Excursion Module, or LEM, which was stored inside the upper part of stage three.

Three hours after launch the Command–Service Module was separated and turned and the nose-cone attached to the LEM. The LEM was then pulled out of stage three of the rocket. The Service Module engine was then fired and stage three of the *Saturn 5* rocket was left behind as the Command–Service Module and LEM together moved out of Earth's orbit and headed towards the Moon.

On 19 July the spacecraft was driven into lunar orbit. Armstrong and Aldrin in the spidery-looking LEM (which had been named 'Eagle') separated from the Command Module, which was to stay in lunar orbit with Collins keeping a lonely, if busy, vigil. Armstrong and Aldrin prepared for landing. On Sunday 20 July the astronauts fired the LEM engine, slowing it and allowing it to drop out of Lunar orbit and descend to its target on the Moon – a site on the Mare Tranquillitatis. TV viewers watched the drama unfolding. The world held its breath until Armstrong's words: "Houston – Tranquillity Base here – the Eagle has landed" were received with relief and jubilation.

The astronauts peered through the spacecraft windows at the unearthly scenery. They could see the long shadow of the LEM cast onto the Moon's dusty surface. Seven hours later Armstrong opened the hatch and carefully climbed down the ladder. With the words "That's one small step for a man – one giant leap for mankind" (at least that is the official wording. I have listened to the recording many times and I always hear ". . . step for man", missing the "a", but I suppose I must be wrong) Neil Armstrong became the first human to set foot on another world.

A little later Aldrin also stepped out onto the moonscape. For about 2½ hours they busied themselves setting up a TV camera, planting the American flag, taking photographs, collecting rock samples, and setting up experiments on the Moon's surface. Here on Earth millions of people watched the astronauts go about their business and listened to the conversations between themselves and Mission Control at Houston. The astronauts moved with a bouncing, almost slow-motion, gait in the low surface gravity (on the surface of the Moon objects have only one-sixth of their earthly weight). All too soon it was time to climb back into the LEM.

After a night's sleep the astronauts blasted off, leaving the lower part of the LEM still sitting on the surface of the Moon, and re-joined the Command Module. Then the journey home. On 24 July the *Apollo 11* capsule (just the nose-cone section) ploughed into the Earth's atmosphere. Hung under three large parachutes for the last part of its descent, the capsule splashed down into the Pacific Ocean. The first great adventure was over. Men had been sent to land on the Moon and returned safely to Mother Earth.

Subsequent *Apollo* missions followed the same basic mode of transporting men to the Moon (*Saturn 5* launch vehicle plus payload, including LEM) but with longer and longer periods spent on the Moon's surface and progressively greater quantities of Moon rock and scientific data collected.

Also, instrument packages were left to monitor conditions (temperatures, seismic activity, solar wind data, etc.) and radio the information back to Earth long after the astronauts had left.

The *Apollo 12* astronauts Charles Conrad and Alan Bean landed their LEM, 'Intrepid', in the Moon's Oceanus Procellarum on 19 November 1969, while Richard Gordon orbited the Moon in the Command Module. They had landed only a couple of hundred metres from the *Surveyor 3* probe which had been landed there 2½ years before. As well as carrying out their other activities, they photographed the vehicle (see Figure 6.2) and added a few parts of it to the booty they brought back to the Earth.

Apollo 13 nearly ended in tragedy as an explosion onboard the Service Module put an end to the mission. The only option for the astronauts James Lovell, John Swigert and Fred Haise was to carry on to orbit the Moon and hope that the Service Module motor could be fired to get them back to the Earth. They made it back despite the crippled state of their spaceship – a sound reminder of the dangers of the enterprise (there had been previous fatalities in both the American and Russian programmes).

Figure 6.2 Clearly *Surveyor 3* bounced before it came to rest on the lunar surface, as revealed by this photograph of one of its feet taken by an *Apollo 12* astronaut. (Courtesy NASA.)

Apollo 14 put the programme back on track. The LEM carried Alan Shepard and Edgar Mitchell down to the Fra Mauro region of the lunar surface (the first manned landing in rougher terrain) on 31 January 1971. They hauled a small hand-cart about in two traverses of the lunar surface while Stuart Roosa orbited in the Command Module.

The *Apollo 15* LEM was landed at the foothills of the Lunar Apennine (Montes Apenninus) mountain range on 30 July 1971. David Scott and James Irwin drove over the lunar surface in their 'rover' vehicle (see Figure 6.3), covering 27 km in three separate traverses, including driving to the edge of the valley Hadley Rille. Alfred Worden orbited in the Command Module.

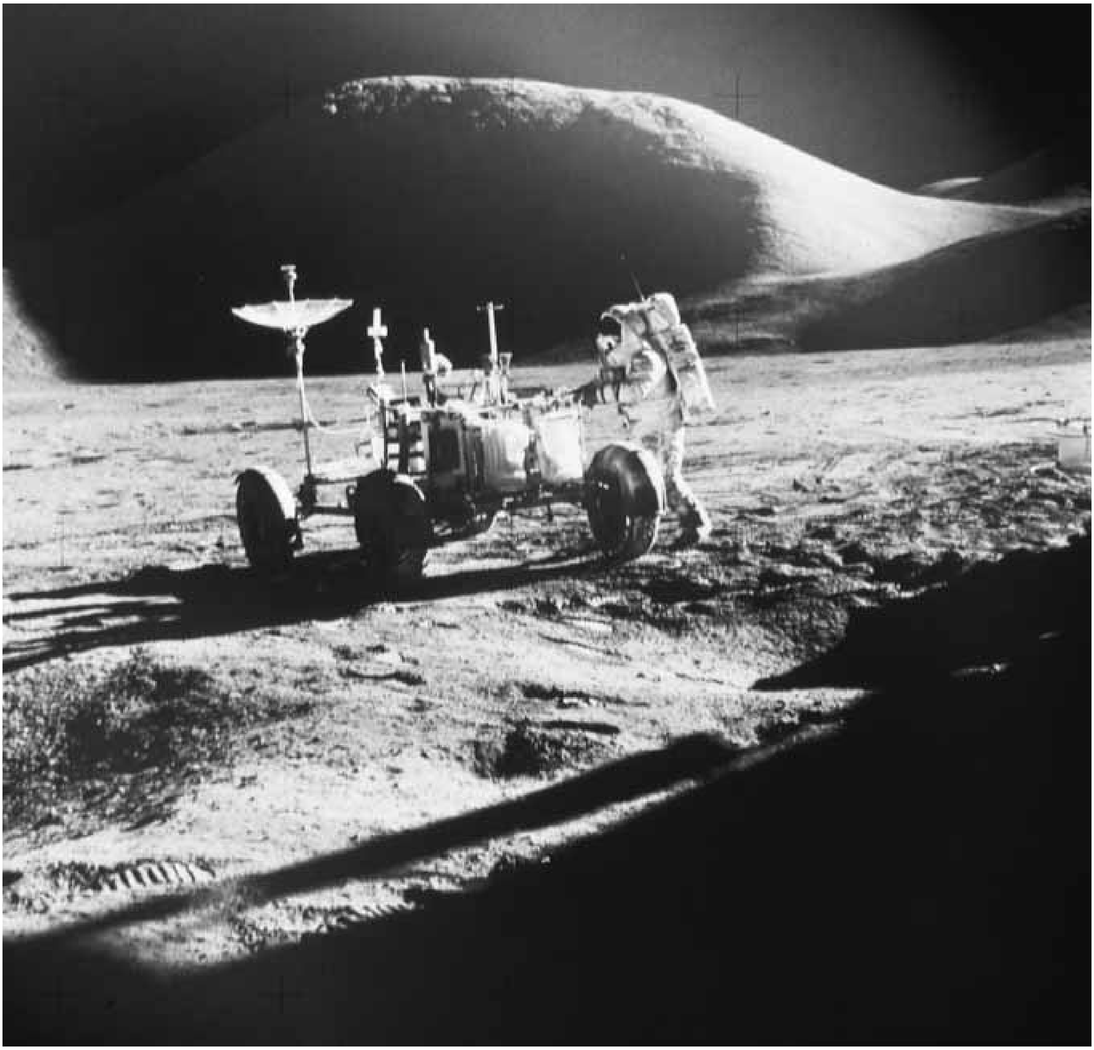


Figure 6.3 *Apollo 15* astronaut James Irwin pictured by the Lunar Roving Vehicle, with Mount Hadley providing a spectacular backdrop. (Courtesy NASA.)

Apollo 16 touched down in the Descartes region of the southern highlands of the Moon on 21 April 1972, with astronauts John Young and Charles Duke in the LEM and Thomas Mattingly in the Command Module. They also had a rover vehicle to aid in their exploration, experimentation, and sample-collecting activities in the stunning rock- and boulder-strewn environment. They also used equipment to make the first astronomical observations from the Moon – ultraviolet photographs of the Earth's atmosphere, interplanetary gas and stars being particularly important.

Apollo 17 was the grand finale as the LEM, with Eugene Cernan and geologist Harrison Schmidt aboard, touched down in the Taurus–Littrow region on 11 December 1972. They went even further in their rover vehicle (see Frontispiece). Each mission bettered the last with the astronauts spending longer periods outside their LEM, doing more photography, and making increasingly sophisticated geological examinations and scientific experiments; also setting up more intricate remote telemetry packages. As a result of the space probes, and particularly the *Apollo* programme, our knowledge of the Moon grew a hundred-fold. When Cernan and Schmidt rejoined Ronald Evans in the Command Module and they headed back to Earth they brought to a close a period unprecedented in human history.

6.3 THE POST-*APOLLO* MOON

Originally, the *Apollo* missions were to go beyond number *17* but the public grew bored, and some vociferously objected to the money spent on the project. Vote-conscious politicians cut back NASA's budget. The programme came to a premature end. Three successful Russian probes, and one failure, went to the Moon post-*Apollo*, the last of these in 1976. To date there have been no further manned missions.

We had to wait two decades before the next probe – *Clementine* – which was injected into a polar lunar orbit in February 1994. By circling from pole to pole as the Moon turned under it, the probe was able to photograph the entire Moon in twelve different wavebands spanning ultraviolet through to infrared (see Figure 8.41(e) in Chapter 8). Some of the images it obtained were of particularly high resolution (the best showing details as fine as 100 m across).

It also carried a laser-ranging system which built up a laser echo map of the Moon with a horizontal resolution of the order of 200 km, though with a vertical sensitivity of about 40 m. The advantage of the laser echo technique was that the picture of the Moon it built up is three-dimensional, containing as it does height information. For the first time scientists realised the true extent of a depression in the Moon's south polar region, known as the South Pole–Aitken Basin. It turns out to be about 12 km deep and 2500 km across, and holds the record for being the largest impact basin known in the Solar System. Other ancient basins were also studied.

The multi-waveband images provide valuable information about surface composition. *Clementine* was a multi-purpose probe, having military as well as scientific goals. For two months it did its work orbiting the Moon. It was then to be dispatched to a rendezvous with the asteroid Geographos but a technical hitch caused it to be sent spinning off into space, instead. As in the words of the ballad, *Clementine* was "lost and gone forever". Allied to the previous space-mission results, *Clementine* provided another leap in our knowledge of the Moon.

More recently, (January 1998), the *Lunar Prospector* probe arrived at the Moon (I will pass over the details of other probes which have passed by the Moon on their way to other targets, even though some telemetry and photography was undertaken). Like *Clementine*, it was sent into polar orbit, following up on the investigations undertaken by the earlier probe. Mapping, studies of surface composition, including the search for ice deposits at the lunar poles, magnetometry, radioactive-particle counts and gravitational data all were planned.

At the time I write these words the first results are coming in. NASA scientists have announced the discovery of ice in the Moon's polar regions; about 6 billion tons of the stuff! This is probably all due to accumulated materials from impacting comets and seems to be mixed up in the upper regolith. However, I should caution that at the time of writing this finding is not universally accepted. What the probe really detected was the signature of hydrogen in chemical combination – this **may** be water ice. The mission is intended to last to the end of the year 2001 at the very least. We can expect another big leap in our knowledge of the Moon by the time *Lunar Prospector* has done its job.

6.4 NOT GREEN CHEESE BUT . . .

The Russian *Luna 16*, *Luna 20*, and *Luna 24* craft returned a total of about 0.3 kg of Moon rock. We already have about 4½ kg of identified lunar material on the Earth, in the form of meteorites blasted from the Moon's surface by impacting meteors, but it was the six *Apollo* manned landings that provided us with the greatest quantity and variety of samples; some 381.7 kg in all.

The chemical composition of the Moon's surface covering is very different to that of the Earth. It is made up of a variety of igneous rock types. In the main these are complex silicates. Unlike earthly rocks, there is a complete absence of water in the chemical make-up of any of the samples so far examined. As far as we can ascertain there is no water natural to the Moon itself. Apart from anything deposited on its surface by external means, the

Moon is a completely arid world. Nor did we find any signs of life, past or present. In fact, the Moon has only trace amounts of the carbon compounds that are needed as building blocks for the genesis of life as we know it. Most of these compounds originated from outside the Moon (delivered onto the Moon by the solar wind plus meteorite and comet impacts with the lunar surface).

However, there are some similarities between the lunar rocks and the exposed **mantle** materials we find on Earth (these are rare but occasionally found amongst volcanic ejecta). Even more significant is that the ratios of the proportions of the three common isotopes of oxygen we find in the Moon-rock samples match closely with those we find in terrestrial rocks.

The highland rocks and mare rocks are themselves very different from each other. Considering the lighter-coloured highland material, there are at least three major categories of distinct subtypes of the silicate-type rocks. *Ferroan anorthosites* are particularly rich in calcium and aluminium and largely composed of a mineral known as *plagioclase feldspar*. The so-called *magnesium-rich* rocks are also plagioclase-based but also have mixed in with them various magnesium-rich minerals such as *olivine* and *pyroxene*. The minerals *norite*, *dunite*, and *troctolite*, are found in highland samples but these are really subtypes of the magnesium-rich rock types, each having various proportions of pyroxene, plagioclase and olivine.

The other major class of rock found in the lunar highlands is the so-called *KREEP*. This is an acronym for potassium (chemical symbol *K*), rare-earth elements (*REE*) and phosphorus (chemical symbol *P*). Rocks with enhanced concentrations of these components are known as *KREEP* rocks – an example being *KREEP norite*.

The lunar maria are composed of iron- and titanium-rich volcanic rock types known as *basalts*. They also have a diversity of compositions within the main type – pyroxenes, plagioclase and *ilmenite* (iron–titanium oxide), olivine, plus many others. The lunar basalts have one important physical characteristic. When they are heated to melting point their viscosity becomes **very** low, much less than is the case for earthly volcanic lavas. To give you some idea, the lunar lavas might have been as runny as the sump oil in a cold automobile's engine. This fact has an important bearing on how the Moon got to look as it does to us today.

6.5 GENESIS OF THE MOON

Four main theories of the Moon's origins were developed by theorists over the years. The first of these is that the Moon was once part of the Earth but broke away from it, leaving a hollow which became the Pacific Basin. We now realise this idea is dynamically untenable. Also, the Moon's chemical composition is so unlike the Earth's any simple separation would be out of the question. This idea is now only of historical interest.

The second theory is that the Moon and Earth were formed at about the same time, 4600 million years ago, but the two bodies were formed in completely different parts of the Solar System (which was also being 'born' at the same time). At some later date, the theory goes, the paths of the Moon and the Earth crossed and the Moon became gravitationally captured by the Earth. Tidal interaction then caused the Moon to settle into a stable orbit around the Earth. This idea is not totally out of the question but the dynamical difficulties are very great and most theorists of today have little confidence it. Further evidence against this idea comes from the oxygen isotope ratios we measure in the lunar rock samples. These vary with location in the Solar System but, as already noted, the ratio is the same as that which we find for terrestrial rocks.

The mathematical difficulties associated with this second theory disappear if we assume that the Moon and Earth formed in the same region of space and at about the same time – the third theory. The isotope abundance ratios would then also be explained. However, even allowing for the chemical differentiation (heavier elements sinking to the core, leaving the lighter elements on the top) that would take place inside a condensing cloud of protoplanetary matter, it is very difficult to explain the sharp difference in the chemistries of the two worlds.

The fourth, and currently the most popular, theory we have today is that at some time very early in the history of the Solar System, perhaps before the Earth had developed a solid crust, our planet had a glancing collision with another planet or protoplanetary body (perhaps it was even as large as the planet Mars is today). This would have 'chipped off' a sizeable chunk of material from both bodies. While much of the resulting shoal of material and the remains of the second planet/protoplanet would be lost, some of this debris would settle into orbit around the Earth and eventually form a new body – our Moon. If the Moon was mostly formed from the material that originated in the impacting protoplanet and from the **mantle** of the Earth then this might explain the compositional differences between the Earth's and the Moon's surfaces.

6.6 THE MOON'S STRUCTURE

The seismic detectors left on the Moon as part of the *Apollo* missions gave us data for years after the last men walked on the Moon. Just as seismologists have built up a picture of the Earth's structure by studying earthquakes, so planetary scientists have been able to build up a picture of the Moon's structure from the results of the very gentle *moonquakes* that trouble the Moon's globe. About 3000 of these were detected each year the seismic detectors were in operation. Lest you should get the wrong idea, though, I should add that the total seismic energy output of the Moon is less than one-ten-billionth the energy the Earth expends in earthquakes in the same period – feeble by any standards. Moonquakes seem to originate about 600–800 km below the lunar surface.

Also, a few spacecraft were deliberately smashed into the Moon's surface to generate much more violent tremors (and some moonquakes have been triggered naturally because of meteorite impacts) to provide further information about the Moon's structure. In addition, the *Apollo* astronauts also conducted seismic sounding experiments. Meanwhile the various heat-flow experiments left by the *Apollo* astronauts indicate a heat-energy flux of about one-third that of the Earth. Models suggest that most of this heat energy is accounted for by radioactive decay deep in the Moon and so the Moon must have lost most of the heat generated by its formation. These results have helped in the refining of the theoretical models.

The *crust* of the Moon extends to about 60 km depth and exists as three distinct layers. The top layer is known as the *upper regolith* and is made of fragmented and impact-welded rocks of the type geologists call *breccias*. Ranging from 1 to 20 metres deep on average, the upper regolith is the result of aeons of bombardment by meteorites large, small and minute (*micrometeorites*), together with the crumbling stresses caused by the diurnal heating and cooling. It could only form as it has on a world which for a long time has been devoid of a protective atmosphere. The soil is also churned and intermixed with materials from underlying layers due to the same forces. This process has the delightful name of *gardening*.

Extending down to a depth of about 20 km is the *lower regolith*, composed mainly of basaltic rocks. The bottom layer of the crust is chiefly made up of the rock type known to geologists as *anorthositic gabbro*.

Below the crust is the *mantle*, rich in certain minerals such as olivine and pyroxene. The mantle becomes less rigid with depth. Gravity data, especially that obtained from the *Lunar Prospector* space probe, indicates the presence of a small iron-rich core. It might be about 600 km across if composed mostly of pure iron, increasing to about 1000 km if it is composed mostly of iron sulphide. It cannot be larger than that because the density of the Moon averages a mere 3.34 times that of water, too low to support a larger core. Overall, the Moon's globe is very iron-depleted compared to the Earth. Given that the Moon has no significant global magnetic field (though there are concentrations of weak magnetism 'frozen' into the surface rocks), it is reasonable to suppose that the core has now solidified.

The presence of an iron-rich core is significant in that the most popular theory of the creation of the Moon (see the previous section) should produce a completely iron-free Moon if the impact had occurred **after** the two colliding planets/protoplanets had become chemically differentiated. Assuming the theory is correct, perhaps either or both were still so 'new-born' as to be largely undifferentiated when the collision occurred?

I mentioned that the lunar crust is about 60 km thick. Actually, this is only an average figure. It is much thinner on the Earth-facing hemisphere, being only 20 km or so in places. However, on the reverse side the crust is over 100 km thick.

The *Luna 3* probe of 1959 had revealed there to be an almost complete absence of maria on the Moon's reverse side, yet about one-half of the Earth-facing hemisphere is mare-covered. This was a real surprise to scientists at the time. The reverse side of the Moon is covered with the same sort of rough, cratered terrain we see in the highland areas of the near side. We now understand the reasons for the asymmetry. The explanation is bound up with the evolution of the Moon after its formation, so let us briefly review our modern ideas on this subject.

6.7 THE EVOLUTION OF THE MOON – A BRIEF OVERVIEW

When the Moon was still a molten body, about 4600 million years ago, its own gravity operated on the components making it up and caused the heaviest to sink towards the core – the chemical differentiation already referred to. The separation continued until the lightest elements floated to the top. These lightest materials formed the basis of the lunar highlands. At the time when the Solar System was still young, space was cluttered with debris left over from the formation of the various planets and moons.

During these early times massive lumps of material were smashing into the Moon and the other planets. Great basins and smaller craters were created by these massive, explosive, impacts on the now solidified lunar surface. The gravitational fields of the Moon and the planets acted as 'celestial vacuum cleaners', gradually disposing of the Solar System leftovers. All the biggest pieces were used up first, only the progressively smaller pieces of debris being left as time went on.

The ferocity of the lunar Blitzkrieg abated until it was all but over by about 3800 million years ago. The Moon's surface was then heavily scarred and saturated with craters of all sizes, though with the greatest numbers of them being the small ones.

I ought to mention that for many years a great controversy raged among astronomers concerning the origin of the Moon's craters. Setting aside those with really wacky ideas, of which there were many, astronomers dichotomised into two camps. Many maintained that the craters were formed by *endogenic* (internal) processes. Endogenicist's theories ranged from violent volcanism, through to more quiescent mud-bubble scenarios.

The evidence they drew on to support their views included a perceived non-random distribution of craters on the Moon (north–south going crater chains), and the fact that smaller craters almost always break into larger ones – and virtually never the other way round.

In fact, the primary craters of the Moon **are** pretty well randomly arranged. Much of the perceived north–south alignment is due to the direction of the incident sunlight, which throws features along the lunar meridians into prominence. This is particularly so when the terminator looms close. In my view, the extreme rarity of larger craters breaking into smaller ones is a little more convincing but even this factor is explainable under the *exogenic* theory, otherwise known as the *impact theory* – the idea that the craters were created by meteorites impacting with the lunar surface.

I am sure that some readers will think I have displayed an unacceptable bias in disposing of the endogenic theories so tersely, without even going into a proper account of them. I wish I could say more here but I must reserve such space as I have for the scenario that most scientists now accept as correct. As an attempt to redress the balance can I please refer interested readers to *The Craters of the Moon* by Patrick Moore and Peter Cattermole. Published by Lutterworth Press in 1967, this is the last book-length account of the endogenic theory that I am aware of, although Patrick Moore does devote some space to it in his 1976 book *Guide to the Moon*, also published by Lutterworth Press. Though both these books are long out of print, perhaps you might pick up second-hand copies, or the inter-library loan service might obtain them for you?

I cannot resist showing you the crater pictured in the centre of Figure 6.4. There can be no controversy about the origin of this one – it was created by the impact of the spacecraft *Ranger 8*!

At an early stage after formation of the Moon, tidal drag between the Earth and Moon locked it into a synchronous orbit with the Earth. Hence it always keeps the same face to the Earth. Moreover, their mutual gravity produced some asymmetry in the internal structure of the Moon, for instance it bulging towards the Earth a little and having the thinnest part of its crust on the Earth-facing hemisphere.

The creations of the biggest basins were real Moon-rocking events, leaving a heavily fractured crust, some of the fissures extending down to the still-molten mantle. Low-viscosity lavas flooded out of the fissures to fill the basins and so form the maria.

Where the crust was thickest the fissures could not reach through to the mantle and the basaltic lavas could not escape to flood the surface. That is why the maria are predominantly on the Earth-facing hemisphere. The crust was too thick to allow the process to happen on the reverse side.

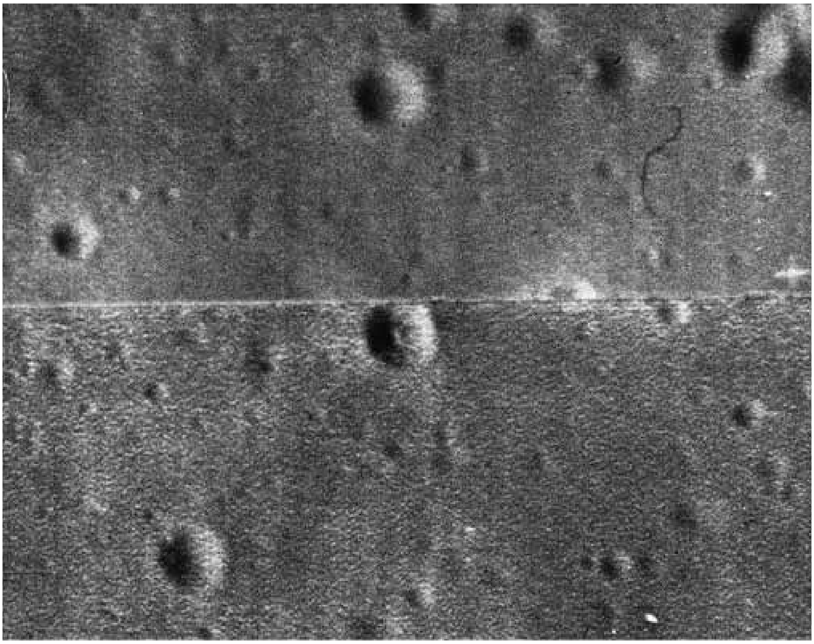


Figure 6.4 A man-made lunar crater! The 13½ km diameter crater at the centre of this *Orbiter IV* photograph was created by the impact of the space probe *Ranger 8*. It even has a central peak! (Courtesy NASA and Professor E. A. Whitaker.)

As the interior of the Moon cooled, so the lava-flooding activity dwindled and eventually stopped about 3200 million years ago. Some small-scale volcanism probably continued for a little longer and the Moon certainly continued to receive impacts thereafter but all the really major activity was over and the Moon then became a much more sedate place.

6.8 LUNAR CHRONOLOGY

The 4.6 billion year history of the Moon has been divided into a number of periods, or eras, marked by specific events. These have been dated by means of the laboratory testing of soil and rock samples brought to Earth. Various techniques have been used to date other lunar features/events with these as primary benchmarks.

The first of these events was the formation of the Nectaris Basin – which later lava-flooded to form the Mare Nectaris (the subject of Section 8.30 in Chapter 8). This occurred some 3.92 billion years ago, according to modern determinations. The first lunar era is thus the *Pre-Nectarian Period* (4.6 to 3.92 billion years ago). The massive amount of bombardment the Moon suffered at this stage has obliterated much of the earliest formed surface features, though an undefined number of Pre-Nectarian structures have survived.

The second benchmark event is the formation of the Imbrium Basin some 3.85 billion years ago. This basin was later lava-flooded to form the Mare Imbrium – the subject of Section 8.24 in Chapter 8.

The period between the formation of the Nectaris and Imbrium basins (3.92 to 3.85 billion years ago) is known as the *Nectarian Period*. Here the determinations of the ages of lunar formations become much more clear-cut. The Moon was still suffering a very heavy bombardment but this had reduced enough so that most of the basins, craters, and other formations created at this time were not completely obliterated by subsequent impacts. About a dozen of the basins we recognise today were created by gigantic impacts in the Nectarian Period, along with thousands of craters. The lunar soil was heavily churned and mixed by the pounding it received during this time.

The 'carpet-bombing' continued to abate during the Nectarian period. After the Imbrium impactor had done its work, only the projectile that created the Orientalis Basin (see Figures 6.1 and 6.5) a few hundred million years later remained as the last really massive piece of debris to hit the Moon. Smaller fragments, though, continued to rain down.

The next accurately-dated event was the formation of the crater Eratosthenes, some 3.2 billion years ago. This crater is described, and pictured, in Section 8.5 of Chapter 8. The period between the formation of the Imbrium Basin and Eratosthenes defines the *Imbrium Period*. Materials ejected from the enormous explosion site of the Imbrium Basin are scattered over a substantial portion of the Moon's globe and the shock waves that permeated the Moon caused much restructuring of the lunar topography. I discuss some of the physical evidence that remains of this Moon-shaking event in Chapter 8. It is during the Imbrium Period that most of the basaltic lava-flooding of the basins occurred.

The formation of the crater Copernicus (see Chapter 8, Section 8.13), 0.81 billion years ago, provides the last of the key chronological markers. The *Eratosthenian Period* (3.20 to 0.81 billion years ago) betwixt the formations of Eratosthenes and Copernicus saw the last vestiges of the episodic lava-flooding of the maria and the continuing diminution of the meteoritic bombardment of the Moon.

This brings us to the *Copernican Period*, which spans 0.81 billion years ago to the present day. Very few of the large lunar craters are younger than Copernicus and only the most minor volcanic happenings have disturbed the Moon's quietude in the last billion years.

Figure 6.5 The north-eastern sector of the Mare Orientalis. This is an enlargement of the view shown in Figure 6.1. The outermost rings are just visible on the limb of the Moon as seen from Earth (as a series of mountain ranges – the basin being virtually edge-on to us), when the libration and lighting angles are most favourable. In fact, H. P. Wilkins and Patrick Moore drew attention to the possibility of there being a far-side lunar sea in the 1940s. They named it Mare Orientalis, meaning the 'Eastern Sea' because it lay on the side of the Moon we then called the east. Of course, by the IAU convention this is now the lunar west!

The impactor that created the basin, the last really big chunk of debris to hit the Moon, was probably a piece of rocky debris several tens of metres across. The concentric rings are, in effect, 'frozen' shock waves in the lunar crust. Radial features are also apparent, especially in the outer parts of the structure, including secondary impact scars. (Courtesy NASA and Professor E. A. Whitaker.)

6.9 FILLING IN THE DETAILS

In order to economise on space, I have had to paint the account of our modern ideas with an extremely broad brush. Consequently, I may well be

guilty of giving the impression that lunar science is simple and straightforward and, even worse, that we now know all there is to know. Nothing could be further from the truth.

For instance, the way space probes behaved in lunar orbit led to the early discovery that there are distinct concentrations of dense material situated some way beneath the lunar surface. These are known as *mascons*, a contraction of 'mass-concentrations'. The first results suggested that these all coincided with the lunar maria. It was assumed that the lunar maria were made of denser-than-average materials, which they are (being mantle material brought to the surface), and this explained the anomalies. In recent years the picture has grown more complicated. In particular, *Lunar Prospector* found several new ones, including four on the lunar far-side, but only some of these coincide with lunar maria. The latest thinking is that the mascons result from dense plumes of convected material from deep in the Moon, rising into its upper mantle. If that is right, I wonder if the basin-forming events somehow triggered lunar mantle plumes to preferentially form under the fractured basin floors, given that most mascons **are** associated with the maria?

My speculations aside, it is only relatively recently that geologists have appreciated just how important mantle plumes are in explaining earthly tectonic and volcanic structures and activity. A salutary lesson that we still have much to learn!

The entire spectrum of lunar features and all the myriad pieces of evidence – those obtained from remote viewing the Moon as well as actual samples of lunar material – have had to be woven into a coherent scenario. The overall scheme might appear simple but the details are rather complex. Given that the main purpose of this book is to be an observer's guide, I have incorporated many of our modern ideas into the accounts of selected lunar features I provide in Chapter 8.

What is the nature of the brilliant ray-systems that some craters possess and why do not all craters have ray-systems? Why do some craters have much brighter interiors than others? What causes the wrinkle ridges on the lunar maria? What are the nature of the lunar rilles and how did they come about? You will find answers to these questions, and more, in Chapter 8. However, for a much more complete account of our post-*Apollo* ideas about the physical nature and evolution of the Moon I can recommend two books, both published by Cambridge University Press. *The Moon – Our Sister Planet*, was written by Peter Cadogan and published in 1981. Larger, and more up to date (published 1991) is *Lunar Sourcebook – a User's Guide to the Moon*. Together, these give a very comprehensive overview of our understanding of the Moon as it stood at the end of the 1980s.

What about more up-to-date information, such as the knowledge we have learned from *Clementine* and *Lunar Prospector*? The next chapter, which in part serves as resource guide, will help you locate a selection of materials available at the time of writing (1998), as well as incorporating a key map which you will find useful in finding your way to the selected lunar features examined in Chapter 8.

CHAPTER 7

The desktop Moon

This very short chapter deals with matters of interest to the amateur working at the desk and computer. In most cases this desktop work will be supplementary to the activity carried out at the telescope. A few people might conduct all their lunar exploration from their desk and computer and I hope that the notes given here will be of some use to them, also. However, this book is intended for the telescopist and since I can only pack so much into the space set by the publisher I must be honest and say that others will probably find this treatment inadequate.

So far I have suggested various books and articles that you might find of use in connection with the subjects covered in each of the foregoing chapters. This chapter is partly a resource guide, in which I 'mop up' some references and materials not mentioned elsewhere. Aside from that, I have included details of the methods for obtaining the heights of lunar features, as many will find this an interesting exercise. After a survey of the lunar maps and atlases available, I finish with an outline chart that I have prepared as a key map for locating the lunar surface features explored in the next chapter.

7.1 THE *LUNAR SOURCEBOOK*

Yes, I have mentioned this earlier but it deserves my highest recommendation. If you want a large (over 700 page) single-volume guide to the science of the Moon then you can do no better than to invest in a copy of the *Lunar Sourcebook – a User's Guide to the Moon*. It is edited by G. Heiken, D. Vaniman and B. French and was published by Cambridge University Press in 1991. It is chock-full of data, information and explanations about the physics, chemistry, and geology of the Moon and how that information was obtained. It includes a list of hundreds of references to scientific papers and the details and contact addresses of many sources of lunar databases, imagery and archives. It is a superb springboard to further studies as well as being a mine of information itself!.

7.2 SPACECRAFT IMAGERY

The amateur astronomer is not limited to the views of the Moon he/she gets through his/her telescope. Spacecraft imagery is now available in various media.

BAA Lunar Section members have long made use of the *Orbiter* imagery in making their own topographic studies of particular areas/features of the Moon. The list of papers in the *Journal of the British Astronomical Association* on this work is a long one. People like Keith Abineri and Ivor Clarke have made significant contributions. Keith Abineri's work is legendary. I will leave you to conduct your own literature search but one excellent paper by Ivor Clarke: 'A comparison of images from *Orbiter IV* and *Clementine*', in the August 1977 *JBAA* will give you a good start (and he gives references to other works).

These *Orbiter* images are available as prints. You can now also get *Clementine* images on a set of 88 CD-ROMs and no doubt more and more imagery will become available in computer media. For all NASA images and information, write to: The National Space Science Data Centre (Americans use the spelling 'Center'), Co-ordinated Request and User Support Office, World Data Center-A for Rockets and Satellites, Code 633.4, Goddard Space Flight Center, Greenbelt, Maryland, 20771, USA, or contact them through the Internet (see the next section).

Chapter 8 of this book is concerned with understanding the detailed topography of the Moon in connection to its history and lunar science. You will find a few examples of space-probe images of the Moon in Chapter 8 and some more in Chapter 6. Utilising spacecraft imagery will expand the scope of your studies beyond that which is possible using your telescope alone.

7.3 THE INTERNET

It is hard to think of things you cannot get on the Internet. Certainly information and images about the Moon are in plentiful supply. Many (most?) amateur astronomers/clubs and societies have their own sites and it is easy to gain access to professional information and images – both from the space missions as well as Earth-based observations. Web-site addresses tend to be ephemeral, so it is a good idea to make a start by looking in publications such as the latest issues of the *Journal of the British Astronomical Association*, the *Handbook of the British Astronomical Association*, and in *Sky & Telescope* and other magazines for web-site addresses. Of course, you can make use of the various search engines available – but do avoid typing in 'mooning'! Many web sites have links to other web sites, so it should not take much 'surfing' to uncover plenty of up-to-date information and images.

One address that **probably** will not change before this book is in print is NASA's home page:

http//nssdc.gsfc.gov/

This is the National Space Science Data Center (NSSDC) at NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

Happy Moon surfing!

7.4 LUNAR EPHEMERIDES

Publications such as the *Astronomical Ephemeris* and the *Handbook of the British Astronomical Association* provide useful ephemera for the lunar observer and many societies and groups also provide hard-copy ephemera, while the ubiquitous Internet probably has innumerable sites where this information can be found (though it is wise to check on the accuracy of any data given).

There are also plenty of programs available commercially, and some available simply by downloading them from the Internet. Some, such as 'Lunar Calculator' (see the January 1999 issue of *Sky & Telescope* for a review) are highly sophisticated, have vast databases, and can do things such as simulate the views of the Moon that you would get from an orbiting spacecraft. Others present you with Earth-based views taking libration into account, as well as providing you with much useful information such as lighting angles, etc. New and improved software is continuously coming on the market, so I will leave you to search out for yourself the up-to-date advertisements and reviews and obtain the product that best suits your own needs.

7.5 MEASURING LUNAR SURFACE HEIGHTS

When studying the Moon through your telescope you might wonder about the relative heights of the lunar surface features. A crater might seem very deep when near the terminator and largely filled with black shadow. On the other hand it seems very shallow when the Sun rides high overhead. What is the true depth of the crater? Which parts of it are above, and which below, the surrounding moonscape? How high are the lunar mountain peaks?

With some effort and a good deal of care you can find out for yourself. The way to determine relative heights on the surface of the Moon is by measuring the length of the shadows cast by features onto their surroundings.

I must 'come clean' and say that the scientists processing the space-probe imagery have been there before you. You will be undertaking this task for your own gratification and your results will not generate any new knowledge for the scientific community.

At one time the amateur astronomer would use a good eyepiece micrometer on an 8-inch (203 mm) or larger telescope to measure heights on the Moon. Nowadays, the amateur would be best advised to use high-quality photographs and CCD images. Having said that, the November 1998 issue of *Sky & Telescope* carries an article 'The Mountains of the Moon' in which a contemporary enthusiast, Bill Davis, describes how he makes measurements at the eyepiece of his 8-inch Schmidt–Cassegrain telescope using an eyepiece micrometer. I recommend reading this article if you are interested in this sort of work. Also, I describe the use of an eyepiece micrometer for lunar shadow measurements, and other projects, in my book *Advanced Amateur Astronomy* (Cambridge University Press, 1997).

Owing to the limited space, I will here assume that either you are familiar with the eyepiece micrometer or that you have sought out the references given and will confine myself to explaining how to get the desired height value(s) from your measurements. Where I refer to distances measured by eyepiece micrometer these can, of course, just as well be distances measured by ruler on a photograph, etc. Here I will give the procedure to be used with the eyepiece micrometer, since it can easily be adapted to making measurements on a hard-copy image, while the reverse process is certainly not so obvious.

The reduction procedure I describe herewith is only applicable to observations/photographs/CCD images made from the surface of the Earth.

As with most linear measurements at the telescope eyepiece, you should use the highest magnification that the seeing permits. The micrometer's transverse fixed wire is aligned along the shadow and the movable wires are positioned to intersect the end of the shadow and the feature (mountain peak, etc.) that is causing it. The drum reading(s) and the known value of the micrometer constant are then used to calculate the apparent length of the shadow in arcseconds. The measurement can be repeated a number of times in order to increase the accuracy as well as to provide a figure for the likely uncertainty in the calculated value (from the spread of readings). However, you should remember that lunar shadows change their lengths very rapidly, especially with the terminator nearby, so try to get the measurements all done in a few minutes.

You will need to know the scale of the image (arcseconds per millimetre) if you are making direct measures from hard-copy images. You will also need to know the date and time of the image so that you can look up ephemeris data, without which you cannot make the calculation.

The apparent length of the shadow is then expressed as a fraction of the Moon's semi-diameter in the same units (arcseconds). This new quantity is s. As an example, if the semi-diameter of the Moon at the time of the observation (this can be found in an ephemeris, such as *The Astronomical Ephemeris*) was 1000 arcseconds and the measured value of the shadow was 3 arcseconds, then the value of $s = 0.003$.

With the measurement completed, you can go on to calculate the height of the lunar feature relative to the ground its shadow falls on by using four equations. You will need some more values from an ephemeris and from a lunar atlas (or other source of lunar latitudes and longitudes). For convenience, I will now list all of the terms you need in the equations:

s = length of shadow/Moon's semi-diameter
L_p = longitude of peak casting the shadow
b_p = latitude of peak casting the shadow
colong = Sun's colongitude
b_S = Sun's latitude
L_E = longitude of Earth
b_E = latitude of Earth

X, the distance of the apparent centre of the Moon's disk to the sub-solar point, may be found from:

$$\cos X = \sin b_S \cdot \sin b_E + \cos b_S \cdot \cos b_E \cdot \sin(colong - L_E). \tag{7.1}$$

The apparent length of the shadow then has to be corrected for the angle the Sun makes to the east–west plane:

$$S = s/\sin X, \tag{7.2}$$

where S is the corrected shadow-length expressed as a fraction of the Moon's semi-diameter. The altitude, A, of the Sun (measured in degrees) as seen from the peak casting the shadow is found from:

$$\sin A = \sin b_S \cdot \sin b_p - \cos b_S \cdot \cos b_p \cdot \sin(colong - L_p). \tag{7.3}$$

At long last we can arrive at the height H, of the peak, expressed as a decimal fraction of the Moon's semi-diameter:

$$H = S \sin A - \tfrac{1}{2} S^2 \cos^2 A - \tfrac{1}{8} S^4 \cos^4 A. \tag{7.4}$$

Multiply H by 1738 and you have the height of the peak casting the shadow expressed in kilometres.

In truth there is another correction that should be applied: the effect of parallax since the ephemeris figures are *geocentric* (as seen from the Earth's centre) but your observed measurements are *topographic* (as made from the Earth's surface). However, the likely instrumental and human errors in the measurement are larger than the error generated by ignoring this correction.

The instrumental and human errors will have their greatest effect when measuring short shadows. Unfortunately, measuring long shadows (the lunar feature then being near the terminator) will also give rise to a large uncertainty in the height determination because the shadow will fall across ground which itself varies in height. Ideally, one should make a series of measurements over a range of lighting angles. In that way a profile of the area can be generated.

Other methods of lunar height determination and explanations of different reduction procedures can be found in *The Observer's Guide to Astronomy*, edited by Patrick Martinez and published by Cambridge University Press in 1994.

7.6 MAPS, GLOBES, POSTERS AND CHARTS

I mention many of the pre-*Apollo* maps and charts of the Moon in Chapters 3 and 4. All these will be difficult to obtain. Though it is just possible that you might come across one or more by way of the second-hand market, national astronomical society libraries and/or the national inter-library loan service are more likely to turn up a few of them.

Of the products currently available, quite a few are obtainable through *Sky Publishing* at: Sky Publishing Corp., 49 Bay State Road, Cambridge, MA 02138, USA. I have taken the following details from their 1999 Catalogue (of course, you can obtain most of these items elsewhere but it is always a handy thing to do your shopping under one roof!):

Atlas of the Moon, by Antonin Rükl. Contains 76 labelled airbrushed maps of the Moon's near side and includes 50 close-range photographs.

Exploring the Moon through Binoculars and Small Telescopes, by E. H. Cherrington. A 229-page book which "reviews every major feature in 28 night-by-night chapters, with lots of black and white photographs".

Moon Map. Sky Publishing's own map. 10½ inches in diameter, with 300 named craters and other named formations. Only a small map but it is orientated with south uppermost to match the view in most astronomical telescopes from the Earth's northern hemisphere.

Mirror-Image Moon Map. Same as the previous map but it has been mirror-reversed to match the view through a telescope with an odd number of reflections (e.g. a Schmidt–Cassegrain with a star diagonal in place).

Moon Poster. Two large (about 50 cm diameter) side-by-side views of the

Moon, near-side and far-side, produced by the *National Geographic Society.* Includes several hundred named features.

Lunar Quadrant Maps. Produced by the Lunar and Planetary Laboratory, at the University of Arizona, contains thousands of named and designated formations and depicts all craters of more than 3.3 km diameter. Set consists of four maps, each about 23 by 27 inches.

NASA Moon Globe. A detailed 12-inch globe, that comes with a plastic base/stand and a booklet.

I must admit that I have no personal experience of the adequacy, or otherwise, of any of these items, though Sky Publishing is a very reputable company selling many high-quality wares (and, no, I do not have any vested interest in the company!).

Another item untested by me is the *Hatfield Photographic Lunar Atlas*, as the manuscript for my book had to be with the publisher before the atlas was published by Springer–Verlag. I gave details about it in Chapter 4. However, I am very familiar with its 1968 edition. Certainly I can attest to the usefulness of that one and I await the new edition with anticipation.

You can often find Moon maps presented in general astronomy books, though they often tend to be limited in size and the details they carry. One fairly good example, containing simple geological maps of the Moon as well as larger-scale topographic maps, is *The NASA Atlas of the Solar System*, by Ronald Greeley and Raymond Batson, published by Cambridge University Press in 1997. *Norton's Star Atlas*, edited by Ian Ridpath, published in its nineteenth edition by Longman in 1998, contains a reasonably good photomosaic Moon chart.

Of course, computer media have the potential for the most detailed and accurate Moon charts. For instance, there is the *Lunar Digital Image Map* available from the NSSDC. It comprises a set of 15 CDs produced from images taken by the *Clementine* spacecraft. Disks 1–14 contain mosaics covering the Moon at a resolution of about 100 metres per pixel. The last disk contains global mosaics at resolutions of 0.5, 2.5, and 12.5 km per pixel. Some other computer media have already been mentioned – but new products are continually coming onto the market, so I urge you to shop around when you come to make purchases for yourself.

7.7 KEY MAP FOR CHAPTER 8

Chapter 8, occupying about half the length of this book, is given over to a detailed study of a representative selection of 48 principal areas/features (many others detailed along with each of these) on the Moon's near-side, the treatment being slanted to the interests of the telescopist. Herewith (Figure 7.1) is a key map intended to help you locate each of the numbered features.

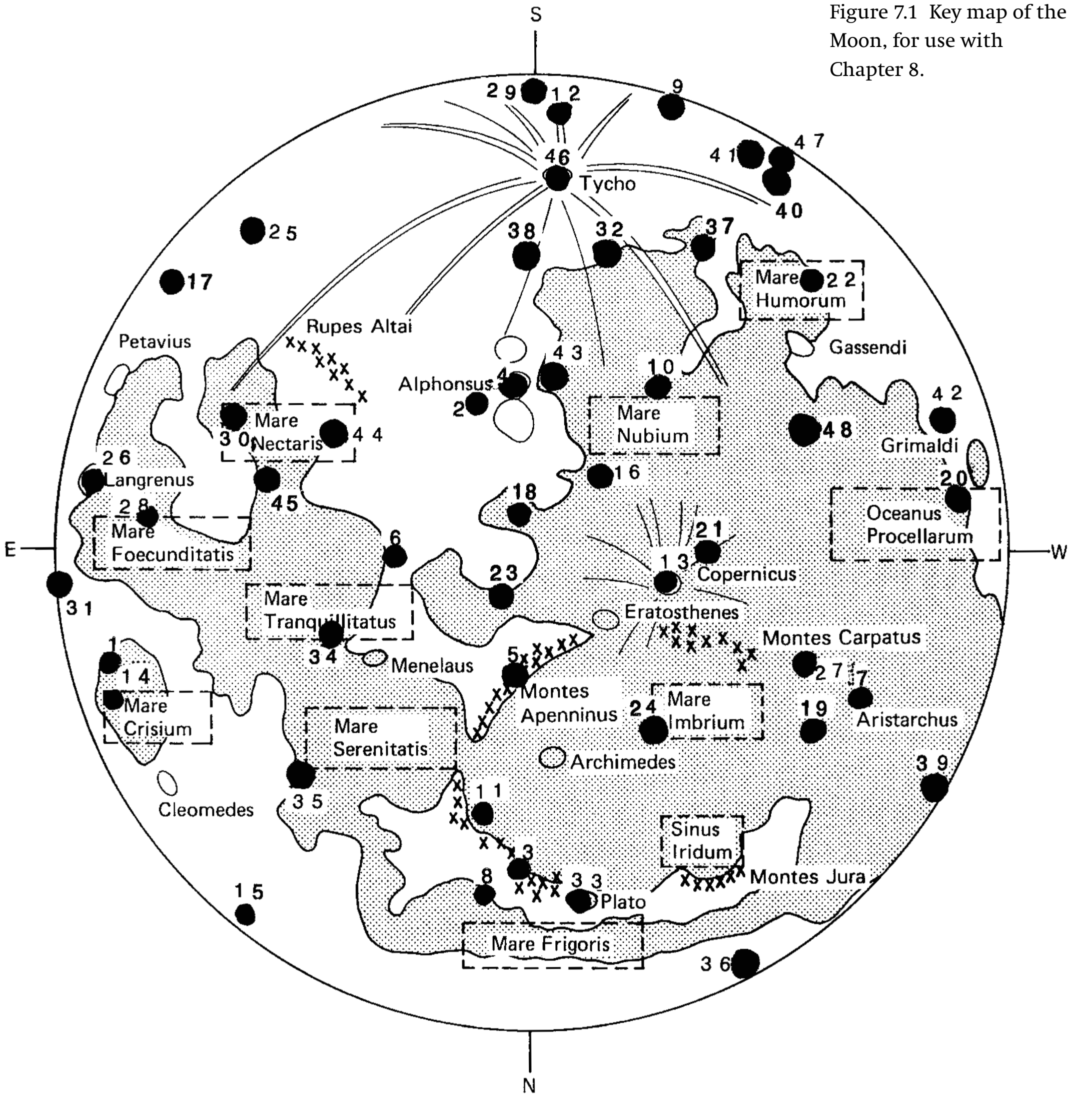


Figure 7.1 Key map of the Moon, for use with Chapter 8.

KEY:

1. Agarum, Promontorium
2. Albategnius
3. Alpes, Vallis
4. Alphonsus
5. Apenninus, Montes
6. Ariadaeus, Rima
7. Aristarchus
8. Aristoteles
9. Bailly
10. Bullialdus
11. Cassini
12. Clavius
13. Copernicus
14. Crisium, Mare
15. Endymion
16. Fra Mauro
17. Furnerius
18. 'Gruithuisen's Lunar City'
19. Harbinger, Montes
20. Hevelius
21. Hortensius
22. Humorum, Mare
23. Hyginus, Rima
24. Imbrium, Mare
25. Janssen
26. Langrenus
27. Maestlin R
28. Messier
29. Moretus
30. Nectaris, Mare
31. Neper
32. Pitatus
33. Plato
34. Plinius
35. Posidonius
36. Pythagoras
37. Ramsden
38. Regiomontanus
39. Russell
40. Schickard
41. Schiller
42. Sirsalis, Rima
43. 'The Straight Wall' (Rupes Recta)
44. Theophilus
45. Torricelli
46. Tycho
47. Wargentin
48. Wichmann

The numbers on the map, and the key to it, follow the same sequence as the numbers and titles of each of the sections in the next chapter. For instance, number 4 on the map corresponds to number 4 in the key and is named as 'Alphonsus'. Look up 'Section 8.4' in the next chapter and you will find it is headed 'Alphonsus'.

In practice, you will normally use the system the other way round. You might be reading Section 8.15 in the next chapter, about Endymion. To find out where Endymion is you can look up number 15 on the map. Of course, it is also named in the key presented with the map.

I do not pretend that the map is anything other than the simplest guide. If you have a more detailed atlas or map to hand you probably will not bother with this one. There is certainly not enough room for anything more detailed in this book. On the other hand, it seemed a pity not to include even the simplest aid to locating the features discussed in the next chapter.

CHAPTER 8

'A to Z' of selected lunar landscapes

In the earlier chapters of this book, alongside the descriptions of observational hardware and techniques, I have tried to provide a picture of the Moon and of lunar science past and present. Necessarily this 'picture' has been painted with a rather broad brush. To really get to know the Moon, one must be prepared to examine it in finer detail. To that end, this chapter presents a selection of 48 specific features/areas of the Moon. Taken together, these provide a representative selection of the types of lunar formation one may encounter at the eyepiece of one's telescope.

Why the particular selection that follows? I can only say that this has been my personal choice. I have tried to cover the fullest possible range of lunar features. You will find descriptions of craters both grand and small, conventional and unusual in their profile. Mountains, valleys, domes, rilles (both sinuous and linear), mare flood-plains and other types of terrain are also described. In some of the sections broad areas are described. A few sections concentrate on particular features of special interest. Altogether, over two hundred named formations are examined. Many are the 'old favourites' of novice and experienced observers. Others are more 'off the beaten track'. Sometimes I have provided detailed descriptions. Other times I have only provided sketchy details and leave you, the reader – and I hope the observer, to find out things for yourself.

In some cases the features described provide an object lesson in particular observational techniques and/or pitfalls for the unwary. Others exemplify particular points of lunar science and geology. All are also of interest in their own right. Everything is described from the viewpoint of the observer with his/her backyard telescope. I have tried to provide a range of targets for the full range of observers, from novice to advanced. My aim is that you will be able to go to the telescope and **interpret** what you see/photograph/image in terms of lunar science (and particularly lunar evolution).

Look at page 152 and you will see a simple key map which may be of use to you in locating the areas/features on the Moon's face described in this chapter. As previously explained, simply use the section number to locate the item on the map. As an example, the principal feature described in Section 8.26 (Langrenus) will be located at the point labelled 26 on the map (also it is named against the number 26 in the key presented with the map). At the head of each section I give the selenographic latitude and longitude of the principal named formation. This immediately tells you in what quadrant you will find the formation on the key map. Going beyond that, even the roughest estimate of position based on the latitude and longitude figures will easily and quickly enable you to find the numbered formation on the key map.

Of course, the latitude and longitude figures will also be of use in locating the formation/area on other Moon maps and atlases – the key map is only intended as an aid to locating the main features discussed here. You will undoubtedly want a much more detailed map/atlas for general use (see the previous chapter).

Let me entice you to take the first steps of a journey of exploration. After taking those first steps with me, I hope that you will then want to continue on your own. The Moon you will discover is both a thrilling and an eerie place of spectacle and wonder . . . .

8.1 AGARUM, PROMONTORIUM [14°N, 66°E]

An impressive cape, projecting into the Mare Crisium, the highest peaks of which reach up to several thousand metres above the mare. From time to time there have been claims of apparent mistiness around the cape, especially to the south, and most frequently soon after local sunrise. The visibilities of some of the tiny craters on the mare in the vicinity also seem variable. I think that these appearances are probably not true Transient Lunar Phenomena (TLP, see Chapter 9), but local variations of albedo with Sun-angle. Why not make a long-term study of this area in order to establish its true behaviour as the Sun rises over it? As explained more fully in Chapter 9, in TLP research it is particularly valuable to establish the true apparent behaviour of lunar surface features as lunations progress and under varying conditions.

Figure 8.1 is centred on the cape. It was taken using the 1.5 m reflector at the Catalina Observatory (of the Lunar and Planetary Laboratory, University of Arizona) on 1966 April 6^{d} 7^{h} 18^{m} UT. At that time the selenographic colongitude was 96°.9.

Figure 8.1 Promontorium Agarum. Details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

Figure 8.2 Albategnius (centre) and Hipparchus (lower). Details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

8.2 ALBATEGNIUS [11°S, 4°E] (WITH KLEIN AND HIPPARCHUS)

This 136 km diameter crater is very old, as witness its heavily degraded walls and the intrusion of other craters into it, notably the 44 km diameter Klein on its western (right in Figure 8.2) side. Moreover, the floors of both these craters have been flooded with mare-type lavas. Notice how the lofty (and unusually massive, for this size of crater) central peak of Albategnius pokes up through the lava, as does the smaller central peak of Klein. Also notice that Klein has degraded Albategnius and not the other way round. So, we can conclude that Klein is younger than Albategnius. What is your opinion about the age of the small crater that has intruded into the north-east rim of Klein? Yes, I know the answer is fairly obvious. I deliberately chose this as an easy example. The point is that you have made a start in unfolding the dynamic history of the lunar surface.

North of Albategnius (near the bottom of Figure 8.2) lies the even mightier and more complex and more ancient Hipparchus. Hipparchus's heavily degraded (almost destroyed along its western section) rim spans 151 km. Notice the almost parallel set of great scars cutting through the terrain in this region of the Moon. Each channel is orientated, roughly speaking, from south-south-east to north-north-west. Other examples exist in the area further west than is covered by Figure 8.2. If you relish a challenge try to deduce the history of this tortured area of the Moon's surface, using spacecraft (*Orbiter*, *Clementine*, etc.) images and, perhaps, your own telescopic observations. I guarantee that you will be kept busy for a great many hours! To get you started, backtrack the scars northwards and you will find them to be radial to a particular major feature on the surface of the Moon. Enough said?

The photograph was taken with the 1.5 m Catalina Observatory telescope on 1966 September 6^{d} 11^{h} 7^{m} UT, when the selenographic colongitude was 167°.5.

8.3 ALPES, VALLIS [CENTRED AT 49°N, 3°E]

Even when seen through a small telescope, the 'Alpine Valley' (properly called Vallis Alpes) is a truly striking spectacle around the times of first and last quarter Moon. This tremendous gorge, nearly 180 km long, seems to slice straight through the Montes Alpes, linking the Mare Imbrium with the Mare Frigoris.

Certainly it is not simply a channel cut through the mountains by a river of lava. I think that there is probably a connection between this feature and the heavy linear scars that cross the highlands in the vicinity of Albategnius and Alphonsus (see Sections 8.2 and 8.4). Perhaps all of these great valleys were really formed by slumping of the crust along stress fractures as a result of a very slight horizontal expansion of the lunar mantle (or at least the deeper layers of the crust) after the regolith

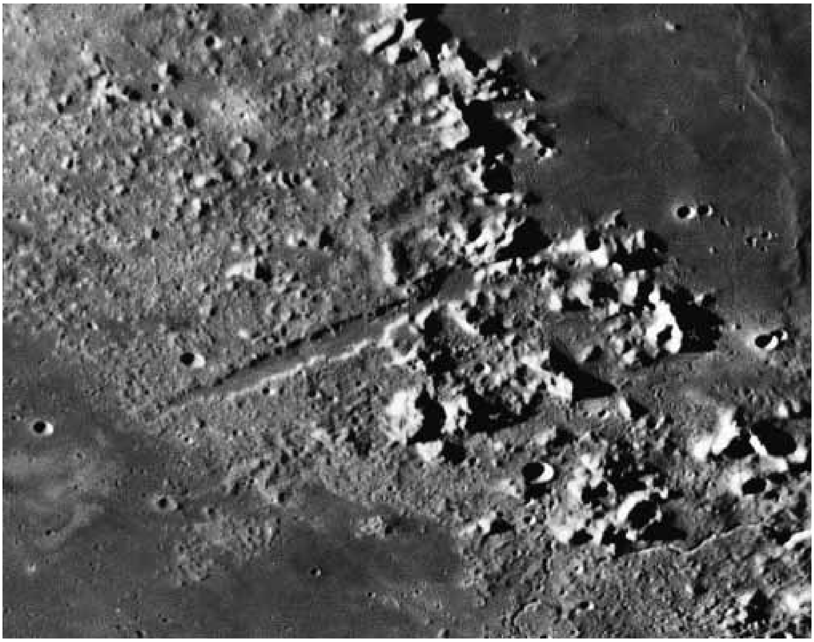


Figure 8.3 Vallis Alpes (centre) cuts through Montes Alpes in this Catalina Observatory photograph. Details in text. (Courtesy Lunar and Planetary Laboratory.)

had first solidified? The most likely explanation, though, is that the crust has shrunk very slightly after its initial solidification and stress fractures developed as a result, with the ground slumping into each fracture.

This type of formation is known as a *graben*. Perhaps the colossal impact event that created the Imbrium basin was responsible for the faults that ultimately produced the graben? Search through the Montes Alpes and you will find other linear features that are at least approximately radial to the Mare Imbrium, lending support to this idea. However none of these other linear features are anything like as strikingly obvious as Vallis Alpes.

Certainly, though, the floor of the Vallis Alpes has been flooded with lava. Also, a sinuous rille meanders along the length of the floor of this great lunar valley. Perhaps a further, minor, episode of lava flowing after the main formation and flooding processes were over? Under appropriate illumination and excellent seeing conditions the rille can be seen in a 13 cm refractor of first-class optical quality. However, it is elusive and you need not doubt your abilities if you fail to see it even when using a more powerful telescope.

The view of the Vallis Alpes shown in Figure 8.3 was taken using the Catalina Observatory 1.5 m reflector on 1967 January 20^{d} 01^{h} 45^{m} UT, when the Sun's selenographic colongitude was 18°.4.

8.4 ALPHONSUS [13°S, 357°E] (WITH ARZACHEL, PTOLEMAEUS, ALPETRAGIUS AND HERSCHEL)

The three adjacent craters Arzachel (southernmost), Alphonsus, and Ptolemaeus (northernmost) are very distinctive around the times of first and last quarter Moon. The area is shown in Figure 8.4(a), the details of which are the same as for Figure 8.2.

The 97 km diameter Arzachel is obviously the youngest of the three. Even a small telescope is enough to show its richly complex structure. The walls are heavily terraced and rise to a greater height (being about 4.5 km above the immediate surrounds) on the eastern side than on the west (height about 3.4 km – the surrounds being so rough and hummocky, these figures are only very approximate).

The crater floor, itself lying nearly 1 km below the level outside the formation, has obviously been partially flooded with lavas. Yet it is very far from smooth. There are a number of small craters, several hills, and at least one rille on the crater floor which are visible to the users of amateur-sized telescopes. Note how much the 'central' mountain mass is offset from the centre of the crater. All these features are well shown on the incredible image obtained by Terry Platt (and shown in Figure 8.4(b)) using his 318 mm tri-schiefspiegler reflector and *Starlight Xpress* CCD camera (other details not available). I used *Hauppauge* '*Image Editor*' software on my own computer to further sharpen Terry Platt's already outstandingly fine image.

Alphonsus is, arguably, one of the most interesting craters on the Moon. This 119 km diameter ring-plain has highly complex walls and many fascinating details can be made out on its flooded floor, especially by users of large telescopes.

Look carefully at Figure 8.4(a) and you will see several small dark patches on the floor of Alphonsus. At the centre of the patches are small craters. These formations are known as *dark halo craters*. At one time these were taken to be volcanic cinder cones, or fumaroles, and were used by the supporters of the endogenic theory to bolster their views on the moulding of the lunar surface. Apparent visual changes in these were even taken as suspicions of some residual volcanic activity by a small minority of researchers. However, the *Apollo 17* astronauts visited an example of this type of formation (a small dark halo crater named 'Shorty', on the south-eastern border of the Mare Serenitatis) and found it to be a conventional impact crater where the impact explosion had excavated dark mare material from beneath a thin layer of lighter regolith. It is likely that the other dark halo craters of the Moon have the same explanation.

Several rilles and faults cross the floor of Alphonsus. These are particularly well shown in the superb image Terry Platt made of the crater and which is presented in Figure 8.4(c) (subsequent image sharpening and

Figure 8.4 (a) Arzachel (upper), Alphonsus (centre), and Ptolemaeus (lower) are the craters that dominate this Catalina Observatory photograph. (Courtesy Lunar and Planetary Laboratory.) Details given in text.

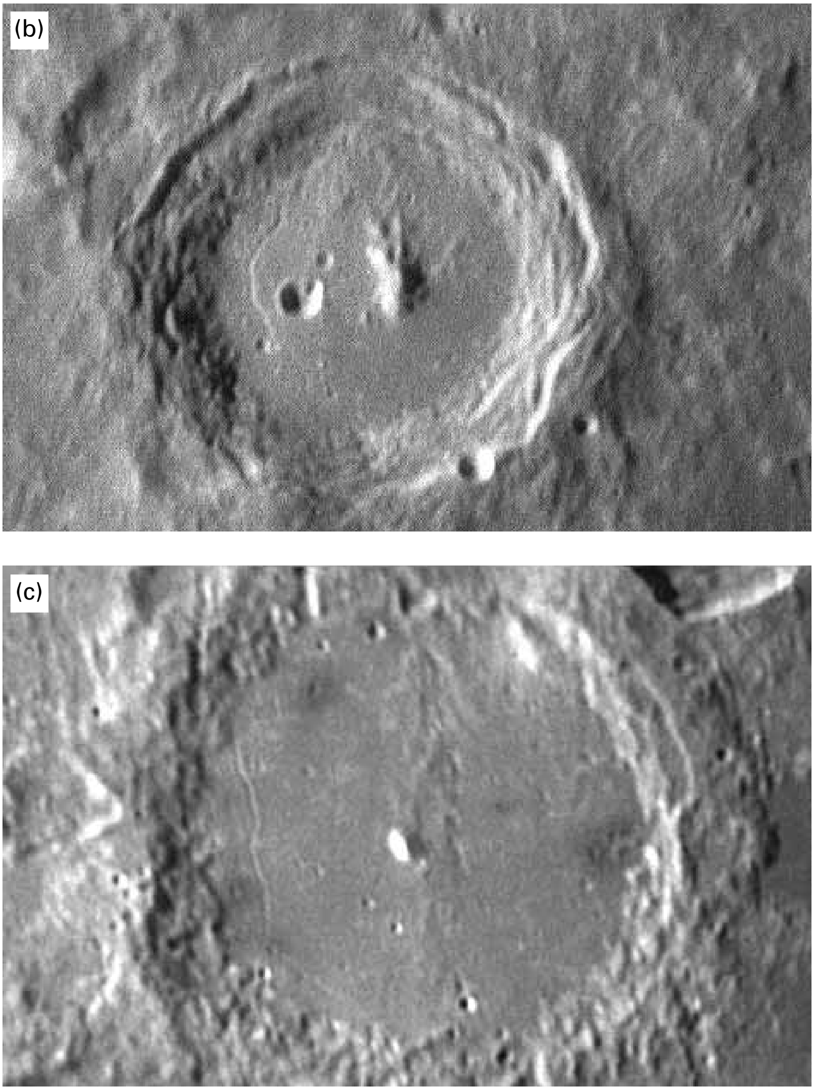


Figure 8.4 (*cont.*)
(b) Arzachel – CCD image by Terry Platt. Details in text.
(c) Alphonsus – CCD image by Terry Platt. Details in text.

other details as for (b)). The apparent changes in the dark halos are now known to be variations in relative albedo with illumination angle.

As far as the controversial subject of Transient Lunar Phenomena (TLP) is concerned, Alphonsus provided the best 'hard-copy' (as opposed to anecdotal) evidence that at least a small minority of the reported instances of TLP are real events at the Moon's surface and not simply illusions or mistakes on the part of the observers concerned. More on this in Chapter 9.

The northern section of the rim of Alphonsus merges with that of the magnificent 153 km diameter 'walled-plain' Ptolemaeus. As one might expect the terrain is highly chaotic and broken down at the merger, Ptolemaeus pre-dating the formation of Alphonsus. The ancient flooded floor of Ptolemaeus is covered in small craters and several crater-chains. These are mostly rather delicate objects for those using moderate telescopes under typical backyard conditions. The apparent brightness of the floor of Ptolemaeus changes considerably during a lunation, as does the appearance of the local 'mottlings' on it. The floor brightens considerably under a high Sun, the Moon then being near full, but appears quite dark at times close to first and last quarter Moon.

The area covered in Figure 8.4 overlaps that shown in Figure 8.2, which lies to the east. Notice the same straight scars in the terrain, each hundreds of kilometres long. What story do they tell? (There is no mystery but you might like to deduce the answer for yourself. I offered a clue in Section 8.2).

The prominent 40 km diameter crater to the north-east of Alphonsus and south-east of Ptolemaeus is called Alpetragius. Notice its prominent central peak, rather 'mound-like' in profile. The walls of this crater are rather finely terraced.

Of similar size to Alpetragius, and positioned just north of Ptolemaeus, is Herschel. You might like to consider making a detailed comparison between Alpetragius and Herschel. Given that the craters are similar in many ways, why are they rather different in others?

8.5 APENNINUS, MONTES [CENTRED AT 20°N, 357°E] (WITH CONON, ERATOSTHENES, PALUS PUTREDINIS, SINUS AESTUUM, WALLACE)

If any feature on the Moon can take the prize for being the most striking when seen through even the smallest telescope at the appropriate time, then surely it has to be the magnificent Montes Apenninus. The "appropriate time" for this formation occurs twice every lunation: near first and last quarter Moon.

Spanning about 600 km along the south-eastern 'shore' of the Mare Imbrium, this stunningly rugged mountain range strikes a breath-taking spectacle when seen under a low Sun. I admit that I find the fine details quite confusing when seen under good conditions with a powerful telescope. I tend to use a higher magnification than I would normally do under the ambient conditions just to enjoy the sheer awesome effect of the view. This also reduces the confusion greatly. The slight softening of the image, due to over-magnification, hardly matters when one gets the thrilling impression of apparently flying over the complex array of mountain peaks, ridges, and valleys!

Its origin dates back about 3850 million years, with the creation of the Imbrium Basin. The impacting projectile caused the highland crust along the south-eastern border to be violently uplifted, so forming the range.

Figure 8.5 (a) The northernmost extent of the Montes Apenninus. Details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

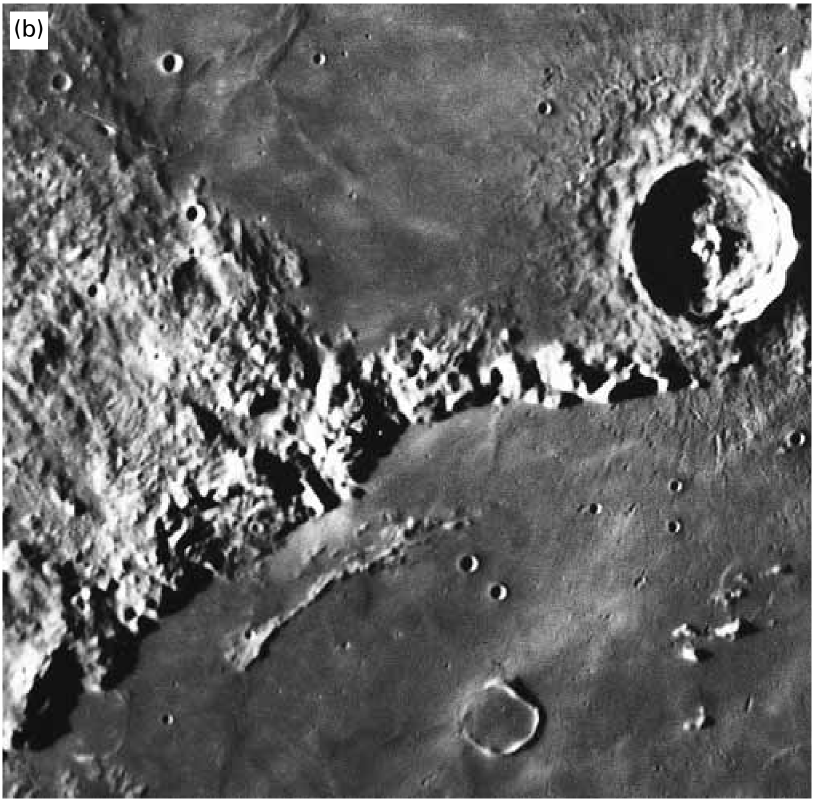


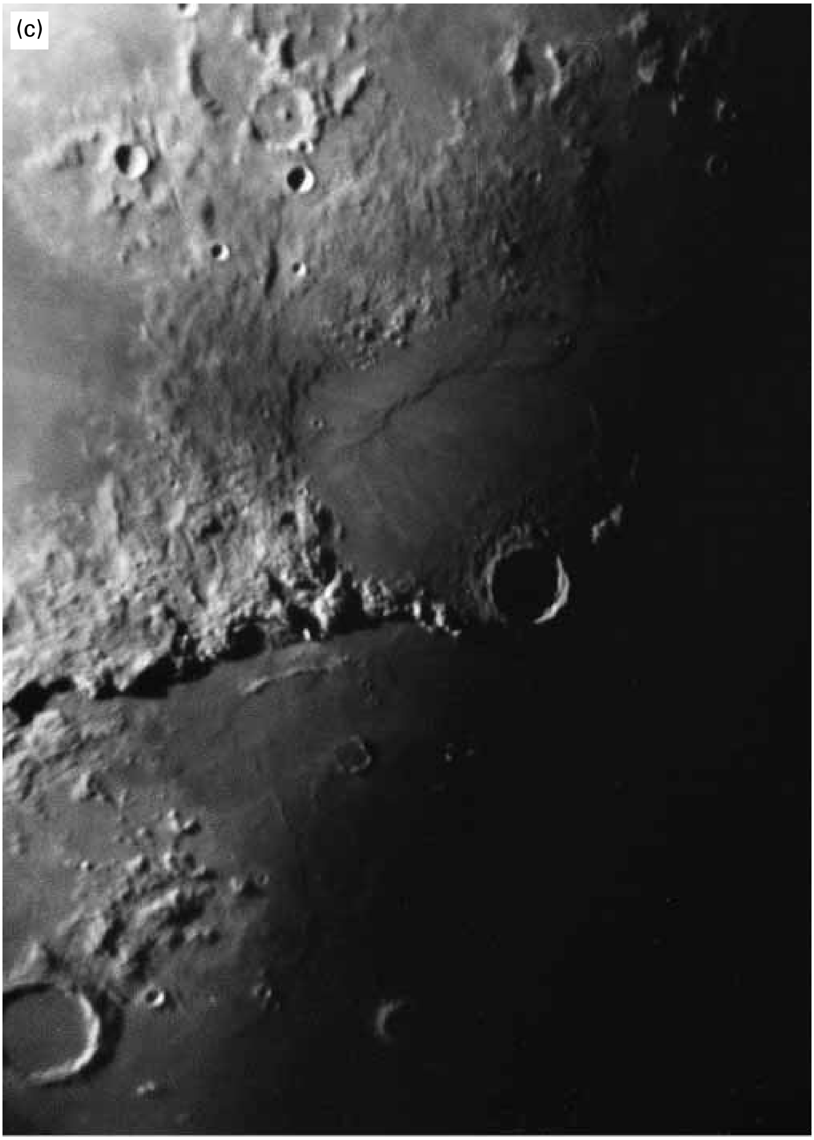
Figure 8.5 (*cont.*)
(b) The southernmost termination of the Montes Apenninus with the crater Eratosthenes (upper right). The ruined crater Wallace can be seen near the bottom of this Catalina Observatory Photograph. Details in text. (Courtesy Lunar and Planetary Laboratory.)

Figures 8.5(a) and (b) are sections of a photograph which was taken with the Catalina Observatory 1.5 m reflector on 1967 January 20^d 01^h 46^m UT, when the Sun's selenographic colongitude was 18°.5. Figure 8.5(a) shows the mountain range to its northernmost extent. The conspicuous crater in the midst of the mountain peaks (just to the right of centre of the photograph) is the 22 km diameter Conon. The area of mare extending from the bay a little north of Conon is called the Palus Putredinis ('Marsh of Decay'). Notice the extensive network of fine sinuous rilles in the area.

The *Apollo 15* astronauts visited the north-eastern border of the Palus, close to the foot hills of the Montes Apenninus and examined one of the rilles (Hadley Rille) close-up.

Figure 8.5(b) shows the southernmost extent of the Montes Apenninus, where it terminates with the prominent 58 km crater Eratosthenes. Under a low angle of illumination Eratosthenes is particularly striking and, largely shadow-filled, then appears to be very deep. The rim of the crater actually rises to just over 2.4 km above the surrounding terrain level, while the floor is depressed by about the same distance below the level of the outside surrounds. A lunarnaut standing on the rim of the crater and looking towards the central mountain complex would see the ground sloping away from

Figure 8.5 (*cont.*)
(c) Eratosthenes and the Sinus Aestuum, photographed by Tony Pacey. Details in text.



him with an average gradient of about 1 in 3 (actually the walls are terraced) down towards the crater floor (at a depth of nearly 5 km vertically below that of the rim). The giant amphitheatre would be harshly sunlit, while the sky above would be inky black. Imagine what a spectacle that would be!

Eratosthenes is somewhat of a lunar chameleon. Despite its stark magnificence when seen at low Sun-angles (see also Figure 8.13(a), further on in this chapter, where it appears alongside Copernicus), the crater takes on a very 'washed-out' appearance when seen under a higher Sun. In fact the crater can even give the completely illusory impression of then being filled with a white, pall-like, mist. Some other craters also show the same optical behaviour and undoubtedly this has led to many a false claim of TLP.

Some of the observers of yesteryear were convinced that changes regularly happened within Eratosthenes (even the growth and dying of vegetation and the migrations of animal/insect life-forms!) but they were certainly mistaken. Near full Moon Eratosthenes becomes really quite difficult to detect, especially as the ray system from the nearby major crater Copernicus then tends to help with the camouflage.

Another notable feature, pictured in Figure 8.5(b), is the ruined crater Wallace. Shown near the bottom of the photograph, the surviving remnants of Wallace's broken walls poke above the level of the Mare Imbrium. This 26 km crater has been almost entirely flooded by the lavas which filled the old Imbrium Basin to form the Mare Imbrium about 3.3 billion years ago.

Figure 8.5(c) provides another view of Eratosthenes, this time almost entirely filled with black shadow. It also shows off one of the more obscure basaltic flood-plains to very good effect. This is the Sinus Aestuum, situated to the immediate south-east of Eratosthenes. This 'bay' spans 230 km. It is quite easy to trace the outline of the original basin that was to be later filled with lava to form the sinus on this excellent photograph by Tony Pacey. He used eyepiece projection to enlarge the image at the f/5.5 Newtonian focus of his 10-inch (254 mm) Newtonian reflector onto FP4 film for this 0.5 second exposure on 1990 February 3^{d} 19^{h} 35^{m} UT, when the Sun's selenographic colongitude was 0°.4.

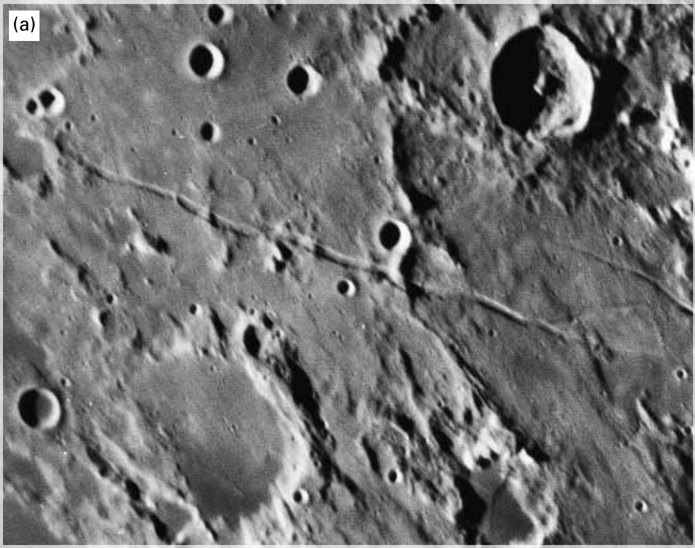
At higher Sun-angles the sinus becomes very hard to see. This is particularly so because the rays from the nearby Copernicus, splattered across this region, then dominate.

Notice how the impact cut through, and obliterated, the southernmost extent of the Montes Apenninus. Clearly the Aestuum impactor did its work **after** the much more massive projectile that created the Imbrium Basin had hit the Moon. As such, the Aestuum Basin must be one of the youngest on the Moon, the Imbrium Basin itself being quite youthful. What about the ages of Eratosthenes and the Imbrium and Aestuum flood-plains relative to each other and the basins? The answer is well established, and is quite easy to fathom but I will leave this as an exercise for you.

8.6 ARIADAEUS, RIMA [CENTRED AT 7°N, 13°E] (WITH ARIADAEUS, SILBERSCHLAG, JULIUS CAESAR, AND AGRIPPA)

Whenever the terminator lies in the vicinity of the Rima Ariadaeus this rille becomes very easy to see even when using quite small telescopes. Roughly 220 km long, it spans much of the rough terrain between the Mare Tranquillitatis (to its east) and the junction between the Mare Vaporum (to the north-west) and Sinus Medii (to the south-west).

Figure 8.6 (a) Rima Ariadaeus. Details given in the text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)



(b)

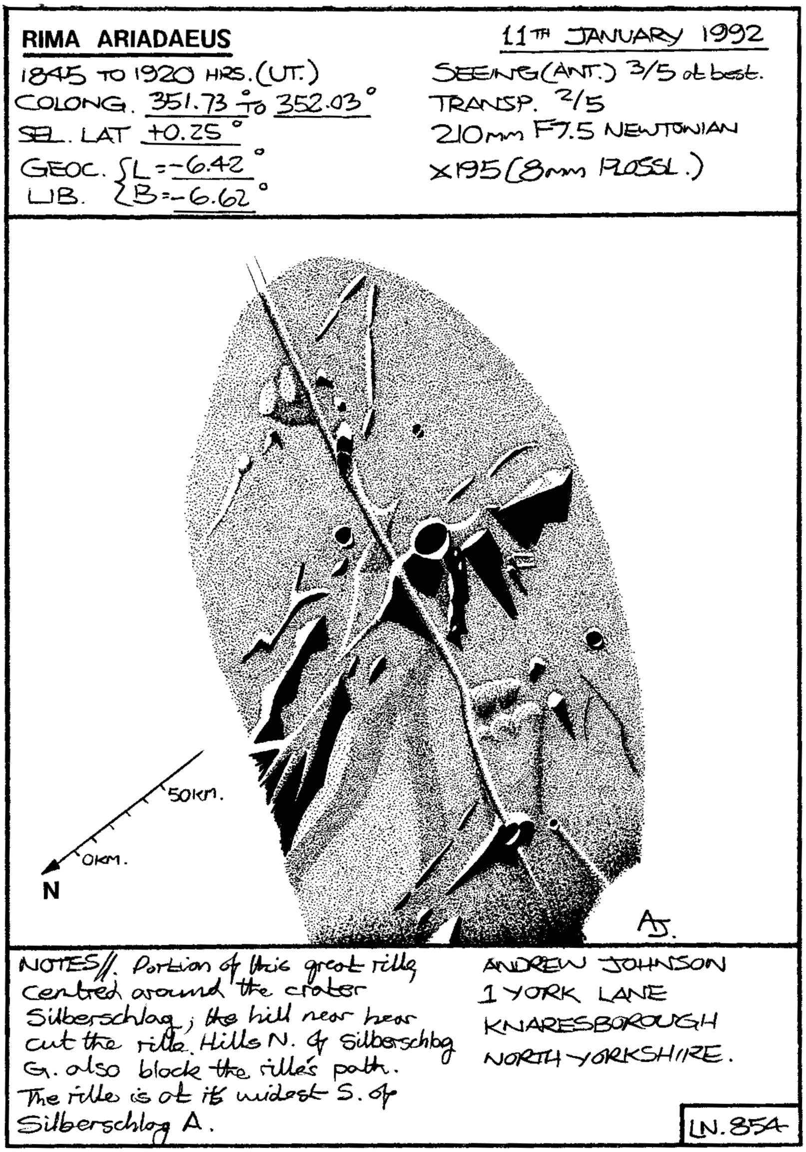


Figure 8.6 (*cont.*)
(b) Rima Ariadaeus drawn by Andrew Johnson.

Figure 8.6(a) is a splendid view obtained using the Catalina Observatory 1.5 metre reflector, taken on 1966 May 27^{d} 03^{h} 56^{m} UT when the Sun's selenographic colongitude was 356°.8. The whole area, especially to the west, is rich in rilles and the right-hand side of Figure 8.6(a) also shows the easternmost part of the famous 'Hyginus Rille', Rima Hyginus. Rilles make a fascinating subject for study at the telescope eyepiece. Figure 8.6(b) shows one such study made by Andrew Johnson. Details as written on the drawing, but do note the orientation when comparing it to Figure 8.6(a). Figure 8.6(a) is, in common with most of the other images in this book, reproduced with south uppermost.

It may superficially look like a sinuous rille, except that it is rather bigger and straighter, but Rima Ariadaeus is actually a graben – the vertical slumping of ground along a stress fracture. Look carefully at Figure 8.6(a) and you will see topographical features, such as mounds, along it that clearly match the 'high and dry' features to either side. Notice that Andrew Johnson has recorded some of these delicate features in his drawing which shows the rille in the vicinity of the 13 km crater Silberschlag (which is also shown near the centre of Figure 8.6(a)).

The easternmost extent of Rima Ariadaeus (far left on Figure 8.6(a)) is marked by the small (11 km) bright crater Ariadaeus, notable for the intrusion of a smaller crater into it.

If you experience any trouble in locating Rima Ariadaeus, then first find your way to the imposing 44 km diameter crater Agrippa (upper right on Figure 8.6(a)) and the ancient ruined formation Julius Caesar (roughly 91 km in diameter and shown at the lower left of Figure 8.6(a)). Apart from near full Moon you should easily be able to identify the rille passing between these two craters and close to Silberschlag, which itself is conveniently half-way along a line between these two craters.

8.7 ARISTARCHUS [24°N, 313°E] (WITH HERODOTUS AND VALLIS SCHRÖTERI)

Even in the lowliest binoculars the crater Aristarchus stands out like a brilliant diamond against the grey expanse of the Moon's Oceanus Procellarum. Aristarchus is the brightest of the large formations on the lunar surface. It is quite easy to identify even when illuminated only by Earthshine. Indeed, the great 18th Century astronomer William Herschel mistakenly believed that Aristarchus was an erupting volcano! The crater is reckoned to be very approximately 300–500 million years old. This is very young for a Moon crater of its size. Its youthfulness is the reason for its high albedo. The solar-wind bombardment has not had time enough to do its work of darkening the materials excavated from below the regolith.

Aristarchus spans about 40 km from rim to rim and close inspection reveals that it has a decidedly polygonal outline. It stands on an extensive plateau, with the rim of the crater rising to over 600 metres above its immediate surrounds. The interior terraced walls slope down to the crater floor at a depth of some 2.1 km below the rim. As Figure 8.7(b) shows, the appearance of the formation is somewhat confusing when seen under a high Sun. With the terminator somewhat nearer the crater, details then stand out readily: contrast Figure 8.7(a) with Figure 8.7(b).

Figure 8.7 (a) Aristarchus (the largest crater shown), Herodotus (right of Aristarchus) and Vallis Schröteri (below Herodotus) at colongitude 63°.7. Details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

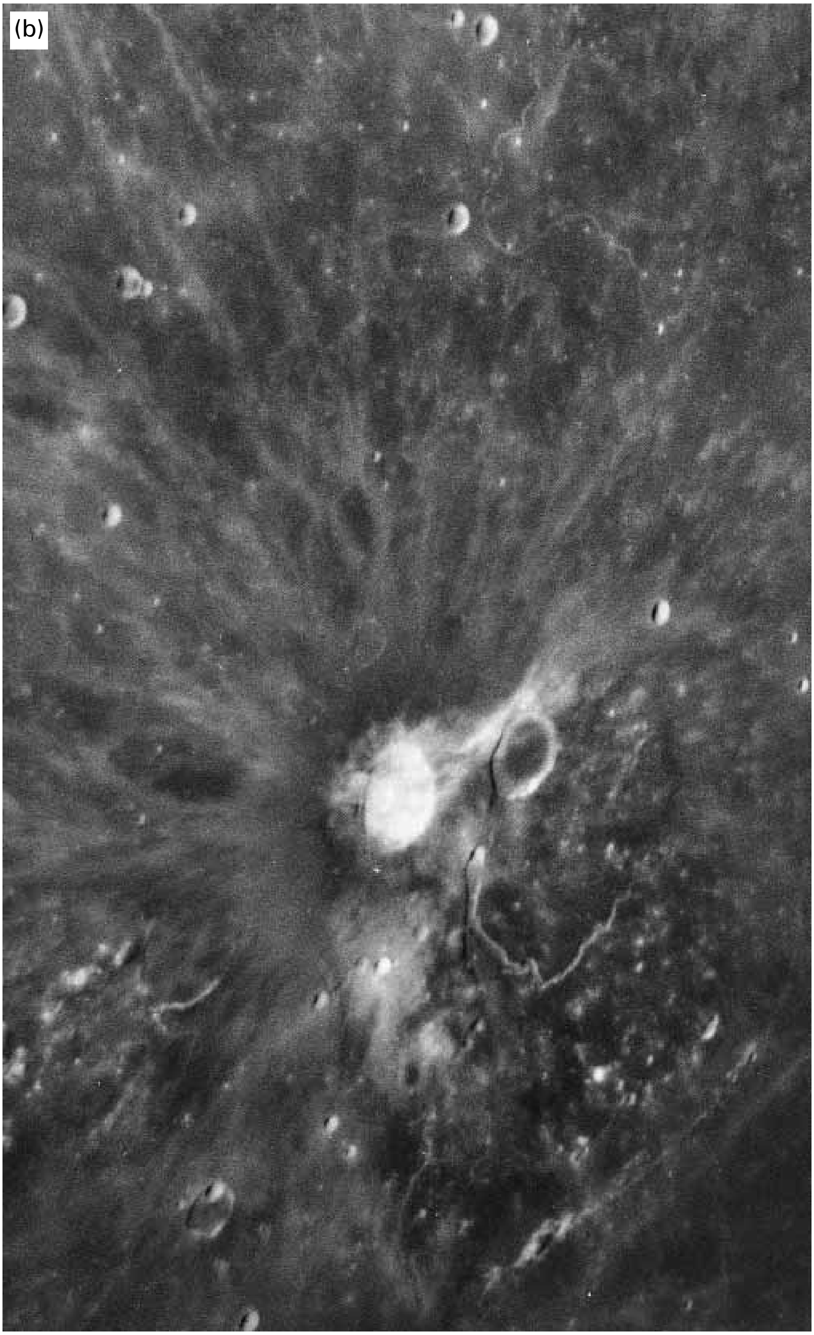


Figure 8.7 (*cont.*)
(b) Aristarchus and environs at colongitude 79°.3. Details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

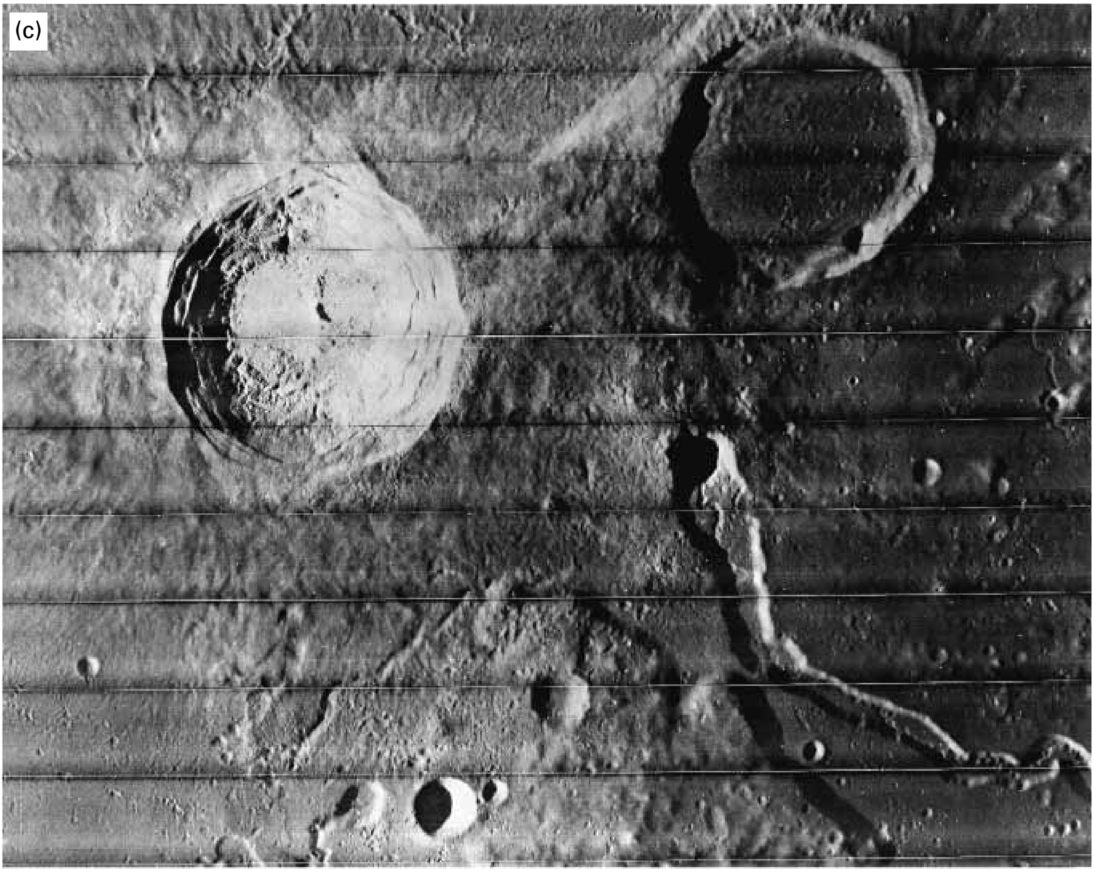
Both photographs were obtained using the Catalina Observatory 1.5 m reflector: (a) was taken on 1965 December 06^{d} 05^{h} 14^{m} UT and (b) was taken on 1966 October 28^{d} 06^{h} 28^{m} UT.

The youthfulness of Aristarchus has already been referred to in connection with its albedo. This characteristic also gives it a degree of thermal lag, when it comes to the diurnal cycle. In the lunar mornings bright features such as Aristarchus show up as cold spots on thermal maps, since they reflect away more of the solar radiation. However, the reverse is the case after sunset. Good reflectors make poor emitters. Then they show up as being warmer than their surrounds. During the local lunar night Aristarchus can remain up to 30 degrees Celsius warmer than its surrounds.

Another indicator of the youthfulness of Aristarchus is the complexity and crispness of the terracing of its walls. Further evidence is provided by its relatively complex floor and central mountain (features on the Moon lose their ruggedness as time passes).

One intriguing feature of Aristarchus is readily apparent in Figure 8.7(a): the system of radial dark bands that extend up the interior terraces

Figure 8.7 (*cont.*)
(c) *Orbiter IV* photograph of Aristarchus, Herodotus and Vallis Schröteri. (Courtesy NASA and Professor E. A. Whitaker.)



of the crater. They were first drawn by Lord Rosse in 1863 but were not recorded, nor even as much as mentioned, by the earlier observers of the Moon. Why was it that the likes of Mädler, Schmidt, or Neison failed to discover the bands when these great selenographers paid considerable attention to Aristarchus? How could they possibly miss a striking feature that even I as a novice observer could so readily see in my 76 mm reflector at the beginning of the 1970s? Could the bands have gone from being very hard to see to very obvious in the intervening century? I, for one, find this very hard to believe. There is a real mystery here.

Take a look for yourself. You should easily be able to see the two most prominent bands in a small telescope and you might count up to nine of them if you use a large telescope under suitable lighting and good atmospheric conditions. The bands do vary in intensity throughout the lunation, being hardest to see when the terminator is close by. You might like to make a study of their changing appearance.

The striking ray system emanating from Aristarchus tells a story about the impactor that created the crater. As is usual for ray systems on the lunar surface, the Aristarchus rays are most obvious when illuminated by a high Sun. Figure 8.7(b) shows the ray system well. Rays radiate in all directions from Aristarchus but note how the majority of the crater ejecta stream off to the south-west. Clearly the projectile hit the Moon at a fairly low angle, and came from the north-east. Look at the shape and offset of the interior 'central' mountain as shown in Figure 8.7(a) and you will find confirmatory evidence for this hypothesis.

The Aristarchus plateau, already referred to, is an approximately square area of rough and hummocky terrain, extending about 200 km × 200 km. Altimetry data obtained by the *Clementine* space probe reveals that the southern edge of the plateau is about 2 km higher than the general level of the Oceanus Procellarum and that it gently slopes downwards to the north and north-west (the average slope being about one degree).

To me, the plateau seems to have a rich 'coffee-brown' tint that contrasts strongly with the white Aristarchus and the greenish-grey mare. As noted in Chapter 2, though, perceived colours are not accurate (and not everybody's eyes are colour-sensitive enough to show them) but the colour contrasts are at the least instructive. Proper colorimetric studies do, indeed, reveal that the plateau is much redder than the average hue of the Moon. The multi-waveband images obtained by *Clementine* indicates that the colour arises due to a layer of reddish pyroclastic glasses.

Other interesting features highlighted by *Clementine* include the presence of the mineral olivine distributed along the southern part of the rim of Aristarchus and the presence of anorthosite on the crater's central (or near-central!) peak.

Sitting on the plateau, alongside Aristarchus, is the slightly smaller and much shallower crater Herodotus. Both craters in effect at least approximately define the southernmost boundary of the Aristarchus plateau. The differences between the two craters could hardly be greater. Herodotus is obviously an ancient crater whose floor has been lava-flooded. Superficially the floor looks smooth but some craterpits are revealed by large-aperture telescopes used under good conditions. Space-probe images show the floor of Herodotus to be covered in tiny craters and fissures.

Perhaps the most remarkable feature in this very remarkable region of the Moon is Schröter's Valley, or more properly Vallis Schröteri. This is the Moon's largest sinuous rille, originating at its southernmost end at a deep crater known as the Cobra's Head and winding on for over 160 km to the western corner of the Aristarchus plateau. The impression is that it was created by a river of lava erupting from the Cobra's Head and cutting its way along a winding path to lower ground. Most lunar experts think that this was, indeed, what happened. A finer sinuous rille runs along the length of the floor of the valley, indicating at least one subsequent lava flow. This is best seen in the *Orbiter IV* photograph presented in Figure 8.7(c).

The whole area abounds with finer sinuous rilles. Clearly the geological (I would prefer to say 'selenological' but that term is not in fashion) history of this region is very complex.

The area is especially interesting for those involved in the controversial study of Transient Lunar Phenomena. About a third of all the catalogued reports of TLP involve Aristarchus or its surrounds. It is the single most 'event prone' of the areas if one is to believe all the reports. However, it must be borne in mind that the brilliance of Aristarchus may well be responsible for many illusory reports. Especially so as *spurious colour*, the prismatic splitting of colours along light–dark boundaries caused by the Earth's atmosphere, is especially evident with this crater. Often the southernmost part of the rim, and extending to the southernmost boundary of the ejecta blanket, shows a yellow or even orange-red glow due to this cause (the complementary colour showing up chiefly along the northern rim of the crater). Also there is the problem of observational selection. Being so apparently 'event prone' observers tend to concentrate their efforts to studying this area, so distorting the statistical evidence. However, it is true that there is some evidence for real TLP in this area and it may be significant that the *Apollo 15* particle spectrometer indicated a higher than average emission of radon gas when it flew over Aristarchus.

Aside from the various effects which have been reported involving Aristarchus itself, various reports of mistiness and coloured effects issuing from the Cobra's Head are on record. The transient event that I have most faith in as being something genuine, of any of the very few that I have witnessed myself, involved the crater Aristarchus. More about this and the whole subject of Transient Lunar Phenomena in the next chapter.

8.8 ARISTOTELES [50°N, 17°E] (WITH EUDOXUS AND EGEDE)

The crater Aristoteles stands proudly just south of part of the 'shore' of the Mare Frigoris and a little way east of the Montes Alpes. It is 87 km from rim to rim and possesses very finely terraced walls, rising to over 3.3 km above the floor. The floor, itself, is far from smooth. A low Sun-angle reveals that it is rippled with small hills. A little to the south lies the 67 km diameter Eudoxus, itself laying at the northern termination of the Montes Caucasus. It's walls rise to a similar height as Aristoteles.

Aristoteles and Eudoxus are a magnificent pair of craters, easily identified at almost all lunar phases. Figure 8.8(a) shows the formations under morning illumination, while Figure 8.8(b) shows them late in the lunar day. Both photographs were obtained using the Catalina Observatory 1.5 m reflector: (a) was taken on 1967 January $20^{d}\ 01^{h}\ 45^{m}$ UT and (b) was taken on 1966 September $04^{d}\ 10^{h}\ 03^{m}$ UT. However, the terminator was not particularly close for either photograph. I will leave you to study the detailed

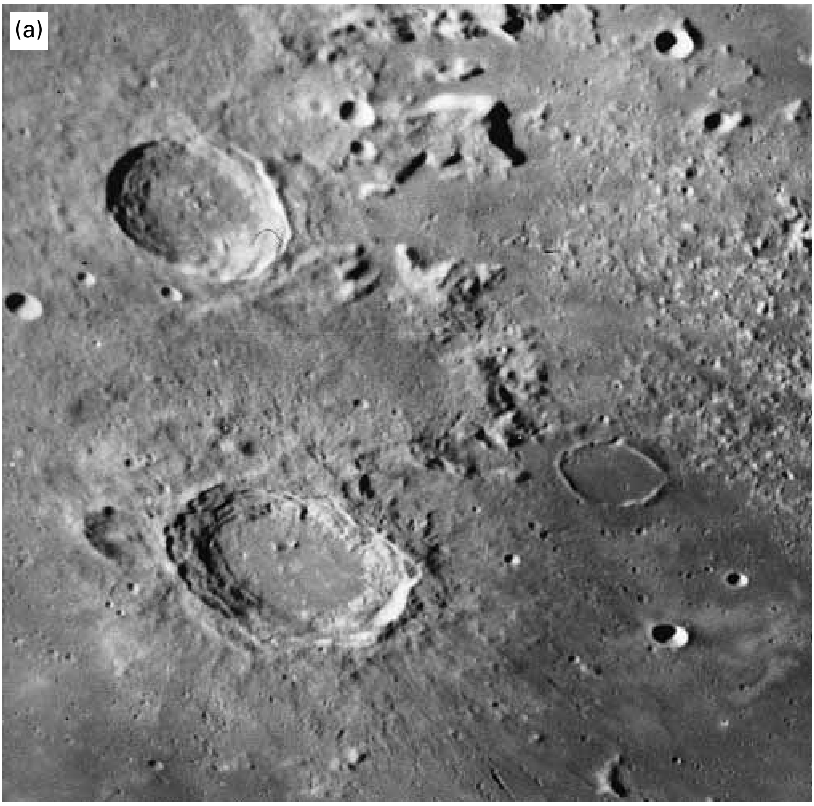


Figure 8.8 (a) Aristoteles (lower crater) and Eudoxus are the largest craters on this Catalina Observatory photograph taken at selenographic colongitude 18°.4. The small, lava-flooded, crater to the right is Egede. Other details in text. (Courtesy Lunar and Planetary Laboratory.)

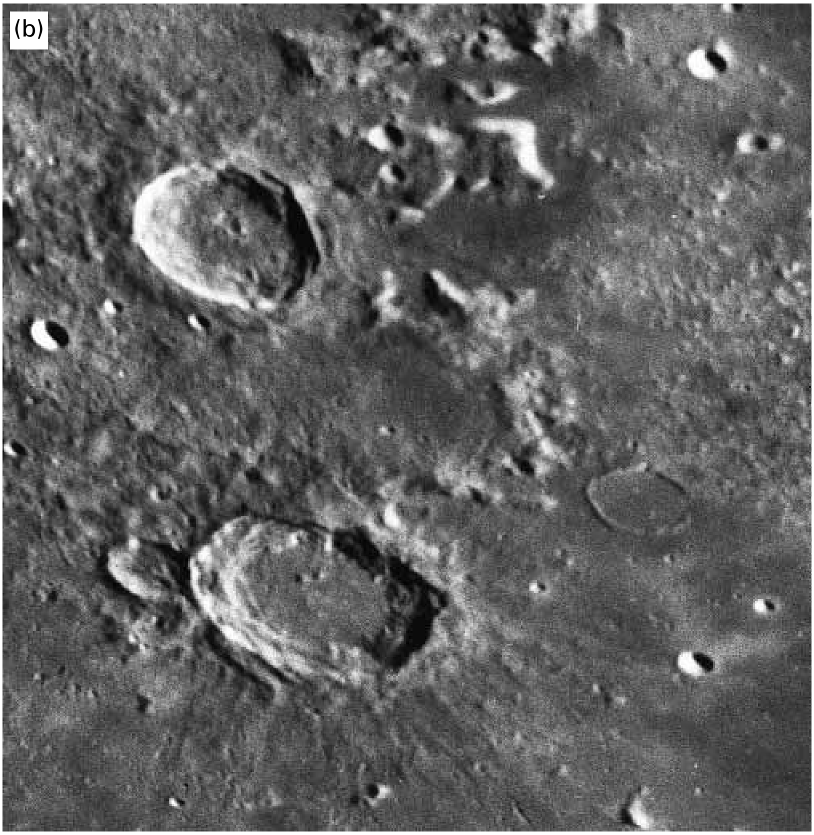


Figure 8.8 (*cont.*)
(b) Aristoteles and environs at selenographic colongitude 142°.6. Other details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory).

topography of the area (and I especially commend to you the arc of mountain peaks which span Aristoteles and Eudoxus to the north) and to work out the chronologies.

However, there is something I will draw to your attention: the highly polygonal outlines of the craters. Notice how the small (37 km) flooded and ruined crater Egede (situated just to the west of the arc of mountain peaks just referred to) also shares the polygonal outline. Ask a casual observer what are the shapes of the outlines of the lunar craters and the answer you will probably get is that they are circular. Actually, many of them are decidedly polygonal. There is also some evidence that many of the faults on the lunar surface are aligned in the same general directions as the distortions to the crater outlines. This has been termed *the lunar grid system*, though not everybody accepts its validity. Has some global twisting of the Moon occurred in recent times (even some of the youngest craters have polygonal outlines) to cause the distortion? This certainly seems highly implausible. The mystery remains.

8.9 BAILLY [67°S, 291°E]

Under old terminology the largest craters were called 'walled plains', or 'ring plains'. Bailly, at 303 km diameter, qualified as the largest 'walled plain' on the Moon's Earth-facing hemisphere. Now, though, Bailly is regarded as one of the smallest *basins*. Basins are spread over both hemispheres of the Moon in approximately equal proportions but those on the Earth-facing side are almost all flooded with mare basalts. By contrast, there is almost no mare-type lava flooding on the Moon's far side and so the basins there are still 'raw', as is Bailly. The huge projectiles that created the basins belong to the early history of the Moon. In all probability Bailly is more than 3 billion years old.

There are two probable, and connected, reasons why Bailly has remained free of lava flooding. One is that the impacting projectile was not massive enough (and so did not convey enough kinetic energy) to cause sufficient fracturing of the Moon's crust to drive fissures deep enough to reach through to the upper mantle. Even near the centre of the

Figure 8.9 (a) Bailly spans this Catalina Observatory photograph taken at a selenographic colongitude of 80°.9. Details in text. (Courtesy Lunar and Planetary Laboratory.)

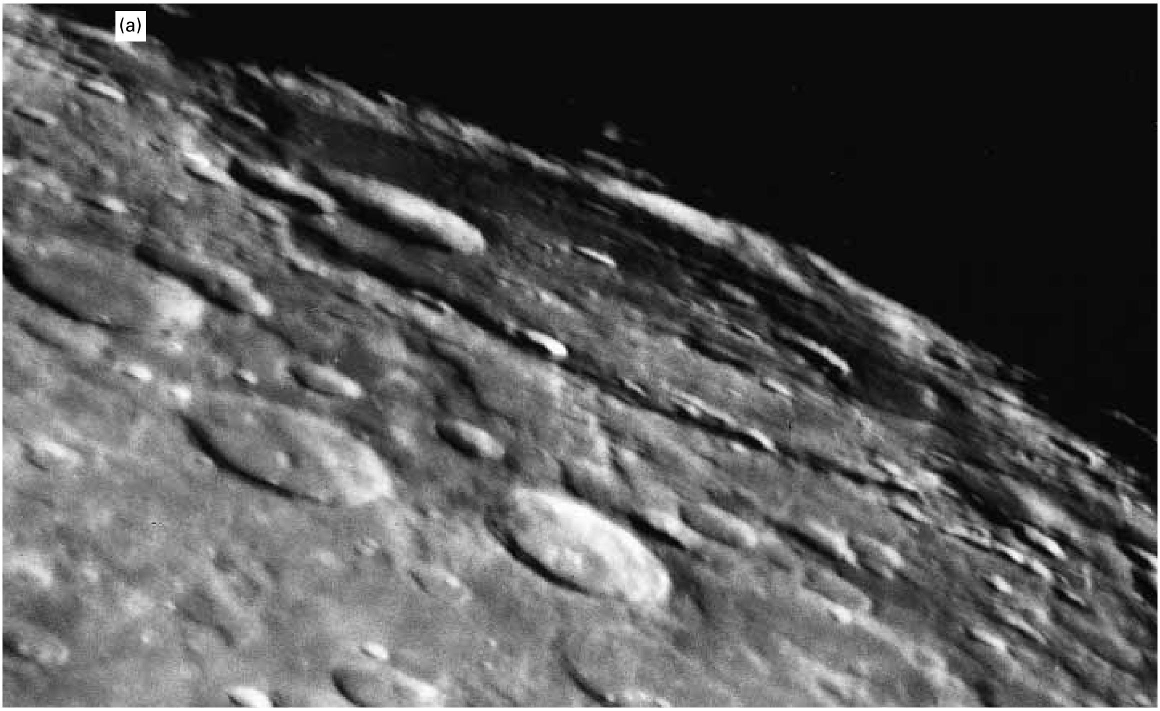


Figure 8.9 (*cont.*)
(b) Bailly is largely in darkness but part of the rim of Bailly B can be seen emerging into the morning sunlight in this view taken at a selenographic colongitude of 61°.0. Other details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

Moon's Earth-facing disk (where the crust is thinnest) the flooded plains are all of greater diameter than Bailly. The second reason is that Bailly, like the great basins of the Moon's far side, is positioned over a region where the crust is thicker than the average near the sub-Earth point.

Being so close to the south-western limb, Bailly is best observed just a little before full Moon, when the crater experiences lunar morning. Even then it can be badly affected by libration. The views of it at lunar evening are often unsatisfactory since the Moon is then a very thin crescent, and so is rather too close to the Sun in the sky to allow for good observing conditions. It is probably because of this that the earliest selenographers missed discovering Bailly. Cassini was the first to record it in his map of 1680.

Figure 8.9(a) provides a magnificent view of this huge formation. This photograph was taken on 1966 January 06^{d} 05^{h} 45^{m} UT with the 1.5 m reflector of the Catalina Observatory. The formation's great age is evident by its general state of ruin. Note how the ramparts have been smoothed and eroded, particularly by aeons of impacts. Even so, in places they still soar upwards to over 4 km above the mean floor level!

When Bailly is on view and the conditions are suitable you might like to examine it for yourself. You will find the floor of this formation littered with myriads of craters and ridges. However, the foreshortening will always prove a challenge to successful examination. Of the two large and overlapping craters at the south-eastern rim of Bailly, the smaller is known as Bailly A. It is 38 km in diameter and actually crosses the rim of Bailly. The larger of the two was, for a time, known as Hare but has now reverted to its original designation of Bailly B. Bailly B is very deep (over 4 km from rim to floor) for its 65 km diameter.

Watching/drawing/photographing/imaging lunar formations as the terminator passes over them is highly instructive. It is in this sort of activity that the very few (and dwindling) possibilities for useful and original topographic study lie. Take a look at Figure 8.9(b). This is another Catalina Observatory photograph but this one was taken on 1967 February 27^{d} 03^{h} 43^{m} UT at a slightly earlier lunar phase. This time the floor of Bailly is **almost** entirely in black shadow. Notice, though, the rim of Bailly B catching the morning sunlight. . . .

An ancient lunar formation full of fascination but a degree of dedication is needed in order to pursue its study at the telescope eyepiece.

8.10 BULLIALDUS [21°S, 338°E] (WITH KÖNIG, LUBINIEZKY AND WOLF)

Measuring just 61 km from rim to rim, Bullialdus may not be one of the largest craters on the Moon but it makes up for that in being one of the most beautifully formed.

Despite its small size, it is very easy to locate, sitting proudly and prominently on the Mare Nubium. Figure 8.10(a) is a Catalina Observatory photograph, taken with the 1.5 m reflector on 1966 December 23^{d} 04^{h} 54^{m} UT. The terraced walls (about 2.4 km in vertical height) are evident in the photograph, as is the somewhat polygonal outline of the crater and its slightly convex floor.

Bullialdus contains a wealth of detail to entertain and interest the observer equipped with a moderate telescope. The central mountain mass is complex and it changes its appearance quite considerably over the lunation as the various shadows develop with changing Sun angle. Another shadow effect concerns the crater floor. Under a low Sun in the local lunar morning it tends to be dark and fairly evenly shaded (the effect of the convexity accepted) but it brightens considerably as the Sun angle increases and various dark markings appear, change shape and prominence, and then fade as local sunset approaches. This effect is caused by the rough and

Figure 8.10 (a) Bullialdus is the largest crater shown on this Catalina Observatory photograph, taken at a selenographic colongitude of 39°.9. Bullialdus A nearly joins Bullialdus and Bullialdus B is just above this. At the top, and over to the right, is König, whilst below König and down at the bottom is Lubiniezky. Other details in text. (Courtesy Lunar and Planetary Laboratory.)
(b) Bullialdus is over to the right and is filled with shadow and Wolf is the prominent formation in the upper left of this Catalina Observatory photograph, taken at a colongitude of 22°.6. Other details in text. (Courtesy Lunar and Planetary Laboratory.)

slightly lumpy nature of the crater floor, the individual shadows generated within the surface relief being too small to appreciate individually but the combined effect producing the behaviour that is noticeable through the telescope.

Near the time of full Moon, the central mountain complex becomes very bright as does much of the crater rim and the interior develops many bright spots.

Away from the time of the full Moon, the careful observer may discern some landslips and even some small craters in Bullialdus's inner terraces. Notice the lines of thin black shadow defining the terraces in the south-west of the interior. Clearly here the steps slump backwards by several degrees. The black spot at the southern end of this section can also become very prominent, indicating a hollow. Under a higher Sun, a ridge, running a short way radially down the terraces, becomes visible in the same location. Look closely at Figure 8.10(a) and you should be able to discern an intriguing raised ridge crossing south-east from the central mountain complex to the foot of the wall terraces.

The outer surrounds of Bullialdus are also of particular interest. The complex array of ridges, most of which are radial to the crater, and chains of secondary craters and some blanket ejecta are visible in Figure 8.10(a). Figure 8.10(b), another Catalina Observatory photograph – this one taken on 1966 May 29^{d} 04^{h} 41^{m} UT – shows some of these features to better effect, here the interior of Bullialdus itself being filled with black shadow.

Almost abutting onto the southern rim of Bullialdus is the 26 km Bullialdus A. The rough ground of their shared outer flanks is interesting. Which crater do you think was formed first? The answer to that ought to be fairly obvious but I will leave that as an exercise for you.

With a gap between their rims of very roughly 20 km, Bullialdus B lies a little further south-south-west of Bullialdus A. Bullialdus B is 20 km in diameter. It is instructive to compare the outlines of these smaller craters with that of Bullialdus itself.

Roughly 80 km, or so, to the west-south-west of Bullialdus B we find the similarly sized (23 km diameter) and even more polygonal König. It has a slightly more 'broken down' appearance than Bullialdus A or B. All three share slight central elevations and generally mound-ridden and pock-marked interiors.

North-north-west of Bullialdus is the broken down and lava-flooded crater Lubiniezky. The 44 km diameter walls are completely demolished in the direction of Bullialdus, as is evident in Figure 8.10(a). Also an intriguing bright streak crosses the floor of Lubiniezky, exactly aligned with a similar streak running tangentially to the exterior of Bullialdus. Careful examination reveals this to be the brightest member of a whole pattern of closely spaced parallel light streaks in the locale, but most prominent in the interior of Lubiniezky. As might be expected, the ancient basalt lava covering of Lubiniezky is ridden with craters but most of these pose a challenge to the eyesight of an observer using even a large telescope in excellent conditions.

The upper-right section of Figure 8.10(b) shows a very peculiar formation, known as Wolf. I will leave this as a challenge for you to investigate, along with the ghost ring which is visible near the middle top of the same photograph. A thoroughly fascinating region of the Moon!

8.11 CASSINI [40°N, 5°E] (WITH THEAETETUS)

Cassini is a rather striking crater situated on the Palus Nebularum and at the southern head of the Montes Alpes. The northernmost extent of the Montes Caucasus lies a short distance to the east. The crater is quite conspicuous at all but the highest Sun angles and so it is surprising that it was not recorded by the earliest selenographers. Cassini was the first to record it on his 1692 map. Just in case there should be any doubt, do let me add that there is no suspicion, whatever, of it being a crater only just over three centuries old! Dating the original impact precisely may well be problematical but we are certainly reckoning in billions of years, not mere centuries.

Figure 8.11(a) is a photograph centred on Cassini taken with the 1.5 m reflector of the Catalina Observatory on 1966 September 06^{d} 10^{h} 44^{m} UT, when the Sun's selenographic colongitude was 167°.3. Cassini, itself, is 57 km in diameter and has complex and rather broad outer ramparts. As is obvious from the photograph, the crater has been partially filled with mare-type lavas, presumably during the period of major flooding that filled the Imbrium Basin about 3.3 billion years ago. However, the crater-forming impact might conceivably have come a little after, perhaps resulting in fissuring of the still thin crust under the crater allowing a subsequent upwelling of lavas.

Certainly, though, the floor of the crater is old, and consequently saturated with small craters, together with a few larger examples. The largest of these, Cassini A, is 15 km in diameter and is situated somewhat north of the centre of Cassini. Near the south-western flank of the interior is the 9 km diameter Cassini B. Other floor details include various hummocks and ridges, as well as more, rather smaller, craters. The most delicate of these are a test for an observer with a powerful telescope working under good conditions. A good CCD image of Cassini is shown in Figure 8.11(b). It was taken by Gordon Rogers on 1997 February 15^{d} 00^{h} 49^{m} UT, using his 406 mm *Meade* LX200 catadioptric telescope and *Starlight Xpress* CCD camera.

The nearest major crater to Cassini, of the order of a hundred kilometres to the south-east and nestling close to the western foothills of the

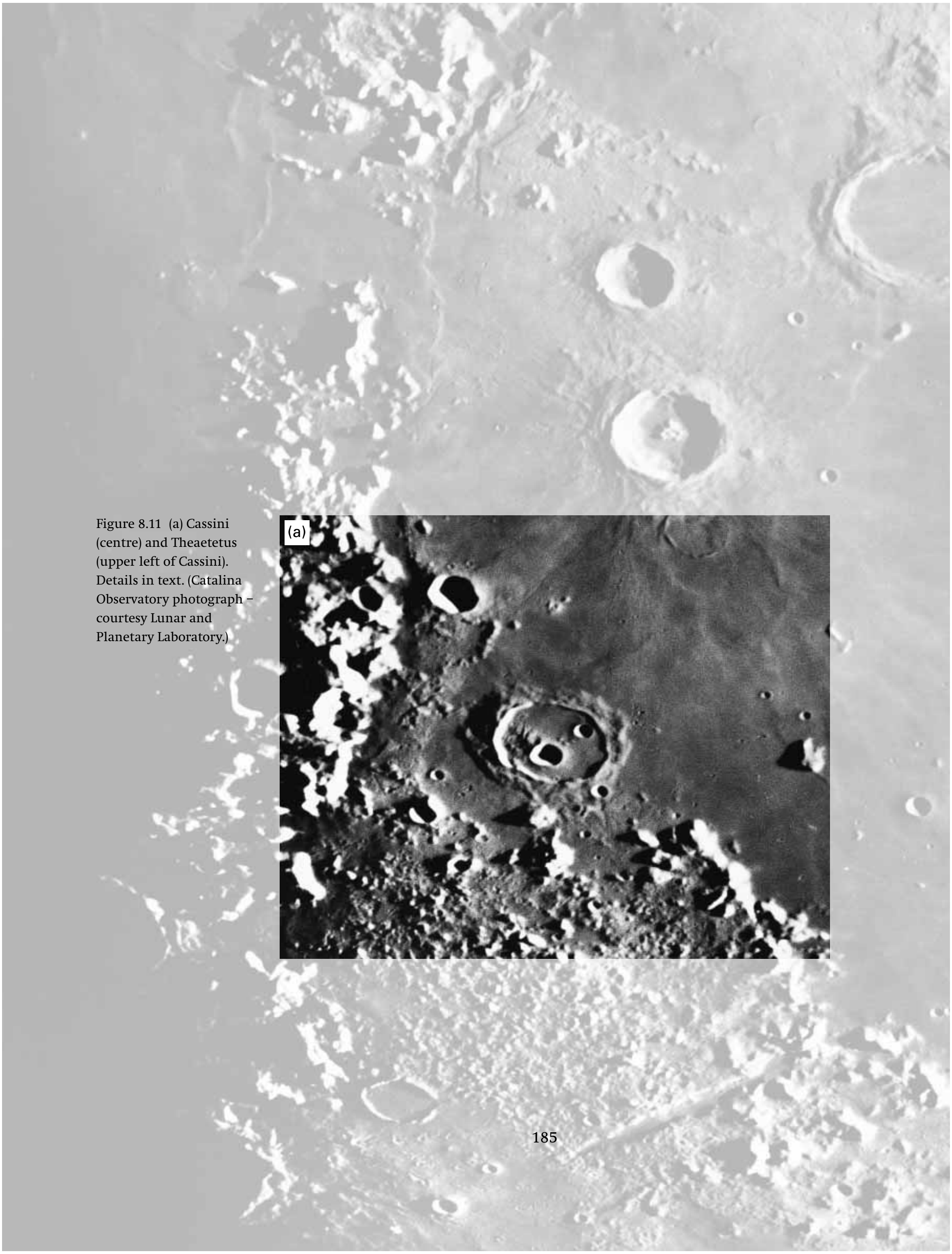


Figure 8.11 (a) Cassini (centre) and Theaetetus (upper left of Cassini). Details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

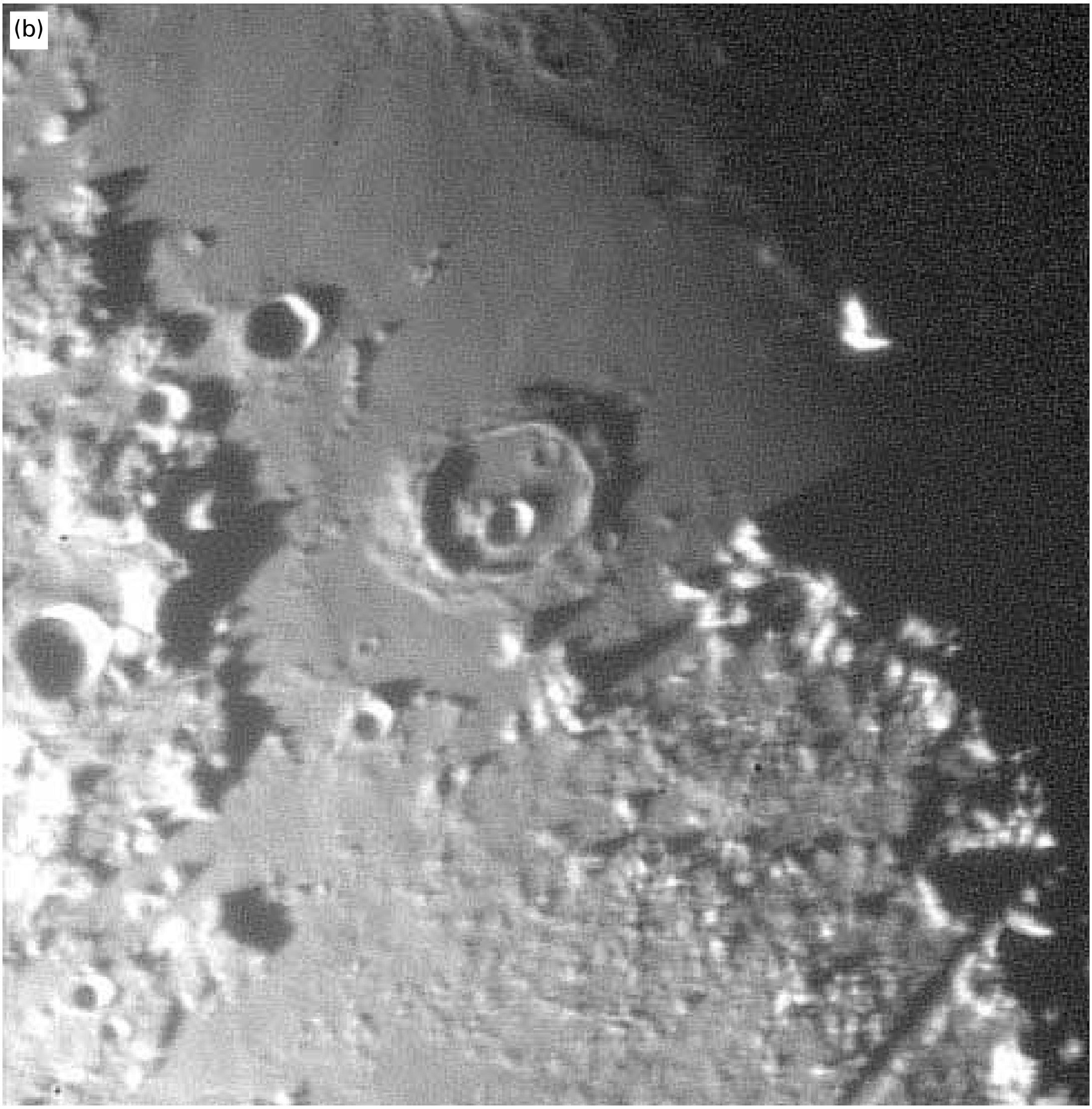


Figure 8.11 (*cont.*)
(b) Cassini – CCD image by Gordon Rogers. See text for details.

Montes Caucasus, is Theaetetus. It is about 25 km in diameter but its outline is obviously rather distorted. The rim of Theaetetus rises some 600 metres above the level of the outer surrounds but the floor of this crater is at a depth of over 2 km below the rim. It possesses a small, rather low, central mound. The terrain to the north and to the east of this crater is highly complex.

The occasional odd appearance has been reported in the vicinity of Theaetetus, by W. H. Pickering and by other observers. In 1902 the French astronomer Charbonneaux, using the 830 mm refractor of the Meudon

Observatory, recorded the formation of a temporary “white cloud” near the crater and in 1952 Patrick Moore, using his 12½-inch (318 mm) Newtonian reflector, saw “a hazy line of light” crossing the otherwise shadow-filled interior of the crater.

8.12 CLAVIUS [58°S, 345°E] (WITH PORTER, RUTHERFURD, CLAVIUS C, D, J, K, L AND N)

A huge formation in the Moon’s southern highlands, Clavius is surely one of the best known and easiest lunar formations to identify. It is a great crater, of the type that used to be called a ‘walled plain’, some 225 km in diameter.

At a lunar phase of about 8–9 days (selenographic colongitude about 17°) it is entirely filled with black shadow. At these times you only need good eyesight, and no optical aid, to see it as a distinct notch in the terminator. Sunrise over the formation is spectacular, with the central regions coming into view first. Andrew Johnson captures something of the grandiosity of the scene in his drawing, which is shown in Figure 8.12(a). This demonstrates that the floor of the crater, though rough and cluttered with detail, does at least follow the general curvature of the Moon’s surface. In fact, it would not be at all obvious to a hypothetical observer stationed within Clavius that he was inside a crater at all. From the centre he could not see the walls and if he was in sight of one wall he could not see its continuation round to the other side of the crater.

Figure 8.12(b) is a Catalina Observatory photograph which shows the formation under a slightly higher Sun angle than the view shown in (a). It was taken with the 1.5 m reflector on 1967 January 20^{d} 01^{h} 52^{m} UT, when the Sun’s selenographic colongitude was 18°.5.

Clavius seems to be of Nectarian age. In other words, it is somewhere around 4 billion years old. Hence it slightly pre-dates the Mare Imbrium and the global flooding of the large basins which formed the lunar maria. However, I would bet that it is slightly younger than Bailly. I will leave you to make a detailed comparison of Bailly and Clavius for yourself.

Although the official classification of a basin is reserved for formations larger than 300 km across, there can be little real doubt that Clavius is just a smaller example of the same. The walls of Clavius rise but little above the outer surrounds. Indeed, to the south they are heavily broken down and here the rim is rather ill defined. This formation is really a great trough sunk over 3.5 km below the outer surface. The nature of the walls vary somewhat going round the crater. From the north and going round to the west the terracing is coarse and broad, becoming narrower and more cliff-like round to the south. The very complicated and hummocky nature of walls bordering the rest of the crater is evident in Figure 8.12(b).

Figure 8.12 (a) Clavius drawn by Andrew Johnson.

Apart from its size, the most striking feature of Clavius must be its interior craters. Starting with the 48 km Rutherfurd (shown on the oldest maps as Clavius A) an arc of craters of decreasing size curves across the floor of Clavius. Clavius D is next, diameter 28 km, then C (21 km), N (13 km), and J (12 km). These are the main ones forming the arc of craters but smaller examples abound, tending to form a closed loop which doesn't quite reach the south-western ramparts of Clavius but curves back towards Rutherfurd. Of course, this closed loop is only approximately circular and is very

Figure 8.12 (*cont.*)
(b) Clavius (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

roughly defined when we are considering the smallest craters. The whole effect is, nonetheless, striking and supporters of the endogenic theories of crater formation made much of Clavius and its interior craters as evidence to support their views. It is not hard to see why.

I find it very difficult to accept that the formation of Clavius's interior craters is the product of purely random impacts. However, I am certainly **not** advocating the abandonment of the impact theory of crater formation! It is just that I think the situation involving Clavius is a little more involved. Could it be that the impactors arrived together and in some sort of formation? That is perhaps not as fantastic as it sounds. One might envisage a partially fragmented asteroidal or cometary body slamming into the already formed great ring of Clavius itself. Having said that, there is one difficulty. The craters show signs of **not** being the same age – at least as regards their ejecta patterns. Clavius D looks to be the youngest. However, the morphology of the area is highly complicated and so the age differences might be illusory. I must here emphasise that the official view is that the arrangement of craters within Clavius is purely a chance one. Whatever the truth, Clavius is certainly not one of the easiest of lunar formations to investigate!

Even if the foregoing idea of a single fragmented body creating the curve of interior craters of Clavius is correct, then Rutherfurd was probably not included in this great event. The reason I say this is that Rutherfurd, unlike the others so far mentioned, shows definite signs of being created by an oblique-angle impact. It has the offset central peak, other interior details, and ejecta pattern (admittedly faint and hard to discern) that suggest a low-angle impact from the south-east. In addition to the details mentioned previously, the interior of Rutherfurd is complex and rather untypical of that of craters of its size. Sets of ridges radiate outwards from the rim of Rutherfurd across part of the floor of Clavius.

While Rutherfurd spans the rim of Clavius to the south-east, Porter does the same in the north-east. At 52 km diameter it is slightly larger than Rutherfurd and is noticeably non-circular. It, too, has a rather complex and hummocky interior and hummocky outer ramparts. On the oldest maps Porter is referred to as Clavius B. Other large craters 'splashed' into the rim of Clavius are Clavius L (diameter 24 km) to the west and Clavius K (diameter 20 km) to the south-east of Clavius L.

One oddity is that the floor of Clavius has some smoother areas, mostly in the east. Perhaps the impact events that created Rutherfurd and Porter are responsible for this. However, could a degree of volcanism have played a part in the early history of Clavius? Spectacular as it is when seen even through the smallest of telescopes, there is much about Clavius that we do not yet fully understand.

8.13 COPERNICUS [10°N, 340°E]

One early example of satire, and surely the only one to involve a heavenly body, must be Riccioli's naming of the lunar crater Copernicus in the seventeenth century. He detested the very idea of the Earth being in orbit around the Sun, as championed by Nicolaus Copernicus a century earlier. So he, in his own words, "flung Copernicus into the Ocean of Storms".

Sited prominently on the expanse of the Oceanus Procellarum as the crater is, Riccioli could hardly be accused of trying to 'bury the opposition'. In fact, now we know that the Solar System really is Sun-centred, it is fitting that one of the most prominent of the lunar formations bears the name of Copernicus. I wonder what Riccioli's reaction would have been if he could have known how his raillery was to so spectacularly backfire!

In their 1874 book *The Moon*, Nasmyth and Carpenter wrote of the crater Copernicus:

> This may deservedly be considered as one of the grandest and most instructive of lunar craters. Although its vast diameter (46 miles) is exceeded by others, yet, taken as a whole, it forms one of the most impressive and interesting objects of its class. Its situation, near the centre of the lunar disc,

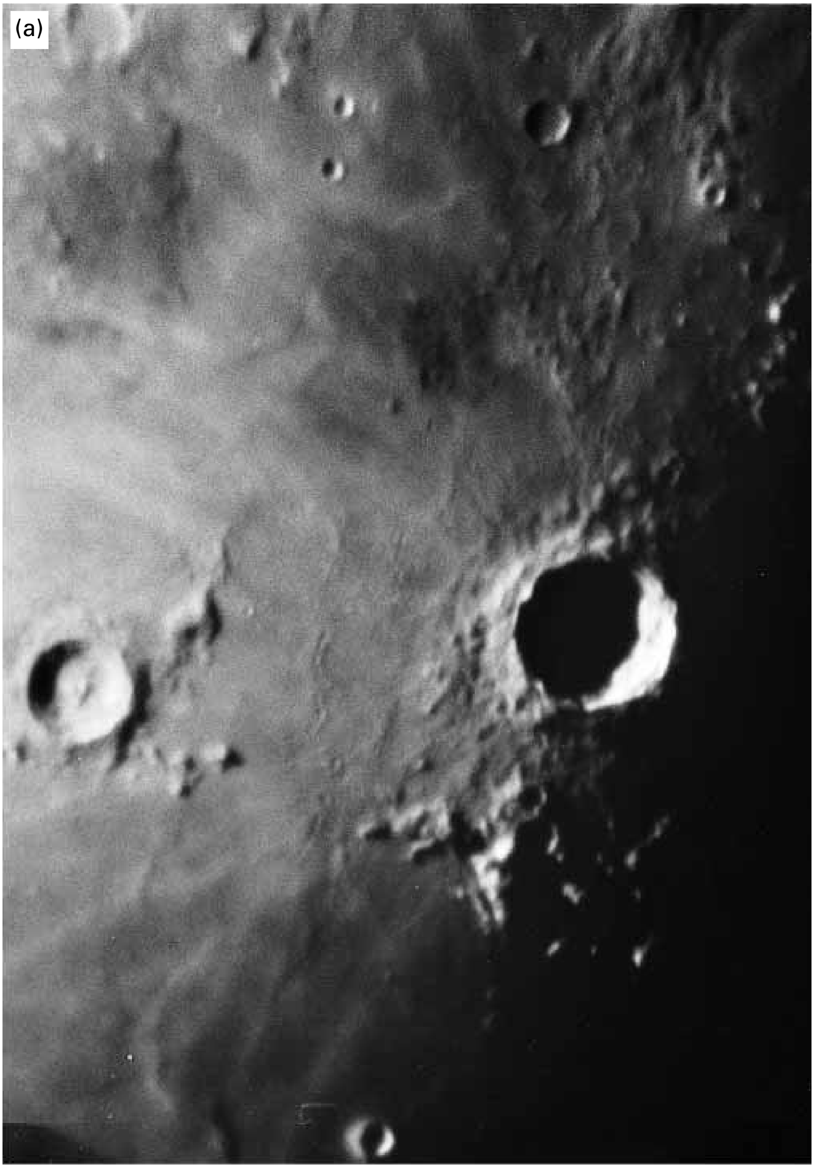


Figure 8.13 (a) Sunrise over Copernicus (the right-hand crater), photographed by Tony Pacey on 1992 February 12^{d} 21^{h} 35^{m} UT, using his 10-inch (254 mm) f/5.5 Newtonian reflector. The image was projected to about f/50, using an eye-piece, onto T-Max 100 film and a 0.5 second exposure given. The film was processed in HC110 developer. The Sun's selenographic colongitude was 22°.3 at the time of the exposure. The crater on the left of the photograph is Eratosthenes, described within Section 8.5.

renders all its wonderful details, as well as those of its immediate surrounding objects, so conspicuous as to establish it as a very favourite object.

Few can disagree with their opinion on the matter. T. G. Elger, the noted observer of the Moon, author of a Moon book, and first Director of the Lunar Section of the British Astronomical Association, christened the crater Copernicus "the Monarch of the Moon".

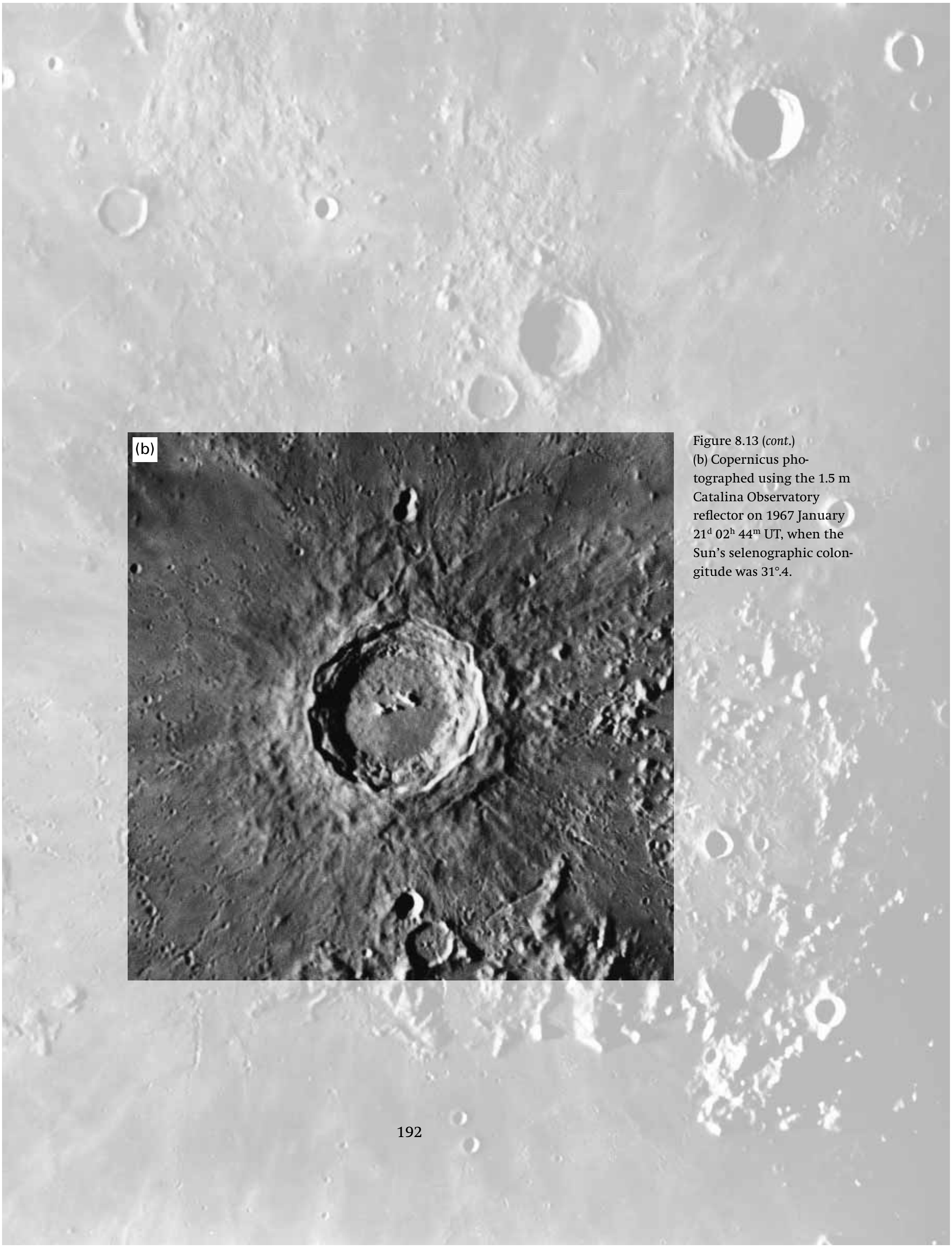


Figure 8.13 (*cont.*)
(b) Copernicus photographed using the 1.5 m Catalina Observatory reflector on 1967 January 21^{d} 02^{h} 44^{m} UT, when the Sun's selenographic colongitude was 31°.4.

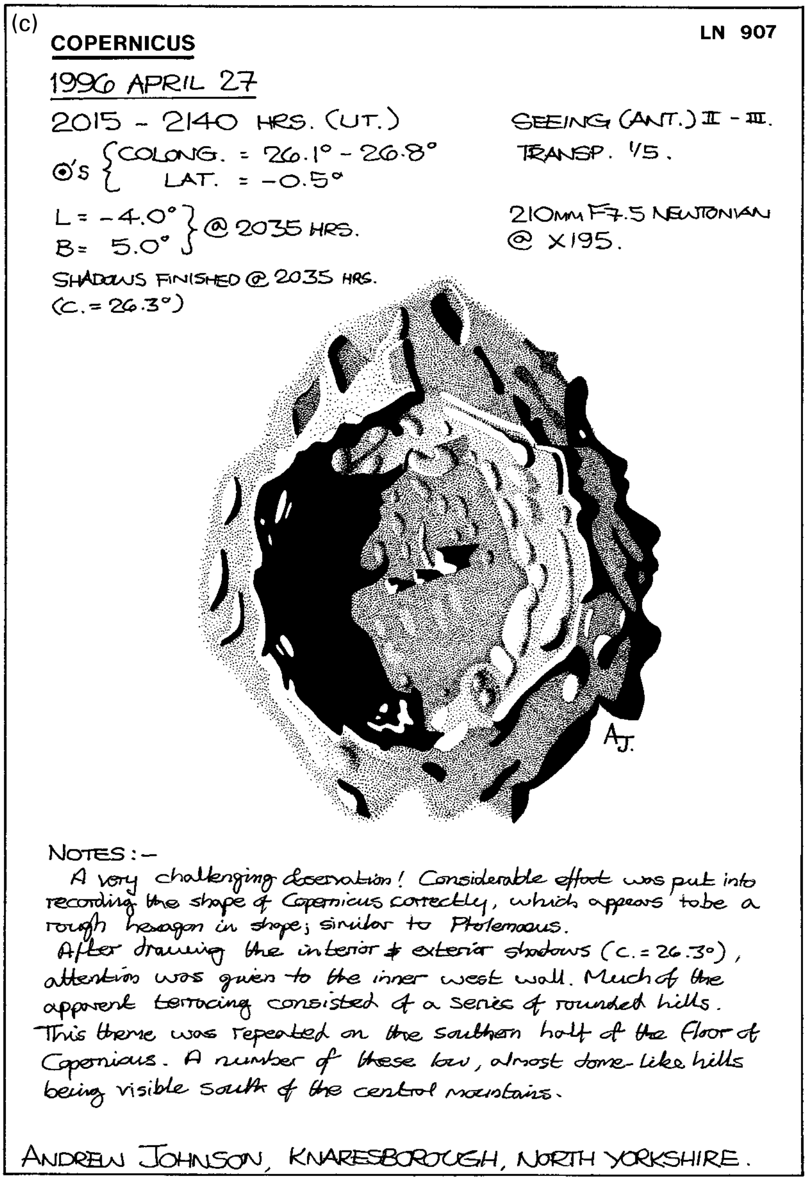


Figure 8.13 (*cont.*) (c) Copernicus drawn by Andrew Johnson.

The modern value for the diameter of Copernicus is 93 km. Just before first and last quarter Moons the crater is entirely filled with black shadow. Figure 8.13(a) shows the Sun beginning to rise over the formation, as photographed by Tony Pacey. More and more of the spectacular interior of this crater is revealed as the Sun rises higher and the shadows retreat to the eastern flanks until views such as that shown in Figure 8.13(b) are displayed.

The first thing to notice is that the outline of the crater is far from being perfectly circular. It consists of roughly linear sections of varying lengths,

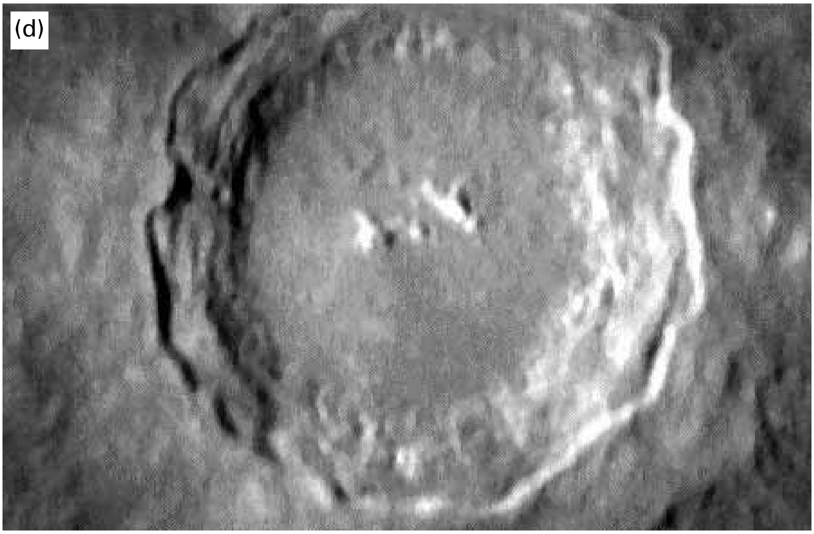


Figure 8.13 (*cont.*)
(d) Copernicus imaged by Terry Platt, using his 318 mm tri-schiefspiegler reflector and *Starlight Xpress* CCD camera (other details not available).

broken again by irregularities on the smaller scale. This polygonal outline is at least approximately carried down towards the crater floor by the complex system of terraces. These were created by the rebounding and interfering shock waves during, and in the immediate aftermath, of the colossal explosion that created the crater (which has been estimated to be of magnitude equivalent to about 20 trillion tons of TNT). The terraces themselves are not the sharply cut steps they appear to be in small telescopes but are somewhat rounded and softened into mounds and ridges. Andrew Johnson represents this appearance in a drawing he made using his 210 mm reflector, and which is shown in Figure 8.13(c).

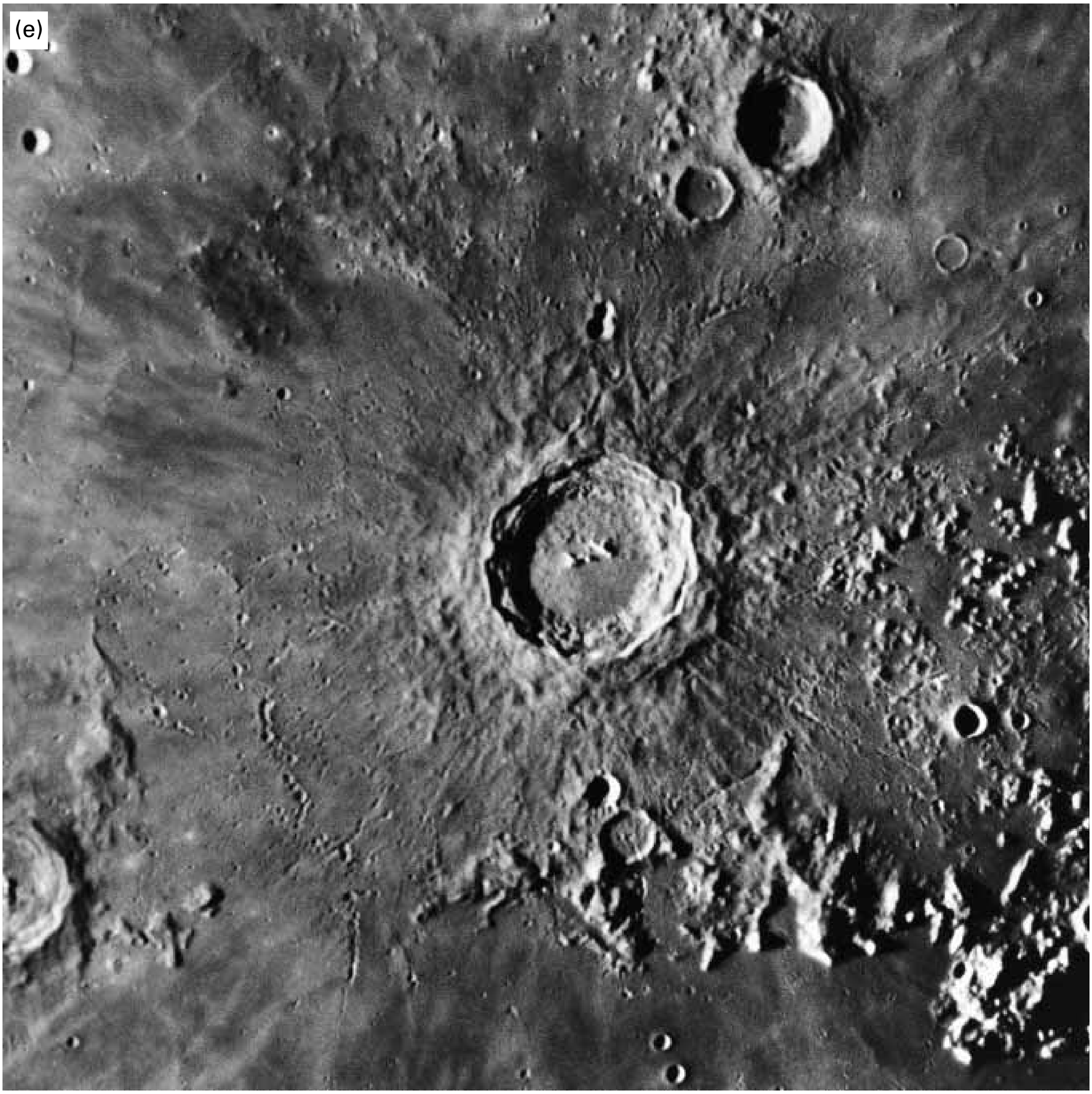
The terracing of Copernicus also shows evidence of some slumping in places. This can best be seen in Figure 8.13(d) which shows one of Terry Platt's incredible CCD images. Note that the Sun angle is higher for this view, revealing more details of the eastern part of the crater interior.

The floor of the crater is an almost circular plain about 62 km in diameter and lies 3.8 km below the crater rim and about 2.9 km below the general level of the outer surrounds. It has a central mountain complex, comprising of several peaks in an arrangement which extends in a roughly east–west direction. The highest of the peaks reaches up about 1.2 km above the crater floor. The southern part of the crater floor is noticeably rougher than the northern section.

The outer slopes of Copernicus are complex, with a chaotic terrain of mounds and radial ridges and crater ejecta. In fact, Copernicus holds a special trophy in that it was the first crater around which secondary craters were depicted (by Cassini in his map of 1680). Look carefully at Figure 8.13(b) and you will see many of the small craters and chains of small craters surrounding Copernicus. These must have been produced by the debris ejected explosively from the impact site during the crater's formation. Figure 8.13(e) provides a wider-angle view. Imagine what it must have been like in the region in the aftermath of that great explosion – blocks of rock and other debris raining down as the seismic shock waves still rumbled through the ground!

It is reckoned that Copernicus was created about 0.8 billion years ago, the time from then to the present day now being known as the *Copernican era* of lunar chronology. The *Apollo 17* astronauts brought back rock samples, including some which are taken to be part of the Copernican

Figure 8.13 (*cont.*)
(e) Wider angle view of (b), showing the extensive pattern of secondary craters which surround Copernicus.



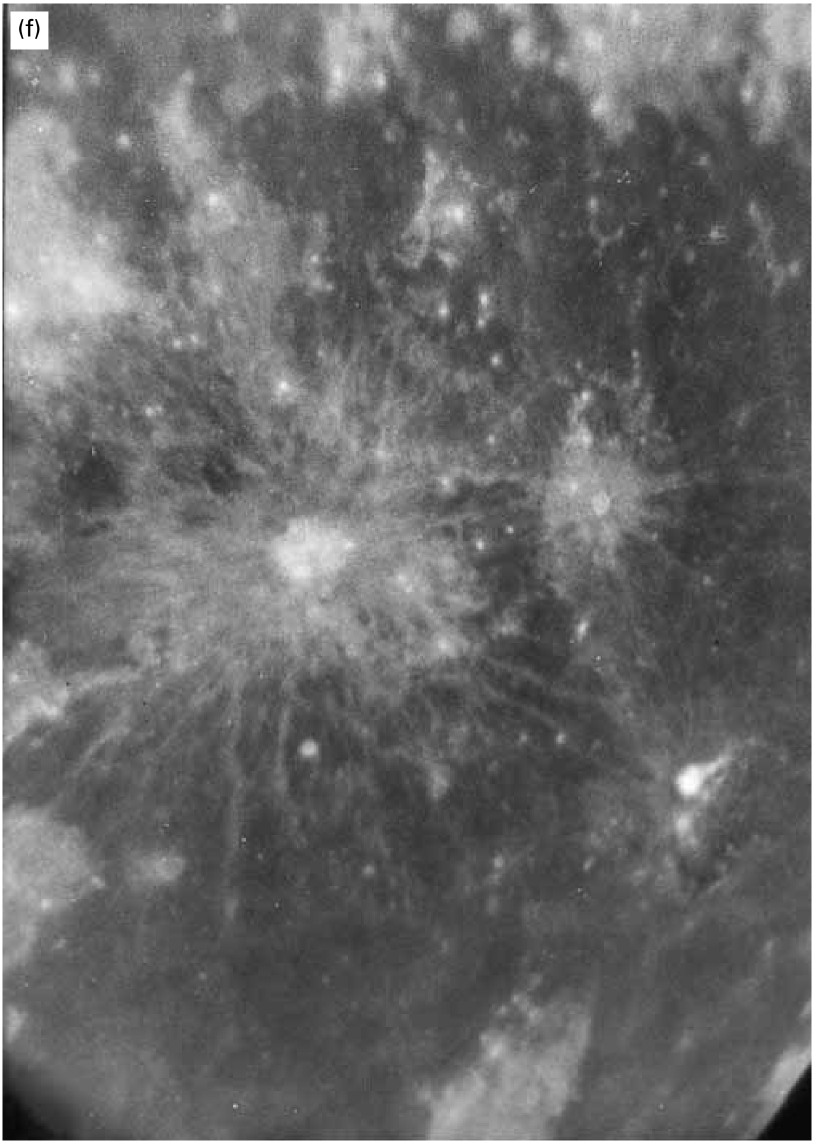


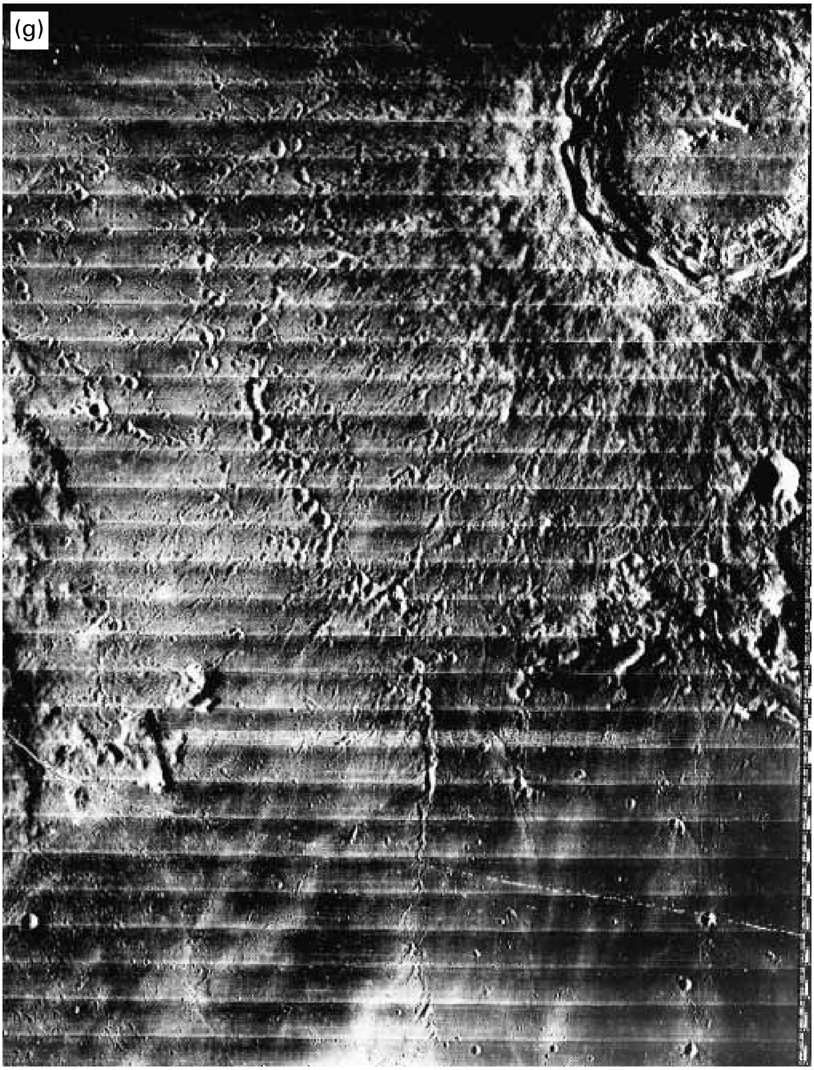
Figure 8.13 (*cont.*)
(f) The ray systems of Copernicus (just left of centre) and Kepler (to the right) show up well in this near full-phase photograph by Tony Pacey, taken on 1991 November 23[d] using his 10-inch (254 mm) Newtonian reflector and eyepiece projection on *Ilford* FP4 film. The bright feature with a comet-like tail, below and a little to the right of Kepler, is Aristarchus.

ejecta blanket. If these have been correctly identified then we can be even more precise with our dating of Copernicus. Laboratory analysis of these rocks suggest an age of 810 million years.

Large craters of similar ages as Copernicus, and younger, tend to have bright interiors and possess ray systems. The ray system associated with Copernicus is the second most prominent and extensive on the Moon.

While traces of the rays can be faintly seen at all but the lowest Sun angles, the rays really only become very prominent around the time of full Moon. Figure 8.13(f) shows a wide-angle view of the Copernican ray system

Figure 8.13 (*cont.*)
(g) *Orbiter IV* photograph of Copernicus and its environs to the north-east, showing the inner part of the ray system and the ejecta pattern of secondary craters. (Courtesy NASA and Professor E. A. Whitaker.)



under a high Sun. The photograph, obtained by Tony Pacey using his 254 mm reflector, shows that the interior of the crater is brighter than the rays. These are wispy and plume-like, unlike the longer and straighter rays of Tycho (the premier rayed crater, discussed in Section 8.46). The whole ray system is very confused with many ray components not being exactly radial to the centre of the crater. Some rays even meet the crater rim tangentially. The confusion is compounded by the Copernican ray system merging with the rays emanating from the crater Kepler to the west of Copernicus.

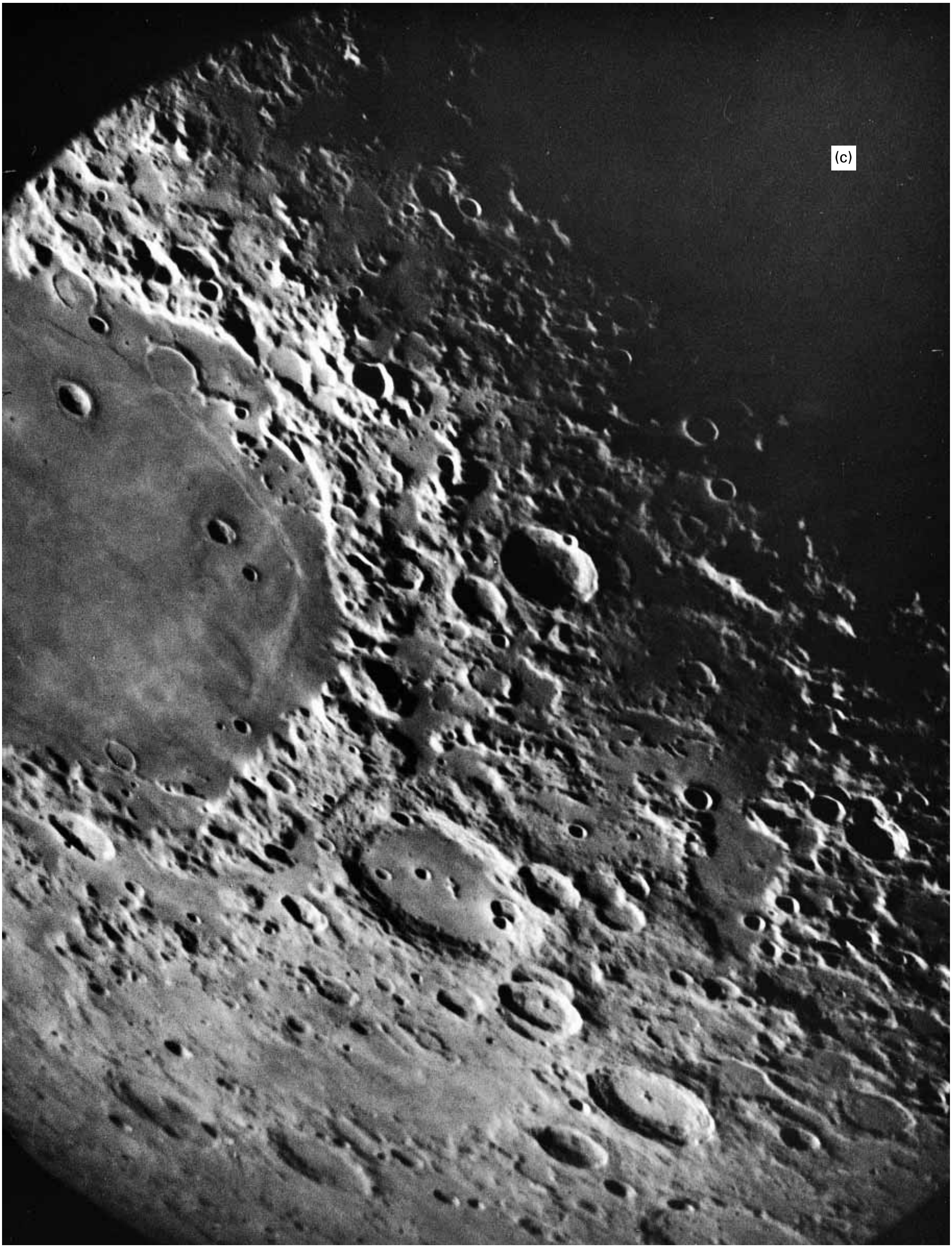
Figure 8.13(g) shows an *Orbiter IV* photograph of Copernicus with the inner part of its ray system and the secondary craters in the quadrant to the north-east of the crater.

8.14 CRISIUM, MARE [CENTRED AT 17°N, 59°E] (WITH CLEOMEDES, LICK, PEIRCE, PEIRCE B, PICARD, PROCLUS, YERKES)

Easily visible to the naked eye as a dark patch near the Moon's north-east limb, the Mare Crisium also tends to grab the attention of the telescope user. This is especially the case when the terminator begins to cross it a little after full Moon (see Figure 8.14(a)). In part, this is because it is completely detached from the main system of lunar maria. It is reckoned that the Crisium Basin was formed about 3.9 billion years ago and the main episode of lava flooding occurred a few hundred million years after that.

Figure 8.14 (a) Evening falls over the Mare Crisium. Below the mare is the prominent large crater Cleomedes. Just to the right of the mare is the brilliant small crater Proclus, with its asymmetric ray system. Photograph by Tony Pacey, taken using his 10-inch (254 mm) f/5.5 Newtonian reflector on 1992 January $22^{d}\ 00^{h}\ 05^{m}$ UT, when the Sun's selenographic colongitude was 115°.7. The image was projected by eyepiece to approximately f/50 onto Ilford FP4 film for this 0.5 second exposure.

Figure 8.14 (*cont.*)
(b) The western section of the Mare Crisium. Same details as for Figure 8.1 (see text, page 156). The largest crater on the mare, here on the left, is Picard. To the upper right of Picard is the incomplete ring of the flooded crater Lick (with a small, well-formed crater immediately below it). The even less complete Yerkes lies on the border of the mare to the right of Picard. To the lower right of Picard are Peirce (the larger crater) and Peirce B. To the west of the mare (and to the middle right on this photograph) is the brilliant Proclus, with its prominent and highly asymmetric ray system. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)


(c)

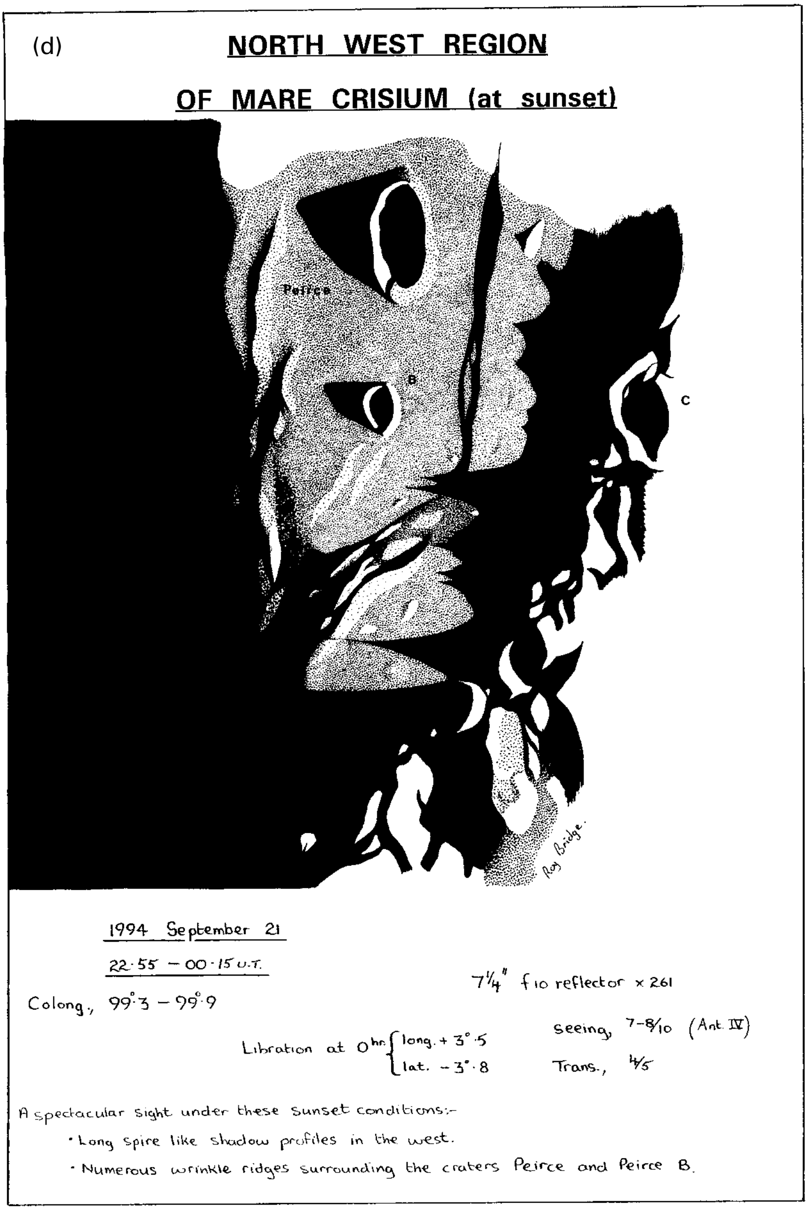
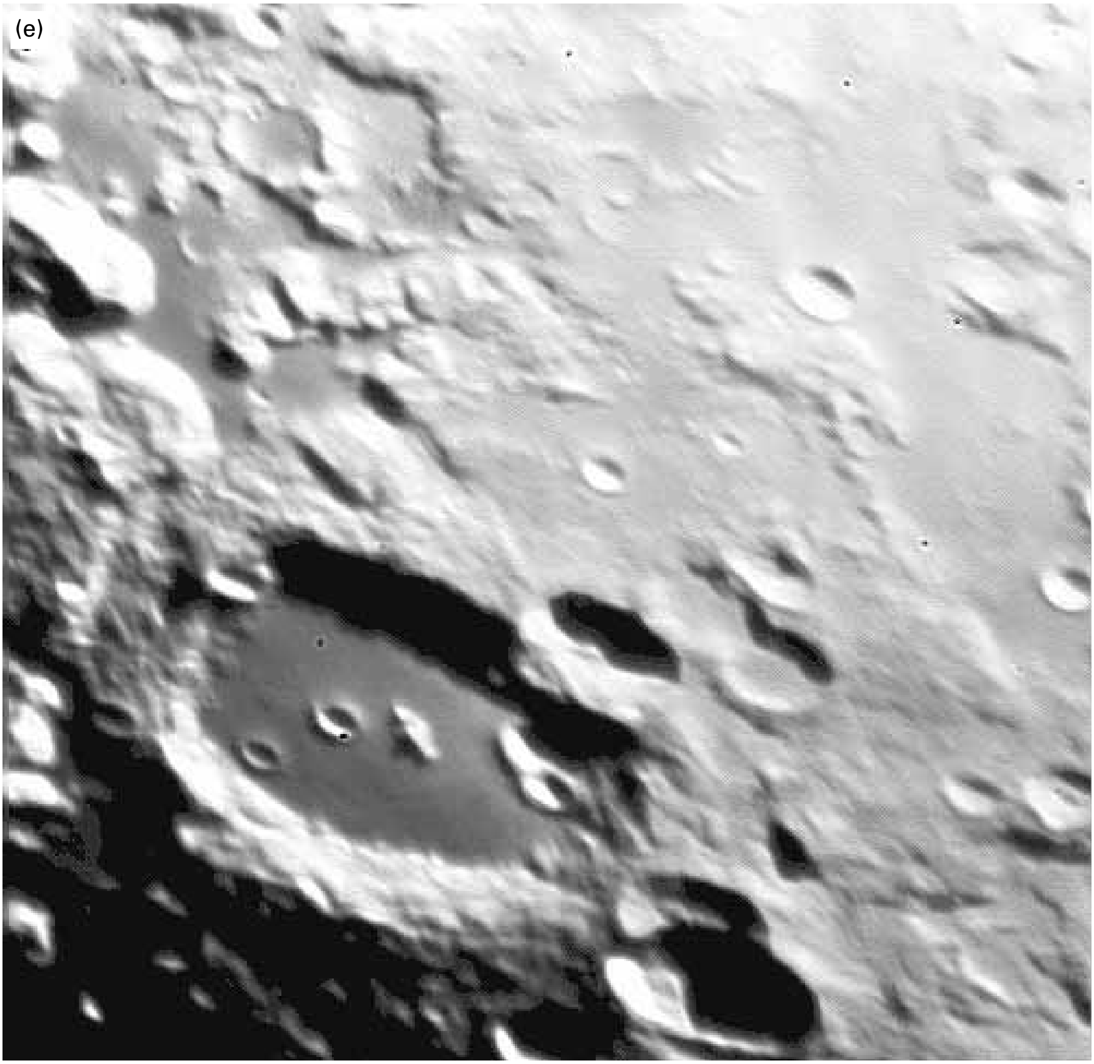


Figure 8.14 (*cont.*)
(c) The northern to the western regions of the Mare Crisium photographed with the 1.9 m reflector of the Helwan Observatory at Kottamia on 1965 August 1^{d} 20^{h} 39^{m} UT (Sun's selenographic colongitude 311°.1). Lower right of the mare is the prominent crater Cleomedes. The 'flying eagle' effect of Yerkes is particularly apparent here. (Reproduced with the kind permission of Dr T. W. Rackham.)
(d) Peirce and Pierce B drawn by Roy Bridge.

The basaltic covering probably extends to about 1 km deep at the middle of the mare, this being the deepest point of the Crisium Basin.

Though the Mare Crisium looks very elliptical and longest in the north–south direction, the appearance is deceptive because of the foreshortening near the limb. Actually it is rather hexagonal (more than truly elliptical) in outline – and it is extended in the east–west direction (570 km,



against its north–south diameter of 450 km)! Clearly the impactor that created the Crisium Basin hit the surface at a very low trajectory.

The south-eastern sector of the Mare Crisium is notable for the Promontorium Agarum, and this is described in Section 8.1 (and shown in Figure 8.1), earlier in this chapter. Figure 8.14(b), reproduced here, shows much of the western half of the mare. The details are the same as for the photograph in Figure 8.1 (see text, page 156). The northern half of the Mare Crisium is well shown in Figure 8.14(c), which is a photograph taken with the 1.9 m reflector of the Helwan Observatory at Kottamia in Egypt.

Figure 8.14 (*cont.*)
(e) Cleomedes is the large crater near the bottom of this CCD image taken by Gordon Rogers on 1996 November 27^{d} 23^{h} 46^{m} UT. He used his 16-inch (406 mm) *Meade* LX200 telescope and *Starlight Xpress* CCD camera. The Sun's selenographic colongitude was 107°.2.

Numerous odd appearances have been reported at various locations in the mare, especially near the Promontorium Agarum (see Section 8.1). These have usually been instances of apparent mistiness obscuring details. However, local changes of albedo with Sun angle are probably the real cause of these. It also used to be said that Mare Crisium shows a very strong green tint to observers, more so than the other lunar seas. However, I have never seen the greenish tint to be any stronger than elsewhere. In my opinion the strongest mare colouration is that of Mare Tranquillitatis, which often looks an inky blue to my gaze. Do let me repeat, though, that the real colours of the Moon are various shades of brown. The observer's eye tends to normalise the overall colour as white, so producing the range of apparent tints actually observed.

Various mottled patches, light spots and streaks abound on the mare and some wrinkle ridges show up under the lowest angles of illumination. The largest crater on the mare is the 23 km diameter Picard. It has a sharp rim and a small central mound on the deepest part of its floor, which lies about 2.4 km below the rim.

South-west of Picard, against the coastline of the mare, is the remnant of an old flooded crater named Lick. Further along the shoreline, and to the west of Picard, lays another broken partial ring, Yerkes. With the raised ridge that joins the surviving wall of Yerkes to a small crater, the whole forms an effect that has been aptly nicknamed 'the flying eagle'. Figure 8.14(c) shows this appearance particularly well.

Going approximately northwards from Picard, Peirce is the next largest of the well-formed craters on the Mare Crisium. It is almost as deep as Picard, despite its much smaller diameter (19 km). Again of similar depth, though even smaller, is Peirce B, just to the north of Peirce. On older maps Peirce B is referred to as Graham, or sometimes Peirce A. The IAU-approved designation is Peirce B. Peirce and Peirce B can look extremely dark under early morning illumination, as is well shown in Figure 8.14(c). Compare their appearance with the views shown in Figure 8.14(a) and (b). An impressive drawing of their appearance under late evening illumination is shown in Figure 8.14(d).

About 70 km west of the western shore of the Mare Crisium resides the 28 km diameter, but rather polygonal, crater Proclus. The early morning view in Figure 8.14(c) shows its shape well. However, under a high Sun the crater becomes one of the most brilliant on the Moon and its structure is then much harder to make out; see Figure 8.14(b) for comparison. At these times it also possesses a very bright system of rays, as can be seen on Figures 8.14(a) and (b). The ray pattern is very asymmetric. Faint rays do cross onto the Mare Crisium but mostly they extend towards the north-west.

Proclus, and particularly its rays, often takes on a distinctly yellowish colour but this is mainly due to spurious colour (the prismatic effect due to the Earth's atmosphere that often produces false colours along brightness boundaries in the images of celestial bodies as seen through telescopes).

Lunar north of the Mare Crisium (north-west as far as the orientation as seen in a telescope goes) lies the magnificent crater Cleomedes. About 100 km of rough ground separates the peculiarly straight section of the border of the mare from the rim of Cleomedes. Cleomedes is very deep. The roughly terraced walls in places plunge more than 2.7 km down to the convex floor of the crater. It contains several interior craters and other features of interest to the telescope user. The crater is well shown in Figure 8.14(c). Figure 8.14(e) shows it under the opposite lighting effect.

8.15 ENDYMION [54°N, 57°E] (WITH ATLAS, ATLAS A, BELKOVICH, CHEVALLIER, HERCULES, MARE HUMBOLDTIANUM)

The limb regions of the Moon offer a challenge to the observer because all details are distorted by foreshortening. The dimensions are only what they seem to be along arcs concentric with the limb of the Moon. Maximum contraction occurs along lines which are radial to the centre of the Moon's disk and the effect increases rapidly with proximity to the limb.

To compound matters, librations often conspire to move formations even closer to the limb just when the sky is clear and the lighting would be suitable over the chosen formation for studying it. On the other hand, librations can sometimes help by moving limb features further on to the Moon's Earth-facing side. One just has to make the best of the opportunities that arise.

The crater Endymion serves as a fairly prominent marker to some limb-hugging formations of particular interest. It is an old ring, 125 km in diameter, with a rather smooth and dark floor, it having been flooded with mare-type basalts. Endymion is shown at the centre of Figure 8.15(a). Before its flooding the crater must have been quite deep. As it is, the walls rise to over 4.5 km above the present flood-plain. Various spots and streaks are visible on the crater floor but any surface relief (craters, etc.) is very difficult for the backyard observer to detect. Figure 8.15(b) is a superb CCD image of Endymion, by Gordon Rogers, in which the shadows cast by the rugged peaks of the crater rim are seen thrown across the crater floor.

A spectacular pairing of craters, Atlas and Hercules, lie to the south-west of Endymion. They are well shown upper right in Figure 8.15(a) and

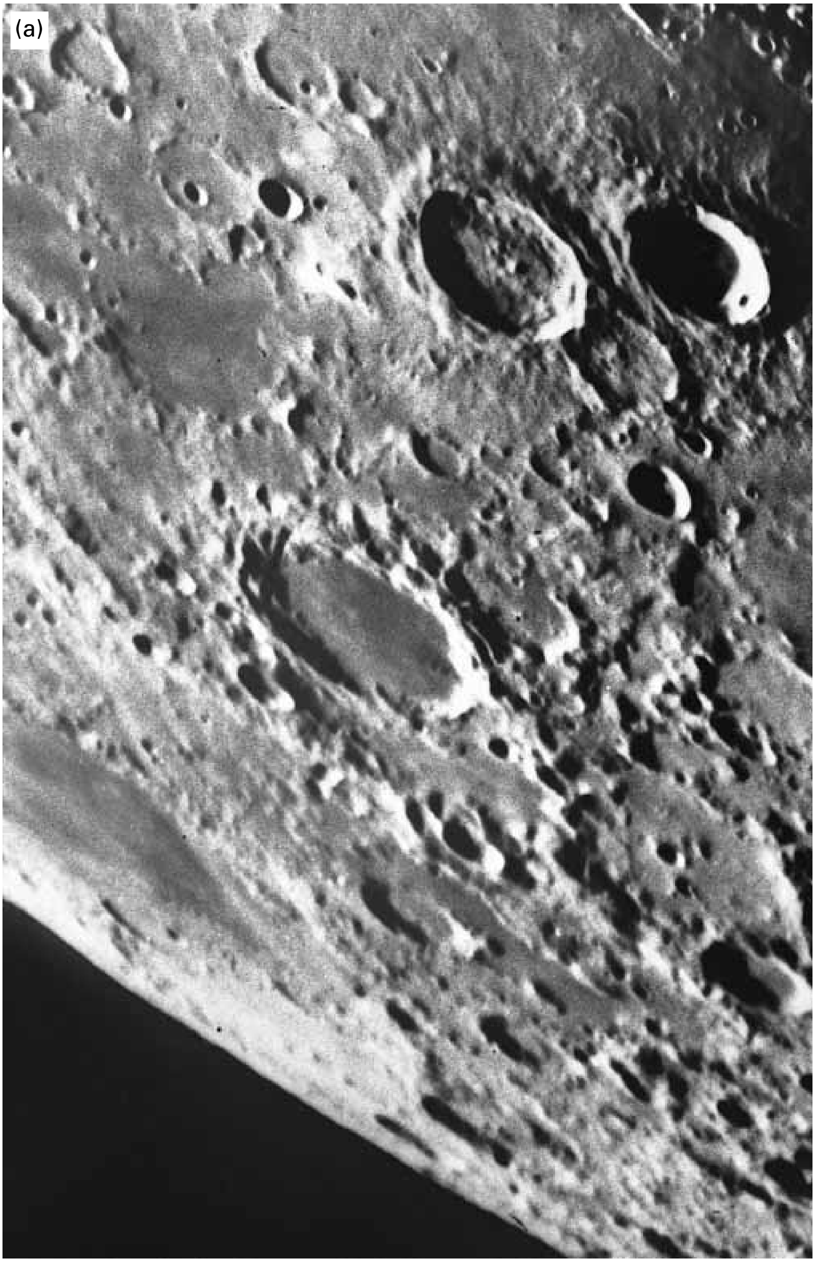
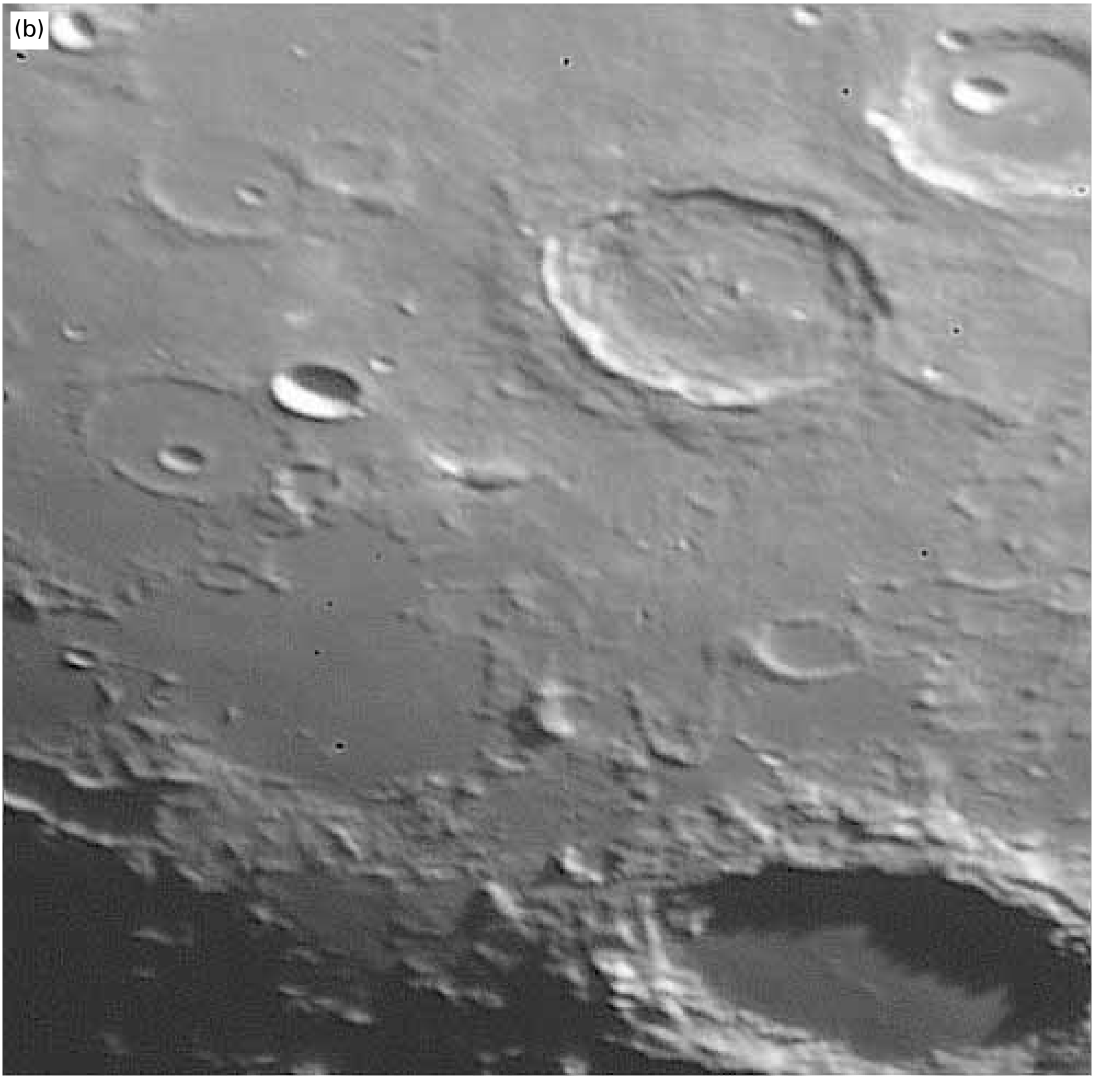


Figure 8.15 (a) Endymion lies near the centre of this Catalina Observatory photograph. It was taken with the 1.5 m reflector but I can't give the date, time and exact colongitude (though I estimate this to be about 38°) as the data are not available. The craters Atlas and Hercules are to the upper right (with Atlas A and Chevallier to their left). Part of the Mare Humboldtianum can be seen near the lower left and the crater Belkovich can (with difficulty) be identified in the lower middle of the frame. (Courtesy Lunar and Planetary Laboratory.)



in the upper part of Figure 8.15(b). The larger of the two is Atlas, at 87 km diameter. Its rim averages about 3 km in height above the deepest part of the crater, near its centre. As is well shown in Figure 8.15(b), the floor is very rough and hummocky and it has a ring of mountains at its centre, rather than a central peak. Numerous fissures and small craters can be seen under particularly good conditions if one is using a powerful telescope.

Hercules is 69 km in diameter and it is obviously older than Atlas, having walls which are clearly broken down to a greater degree. Various

Figure 8.15 (*cont.*)
(b) Endymion (lower-right corner), Chevallier, Atlas A, Atlas and Hercules (extending from middle left to upper right) are shown on this image made by Gordon Rogers using his 16-inch (406 mm) *Meade* LX200 telescope and *Starlight Xpress* CCD camera on 1996 November 28^{d} 00^{h} 50^{m} UT, when the Sun's selenographic colongitude was 107°.7.

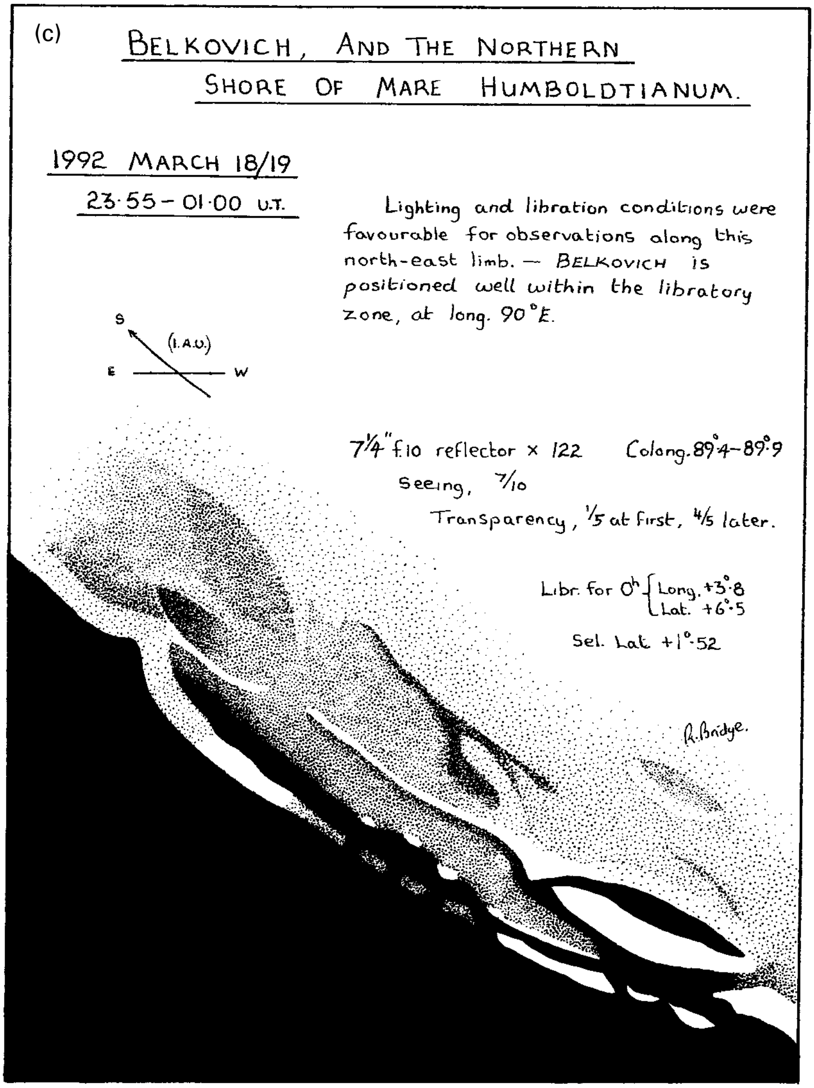


Figure 8.15 (*cont.*) (c) Belkovich and northern Mare Humboldtianum drawn by Roy Bridge.

landslips in the terraces also become evident when the lighting is correct and I wonder how much of the damage we see today was caused by the impact which gave rise to the nearby Atlas? The floor of Hercules is more heavily covered with larger craters than that of Atlas, another indicator of its greater age.

If you take a look at Figure 8.15(a) and project a line from the upper part of the rim of Hercules, head it towards the upper part of Atlas and continue it on for a distance roughly equal to the diameter of Atlas you will come to a small but prominent well-formed crater. This is Atlas A, which is 22 km in diameter. Immediately to the left of Atlas A is a 'ghost ring' crater – one that has been flooded almost up to its rim. This is the 52 km diameter Chevallier. Note the small crater within Chevallier, obviously post-dating the episode of flooding.

In fact, it probably strikes you that this is an area of the Moon which shows extensive evidence of mare-type flooding. This characteristic is very evident in Figure 8.15(b). Yet this area in not actually on a lunar sea. The Mare Frigoris and Lacus Mortis are nearby, though, and the demarcation between lunar maria and lunar terrae is here rather less definite than in most other places.

The extreme limb features, first referred to, are the Mare Humboldtianum and the crater Belkovich. Mare Humboldtianum was named by Mädler, with a sense of appropriateness, after the German explorer Alexander von Humboldt. Humboldt's discoveries spanned, and you could say linked, the eastern and western hemispheres of the Earth.

Mare Humboldtianum is one of the smaller of the lunar 'seas'. Its diameter averages about 260 km but its shape is decidedly irregular when seen in plan view. Belkovich attaches to it on the north-western side. It is an old crater (of what used to be called the 'walled plain' variety), 198 km diameter, with two large craters intruding into its walls on the west and a further flooded ring on the eastern flank (and spanning the connection to the mare). The northern part of the mare is shown on the lower left of Figure 8.15(a) and Belkovich can be made out almost attaching to the mare's northernmost section. Neither are well shown, despite the very favourable libration when this Catalina Observatory photograph was taken. Roy Bridge has made a valiant effort to draw these features and the result is shown in Figure 8.15(c). If you relish a challenge, you might like to try recording this very difficult area yourself.

8.16 FRA MAURO [6°S, 343°E] (WITH BONPLAND, GUERICKE, PARRY)

This area of the Moon lies a little beyond the north-west border of the Oceanus Procellarum and on older maps occupied part of the Mare Nubium. However in 1964, after the successful flight of *Ranger 7*, the area was re-named Mare Cognitum (the Known Sea). *Ranger 7* transmitted the first close-range photographs of a lunar mare before it was deliberately crashed in this section of the mare. Officially the Mare Cognitum extends out to an average radius of 170 km centred on a position 10°S, 337°E.

Several spacecraft have either been deliberately crashed or have soft-landed in this area. In particular, the *Apollo 14* astronauts Alan Shepard and Ed Mitchell landed in the foothills less than 30 km to the north of the northern rim of the great crater Fra Mauro (see Chapter 6 for more details).

Figure 8.16 (a) Fra Mauro is the largest crater in the lower right section of this Catalina Observatory photograph, taken on 1966 May 29^{d} 03^{h} 51^{m} UT (at a colongitude of 22°.2) with the 1.5 m reflector. The two craters attached to the upper part of Fra Mauro are Parry (on the left) and Bonpland. The largest crater in the upper-left section of this photograph is Guericke. (Courtesy Lunar and Planetary Laboratory.)

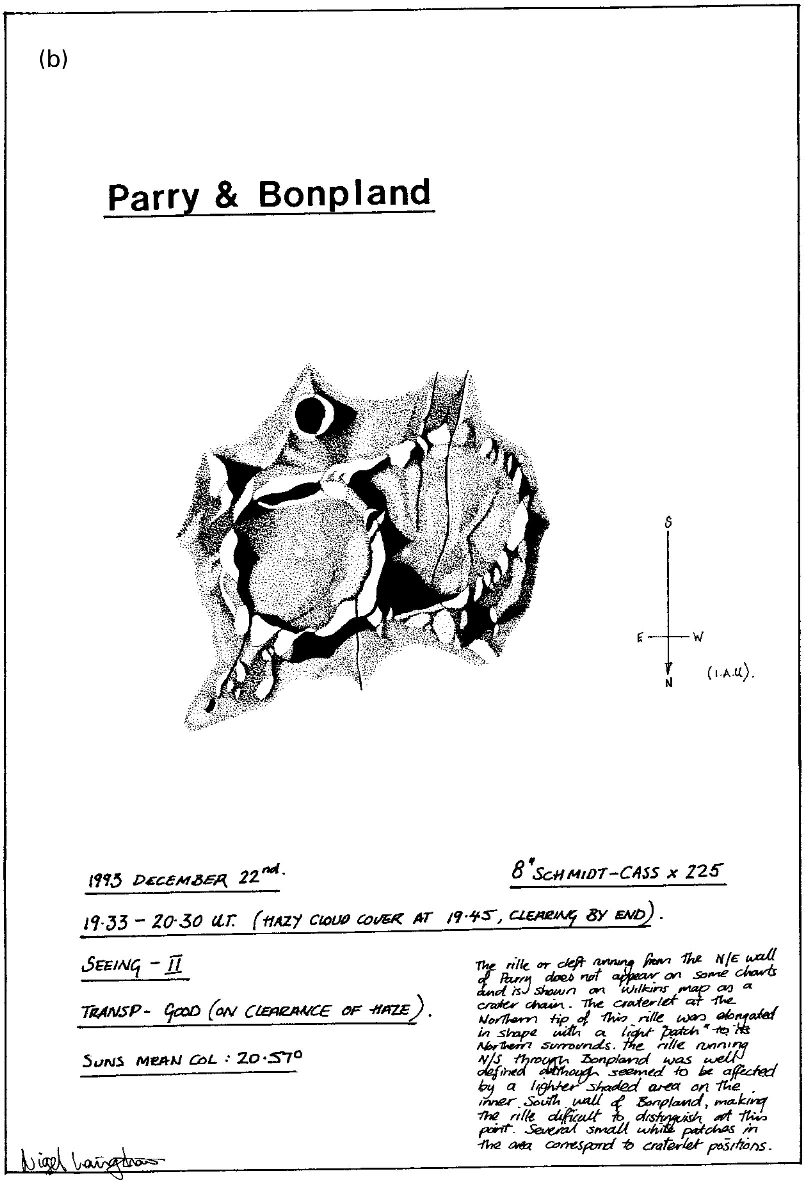


Figure 8.16 (*cont.*)
(b) Parry and Bonpland, drawn by Nigel Longshaw. Necessarily being reduced in size for reproduction in this book, some of the hand-written notes are too small to read easily. The block of descriptive text reads (with no editing by me): *The rille or cleft running from the N/E wall of Parry does not appear on some charts and is shown on Wilkins' map as a crater chain. The craterlet at the northern tip of this rille was elongated in shape with a light 'patch' to its northern surrounds. The rille running N/S through Bonpland was well defined although seemed to be affected by a lighter shaded area on the inner south wall of Bonpland, making the rille difficult to distinguish at this point. Several small white patches in the area correspond to craterlet positions.*

Whenever I look at the area north of Fra Mauro through a telescope I can never help but imagine them scuttling about 'down there', wheeling their Modular Equipment Transporter ('handcart', to you and me) all those years ago.

The Imbrium ejecta blanket is very evident in this region of the Moon and the patterns of ridges and scarring, radial to the Imbrium Basin, are

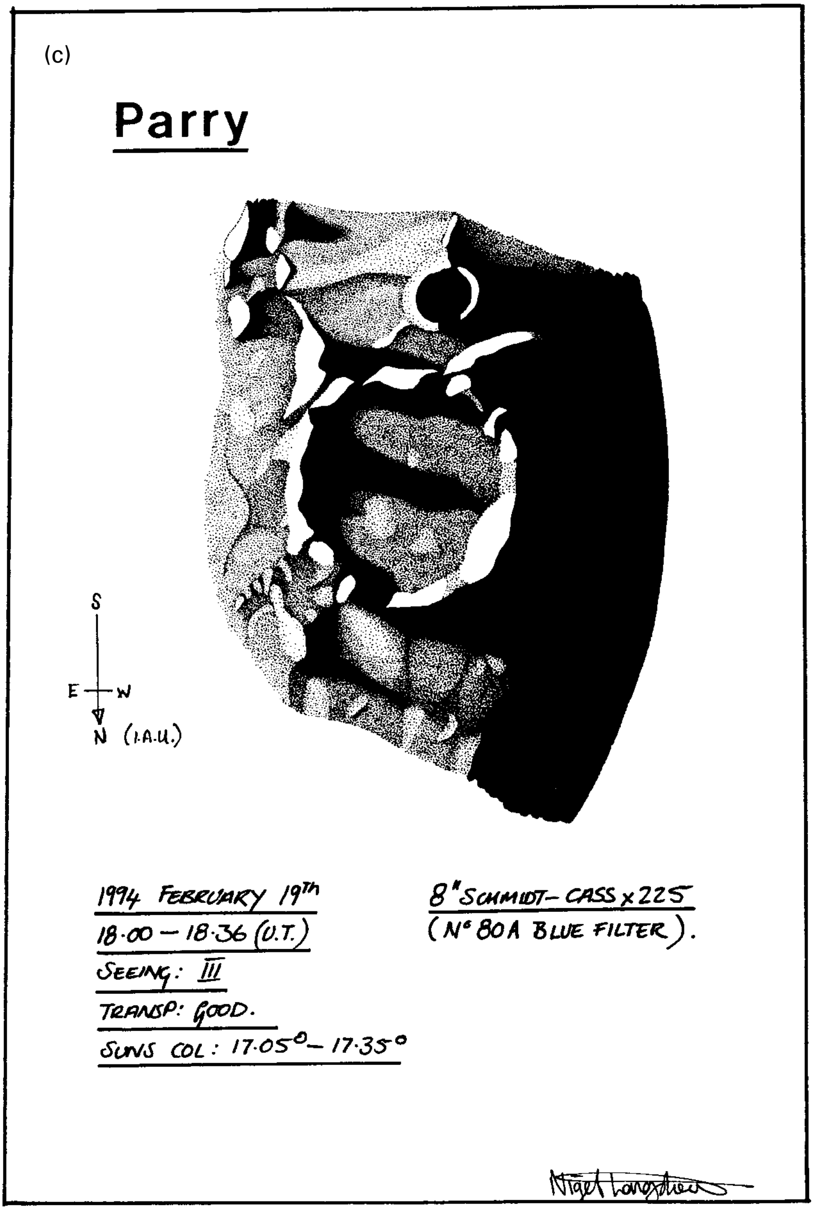


Figure 8.16 (*cont.*)
(c) Parry, drawn by Nigel Longshaw.

obvious even through small telescopes. Spacecraft results show this area to be very rich in *KREEP* (see Chapter 6), being one of the main 'hot spots' in gamma-ray maps.

Fra Mauro, itself, is 95 km in diameter. As can be seen from Figure 8.16(a), it is an old, ruined and flooded, 'ring-plain'. A section of the wall to the east is completely missing. The floor is extensively cratered and ridged,

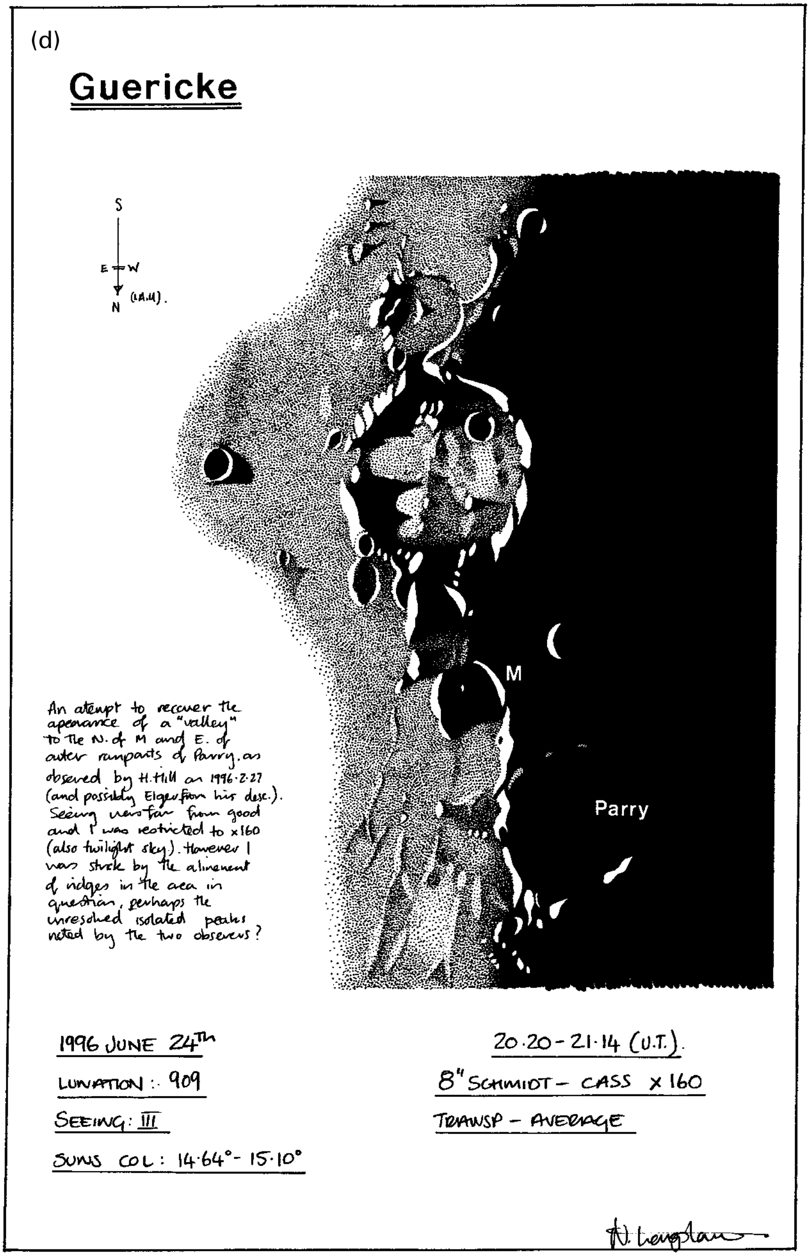


Figure 8.16 (*cont.*)
(d) Guericke, drawn by Nigel Longshaw. The block of descriptive text reads: *An attempt to recover the appearance of a 'valley' to the N. of M and E. of outer ramparts of Parry as observed by H. Hill on 1996.2.27 (and possibly Elger from his desc.). Seeing was far from good and I was restricted to ×160 (also twilight sky). However, I was struck by the alignment of ridges in the area in question, perhaps the unresolved isolated peaks noted by the two observers?*

mostly in the roughly north–south direction in common with the radial ejecta pattern from the Imbrium Basin. Another two ‘ring-plain’ craters attach to Fra Mauro: Bonpland and Parry.

Bonpland is the larger of the two, at 60 km diameter, and shares its rim with that of Fra Mauro along the southern section of the latter. Although Bonpland superficially looks older (more degraded) than Fra Mauro, a close examination of the shape of the augmented rim at the intersection, suggests the opposite. In turn both Fra Mauro and Bonpland have been intruded upon by the still younger Parry. Parry is 48 km in diameter. The grouping is well shown in Figure 8.16(a) and in the special studies by Nigel Longshaw in Figures 8.16(b) and 8.16(c).

To the south-south-east of the ‘Fra Mauro trio’, and separated from them by about 100 km of very interesting terrain, is another ancient relic of a crater: Guericke. It has a diameter of 64 km. It, too, is well shown in Figure 8.16(a). Figure 8.16(d) is another of Nigel Longshaw’s splendid drawings.

Rather than me providing all the intricate details of this very interesting area of the Moon, I thought I would leave this as a project for you. With the features generated by the Imbrium Basin event 3.85 billion years ago as a ‘time marker’, you might like to have a go at ‘untying the temporal knot’ and reconstruct the sequence of events which generated the features we see today.

The Fra Mauro region of the Moon may not be the most attention grabbing when one is looking through the telescope eyepiece but it more than makes up for that if one is prepared to really study the small details.

8.17 FURNERIUS [36°S, 60°E] (WITH FRAUNHOFER, FURNERIUS B, FURNERIUS J, PETAVIUS)

Furnerius is the southernmost member of what used to be called “the great western chain of craters”. This was before the IAU reversed east and west on the Moon, so we might now call the arrangement ‘the great eastern chain’. All lying on virtually the same meridian, the ‘chain’ comprises the craters Furnerius, Petavius, Vendelinus and Langrenus, with the Mare Crisium also included and the crater Endymion to the north of the Mare Crisium (Cleomedes is a little further from the shared meridian than the other members). This ‘chain’ was used as evidence that craters were distributed in definite patterns, rather than randomly, and so must be of endogenic rather than impact origin.

The evidence for the impact scenario is so overwhelming that it surely must be the correct one (though a few individuals still support the endogenic scheme). However, ‘the great eastern chain’, as I propose to call it,

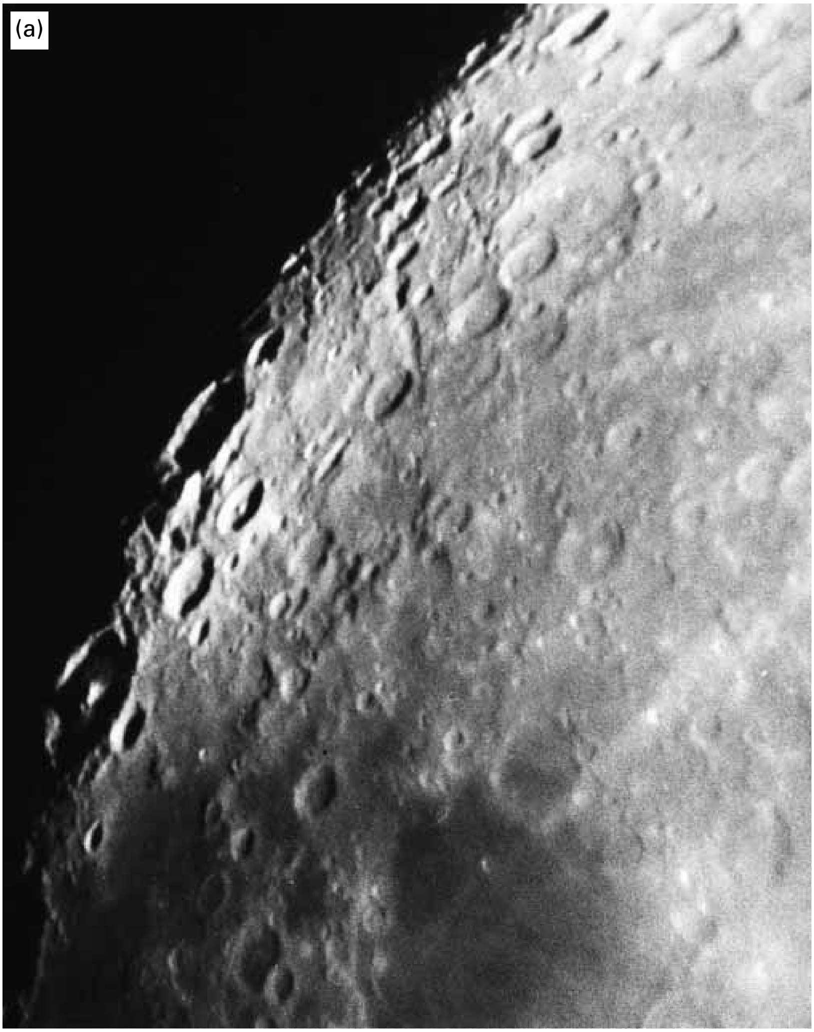


Figure 8.17 (a) The two prominent craters, largely filled with black shadow, on the Moon's terminator are Furnerius (upper) and Petavius (lower, with central mountain poking up into the sunlight). Photograph by Tony Pacey. He used his 10-inch (254 mm) Newtonian reflector, with eyepiece projection to obtain this view on 1991 November 23d. Others details not available.

certainly makes one pause for thought when the ambient lighting throws it into prominence (see Figures 8.17(a) and (b)). It really does seem, though, to be a coincidence. Certainly the members of the 'chain' are all of different ages.

Of the other 'chain' members, Vendelinus and Langrenus are discussed in Section 8.26 further on in this chapter, while the Mare Crisium is discussed in Section 8.14 and Endymion in Section 8.15, earlier in this chapter.

The 125 km diameter Furnerius is obviously very old, as witness its somewhat degraded appearance and the number of large craters strewn over its interior. The crater walls climb to about 3.5 km above the level of its interior. Figure 8.17(c) is a magnificent drawing of this feature by Nigel Longshaw. The

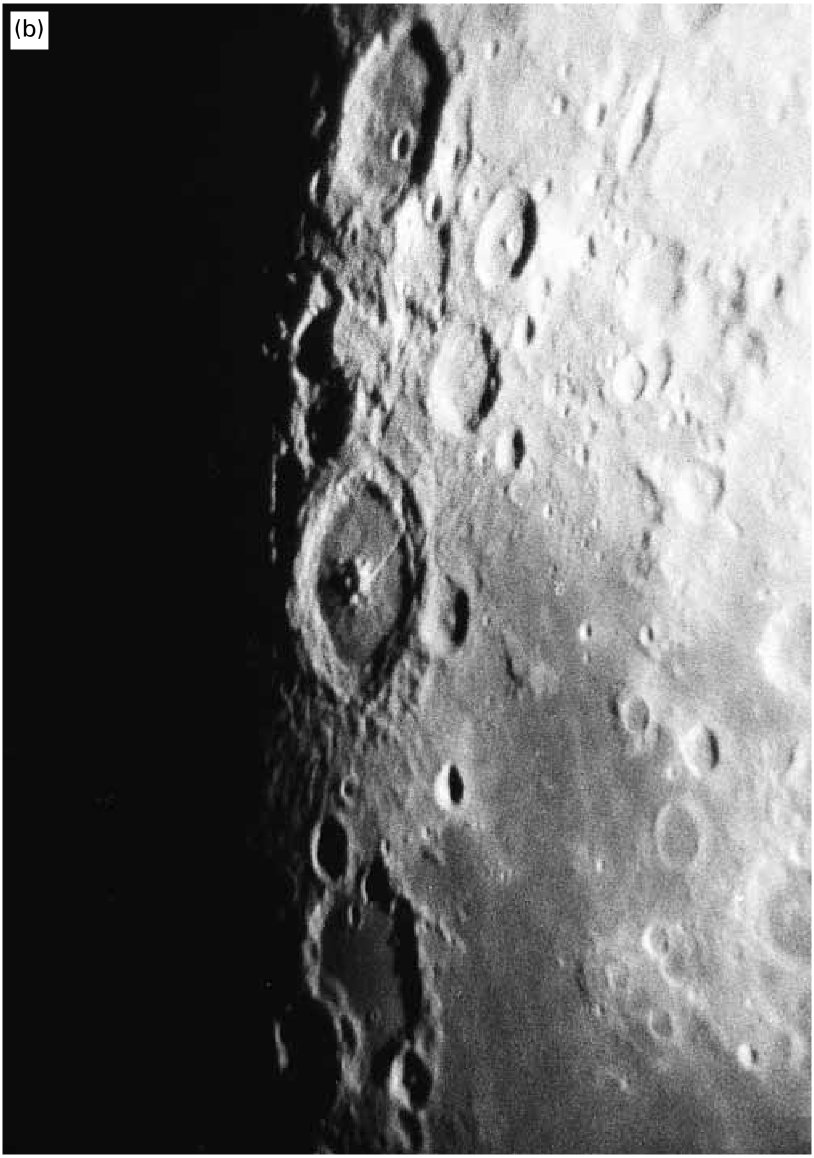


Figure 8.17 (*cont.*)
(b) Furnerius (upper crater), Petavius (middle) and Vendelinus (lower) photographed by Tony Pacey on 1989 October 16[d], same details as for (a).

largest crater in the interior of Furnerius is Furnerius B. This 22 km diameter crater is situated near the western rim of Furnerius. The slightly larger (24 km) crater that spans the north-east rim is Furnerius J. The floor of Furnerius abounds in interesting details, including the prominent rille that snakes from the north-west wall through the centre of the crater.

One month earlier, Nigel Longshaw observed Furnerius at a slightly later colongitude. His drawing is shown in Figure 8.17(d). The crater to the

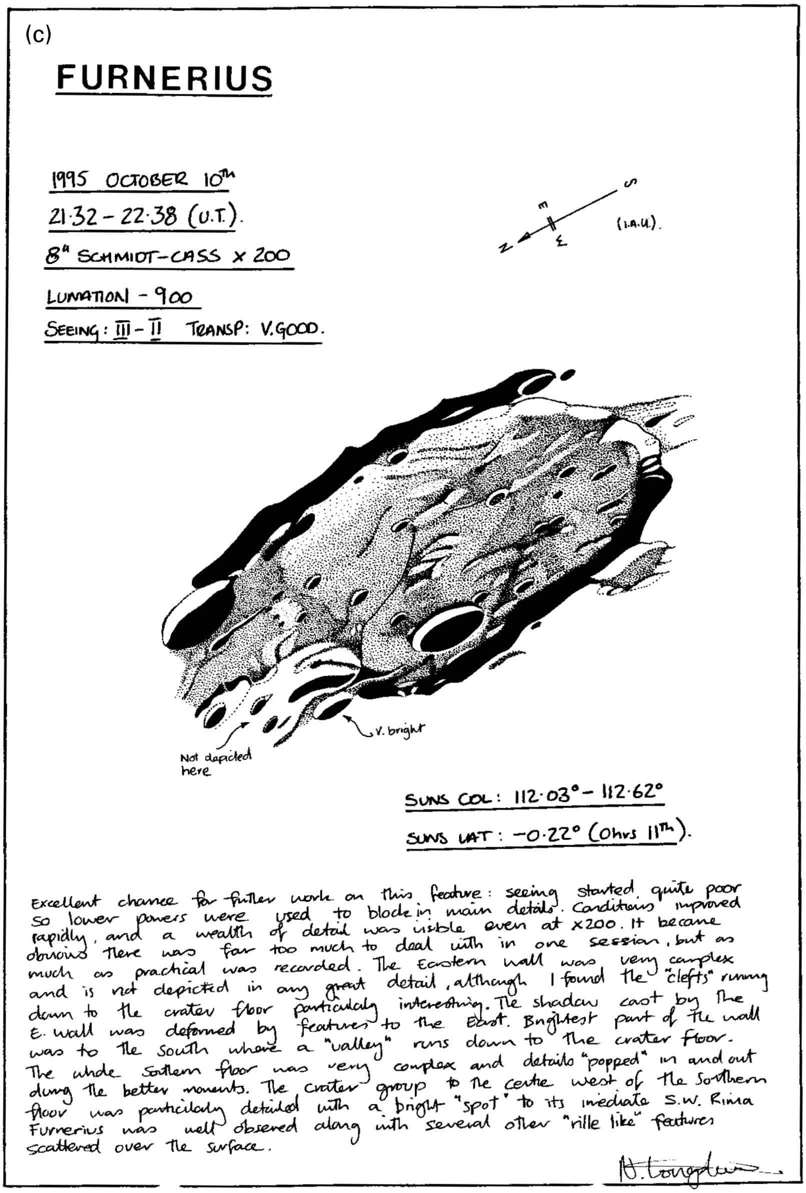


Figure 8.17 (*cont.*)
(c) Furnerius, drawn by Nigel Longshaw. The block of descriptive text reads (with no editing by me): *Excellent chance for further work on this feature: seeing started quite poor so lower powers were used to block in the main details. Conditions improved rapidly, and a wealth of detail was visible even at ×200. It became obvious there was far too much to deal with in one session, but as much as practical was recorded. The eastern wall was very complex and is not depicted in any great detail, although I found the 'clefts' running down to the crater floor particularly interesting. The shadow cast by the E. wall was deformed by features to the east. Brightest part of the wall was to the south where a 'valley' runs down to the crater floor. The whole southern floor was very complex and details 'popped' in and out during the better moments. The crater group to the centre west of the southern floor was particularly detailed with a bright 'spot' to its immediate S. W. Rima Furnerius was well observed along with several other 'rille like' features scattered over the surface.*

south of Furnerius, and almost attached to it, is the 57 km diameter Fraunhofer. Sequence drawings of the Sun rising and/or setting over a lunar feature are particularly instructive as the detailed height relationships are then revealed. Note which parts of Furnerius are last to sink into the darkness of lunar night on Nigel's drawing. An *Orbiter IV* photograph of Furnerius is presented in Figure 8.17(e).

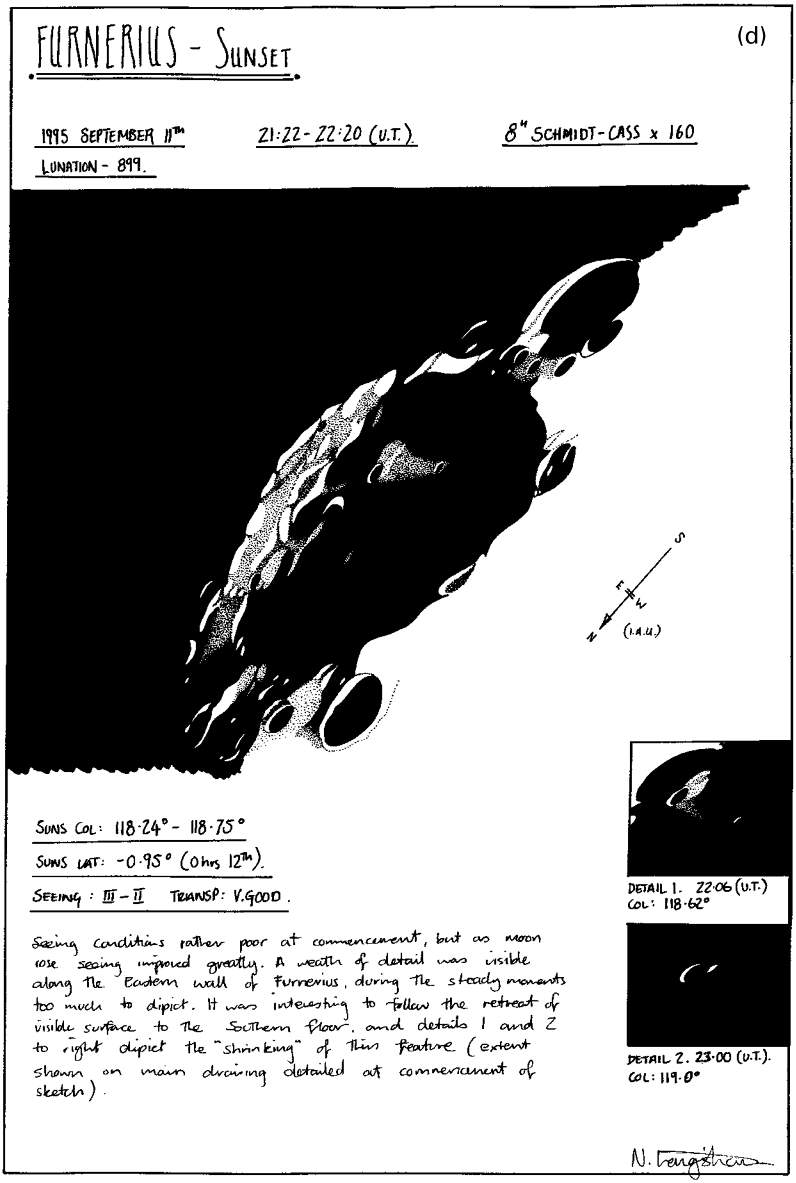
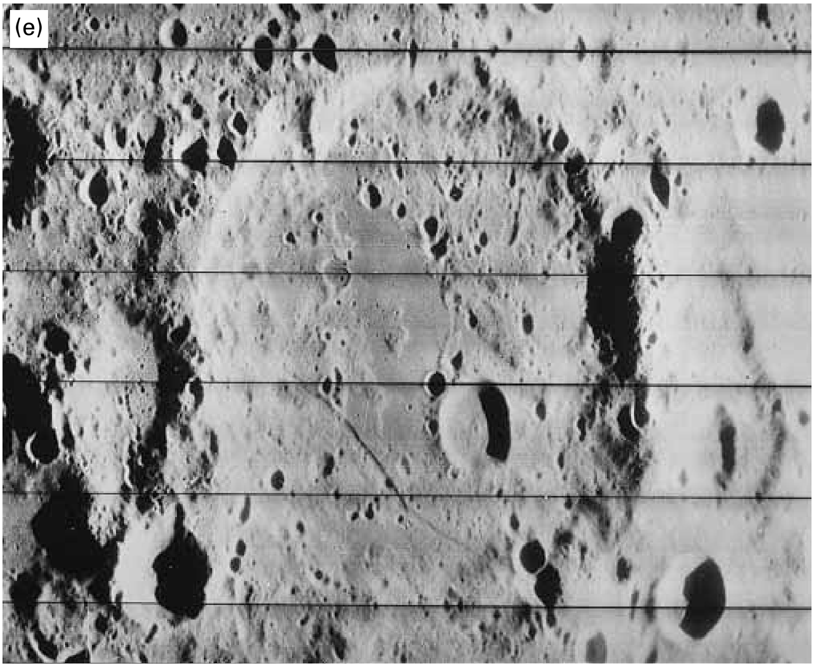


Figure 8.17 (*cont.*)
(d) Sunset over Furnerius, drawn by Nigel Longshaw. The block of descriptive text reads: *Seeing conditions rather poor at commencement, but as Moon rose seeing improved greatly. A wealth of detail was visible along the eastern wall of Furnerius, during the steady moments too much to depict. It was interesting to follow the retreat of the visible surface to the southern floor and details 1 and 2 to the right depict the 'shrinking' of this feature (extent shown on main drawing detailed at commencement of sketch.)*

North of Furnerius, the crater Petavius must rank as one of the most beautifully sculpted objects on the Moon. It is the centre one of the 'chain' of craters shown in Figure 8.17(b). The outer walls of this great 'dinner plate' of a crater span 177 km but notice the unusually wide inner terraces, even tending to a double-ring type of structure along the western periphery. The inner ramparts extend upwards to approximately 2.1 to 3.3 km above the floor, the height varying around the crater.



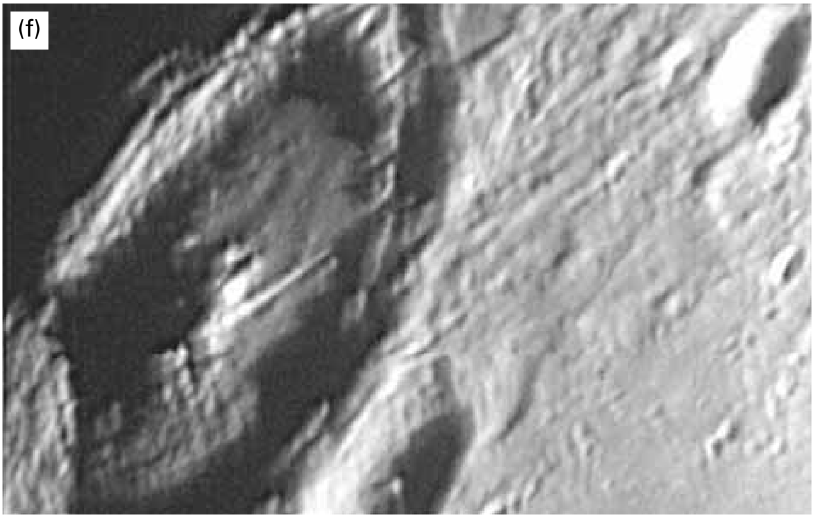


Figure 8.17 (*cont.*)
(e) *Orbiter IV* photograph of Furnerius. (Courtesy NASA and Professor E. A. Whitaker.)
(f) Petavius. CCD image by Terry Platt, obtained using his 318 mm tri-schief-spiegler reflector and *Starlight Xpress* CCD camera. No other details available. The author has applied slight image sharpening and brightness and contrast re-scaling.

The mighty central mountain complex soars up to 1.7 km above the crater floor but is raised another 0.5 km, or so, above the level at the periphery because the crater floor is highly convex.

It is fascinating to watch the progression of shadows when Petavius is close to the terminator. The area around the central mountains, and then the central mountains themselves, are always last to disappear at sunset and first to appear at dawn, with the rest of the interior of the crater largely filled with deep-black shadow at these times. Something of the effect is shown in Figure 8.17(a).

Figure 8.17(f) shows one of Terry Platt's incredible CCD images. The fineness of the detail shown is readily apparent by considering that only part of the formation fits into the frame!

The convexity of the floor gives a clue to the origin of one of the most outstanding of Petavius's features: the remarkable fissure that crosses the floor from the central mountains to the south-west wall. This used to be called "the Great Cleft of Petavius" but the term 'cleft' is now obsolete. I suppose that it should now be known as 'the Great Rille of Petavius'. It seems to be a graben, a deep-seated stress fracture caused when the ground is pulled apart to either side and the ground along it slumps downwards into the crack. Other rilles are visible, mostly at least approximately radial to the central mountains. However, these are all very much harder to see than 'the Great Rille'. When the Sun-angle is low over the area 'the Great Rille' is easy to see even through a 60 mm refractor. Of course when the Sun is high it becomes a difficult object to view even through a large telescope.

As I said, the convexity of the floor provides the clue to its formation. It seems that enormous forces have built up under the floor of the crater, raising its floor and causing the stress fractures. As to the cause of the forces . . . .

8.18 'GRUITHUISEN'S LUNAR CITY' [5°N, 352°E]

Baron Franz von Gruithuisen was born in Bavaria in 1774. He took a medical degree but turned to astronomy as a profession, becoming Professor of Astronomy at Munich in 1826. He was an energetic selenographer and generally a good observer. However he did tend to bring ridicule upon himself by making some extraordinary claims – the fruits of a vivid imagination.

Most famously, in 1824 he announced his "discovery of many distinct traces of lunar inhabitants, especially of one of their colossal buildings". He further described "a lunar city" with "dark gigantic ramparts". The site of this edifice is quite near the centre of the Moon's disk, less than a hundred kilometres north of the ruined 35 km diameter crater Schröter.

(a)

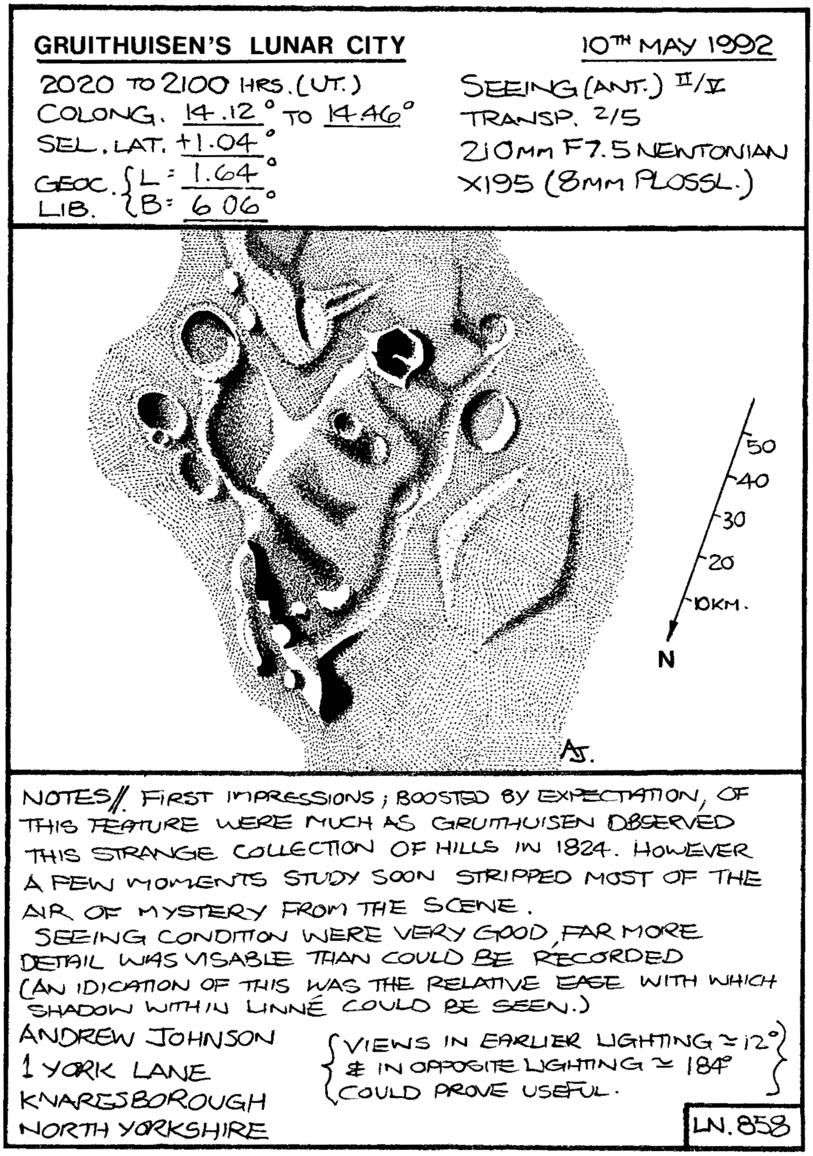


Figure 8.18 (a) What a pity there are no selenites busying themselves in the morning within the confines of the 'lunar city', as Gruithuisen had interpreted this structure! Drawing by Andrew Johnson.

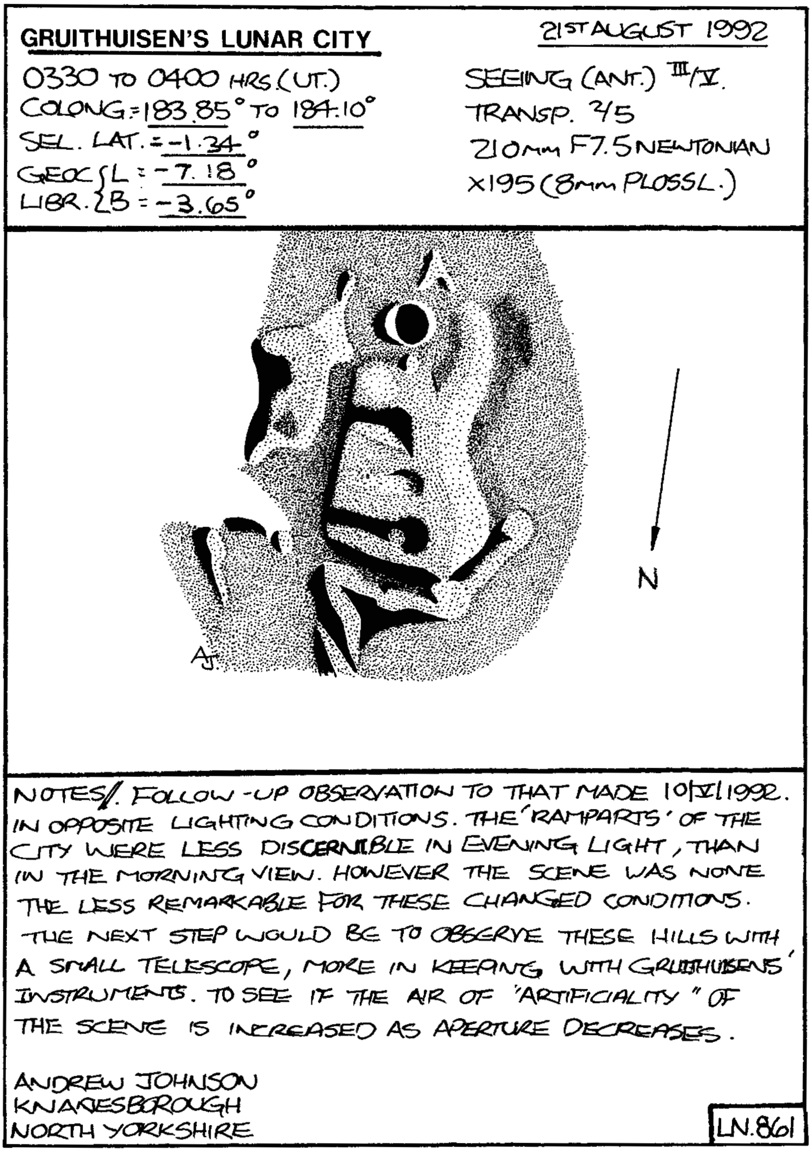
Actually, the southern point of the "lunar city" is the 10 km crater Schröter W.

Of course, there is nothing but a rough arrangement of hills to be seen in that location. Figures 8.18(a) and 8.18(b) show two splendid studies of Gruithuisen's fabled 'city' made by Andrew Johnson.

Not everything one does at the eyepiece of the telescope has to be for serious study. Just for the fun of it you might like to take a look at the area yourself, particularly around the times of first and last quarter Moon, and

Figure 8.18 (*cont.*)
(b) Gruithuisen's 'lunar city' in the late afternoon, as drawn by Andrew Johnson.

(b)



see if you can force your imagination to create a lunar city out of the jumbled topographic features in the area just north of Schröter.

Before we laugh too loudly at the memory of Gruithuisen, we should remember that he made many good contributions to the study of the Moon in his day and has been commemorated with a 15 km crater named after him positioned at 33°N, 320°E on the lunar surface, at the junction of the Mare Imbrium and Oceanus Procellarum. He can even be said to be the originator of the impact theory of the formation of lunar craters – after many years of dispute among experts, now the accepted scenario!

8.19 HARBINGER, MONTES [27°N, 319°E] (WITH PRINZ)

The Harbinger Mountains, more properly Montes Harbinger, are a small but interesting cluster of hills situated in a fairly barren part of the Oceanus Procellarum just a little north-east of the prominent crater Aristarchus (see Section 8.7). The proximity of Aristarchus is evident in Figure 8.19(a), which is a Catalina Observatory (1.5 m reflector) photograph taken on 1965 December 6^{d} 05^{h} 14^{m} UT, when the Sun's selenographic colongitude was 63°.7. You might find this view useful in helping to locate the mountain group through the telescope eyepiece.

The individual peaks are like islands rising up from the Ocean of Storms. A ruined crater, Prinz, attaches to the south-west of the range. Prinz forms an incomplete ring with a diameter of 47 km. Clearly the Procellarum lavas have partially buried this crater, along with the lower parts of the Harbinger Mountains and doubtless other low-lying features. Prinz is completely open to its south-west.

Numerous rilles and even some *domes* (volcanic swellings) are evident in the area and become evident at different stages of illumination. Figure 8.19(b) is a drawing by Roy Bridge showing the group under the first light

Figure 8.19 (a) Montes Harbinger is at the centre of this photograph, with the incomplete crater Prinz abutting the mountain group to the upper right. The crater at the top-right corner of this Catalina Observatory photograph is Aristarchus. (Courtesy Lunar and Planetary Laboratory.)

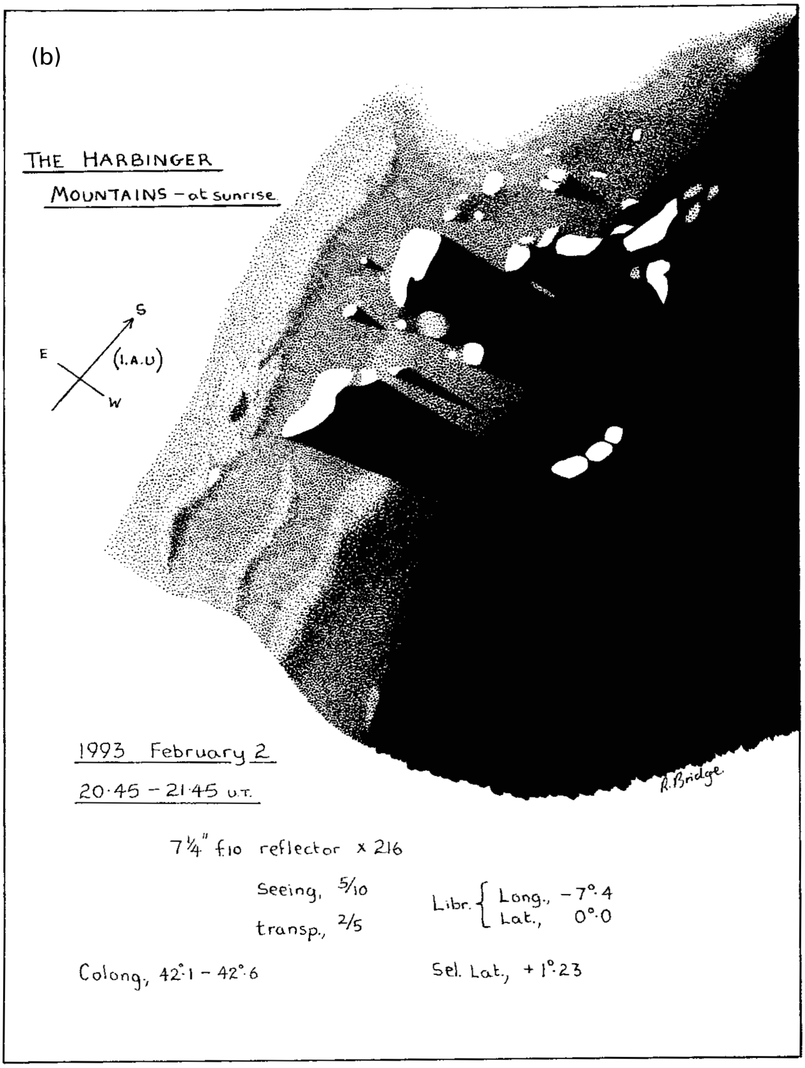


Figure 8.19 (*cont.*)
(b) Sunrise over Montes Harbinger, drawn by Roy Bridge.

of lunar dawn. Figure 8.19(c) shows the area under a much higher Sun. Figure 8.19(a) shows it under a slightly higher Sun-angle, still.

I would unhesitatingly recommend the aspiring draughtsman of the lunar scene to gain practice at drawing mountains by observing and recording the Harbinger–Prinz complex under as many different illuminations as possible. The details are delicate enough to make it a real challenge but not so overwhelmingly complex as to be off-putting. After-all, even the most practised observer–draughtsman would balk at the

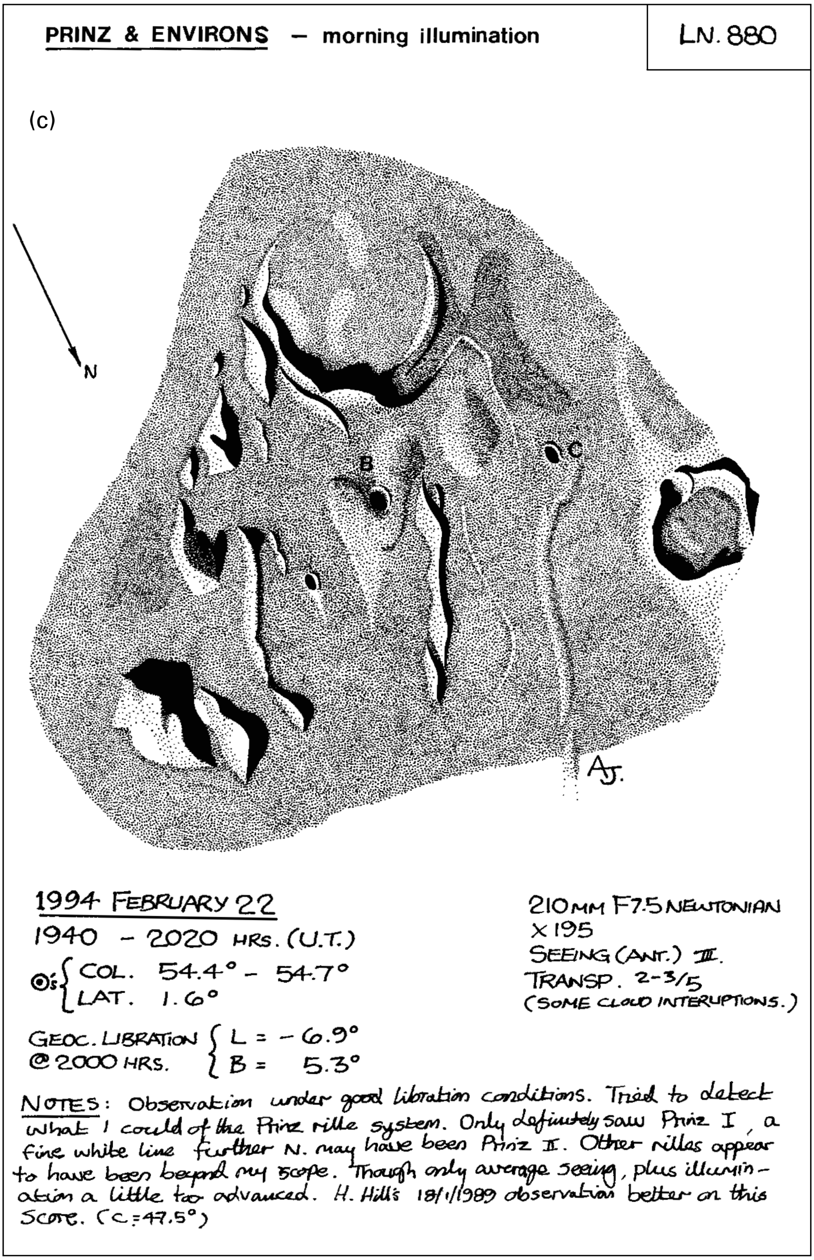


Figure 8.19 (*cont.*) (c) Prinz and Montes Harbinger, drawn by Andrew Johnson.

prospect of trying to record even part of extensive ranges, such as Montes Apenninus!

8.20 HEVELIUS [2°N, 293°E] (WITH CAVALERIUS, GRIMALDI, LOHRMANN)

The impression of the apparent non-accidental alignments of some craters on the Moon is, at least in part, generated by the presence of the terminator. How many prominent chains of large craters can you find that extend in even a roughly east–west direction? Yet time and time again crater chains along the north–south meridians spring into prominence as the morning and evening terminator looms close. Such an example is provided by the craters Grimaldi, the southernmost member, and extending northwards, Lohrmann, Hevelius and Cavalerius. Seen just before full Moon this line of large craters appears strikingly prominent even in the smallest telescope.

Figure 8.20(a) shows a 'snapshot' of the spectacle I took myself. Figure 8.20(b) is another example, though this time with the terminator slightly less advanced and the largest crater (Grimaldi) here entirely filled with shadow and forming a distinct 'notch' in the Moon. This 'notch' is obvious even when seen through low-power binoculars.

Figure 8.20 (a) The line of craters Grimaldi to Cavalerius is very apparent along the terminator in this photograph taken by the author on 1983 October 19^{d}, using his 0.46 m Newtonian reflector. The camera, fitted with a 58 mm lens, was hand-held to a 44 mm Plössyl eyepiece (EFR = f/7.4) for a 1/500 second exposure on Ektachrome 200.

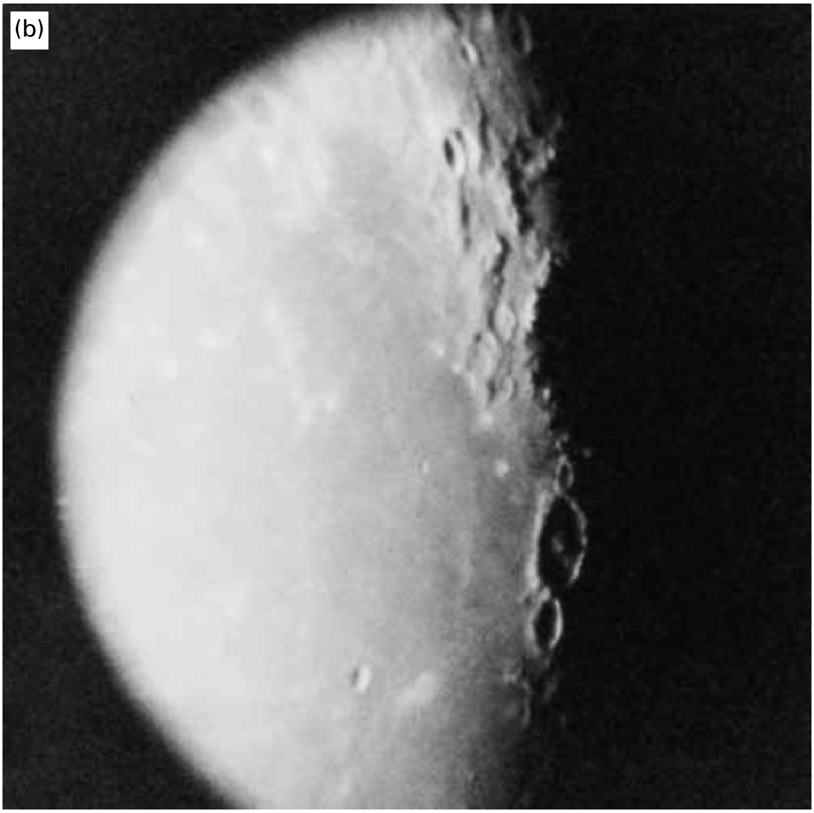


Figure 8.20 (*cont.*)
(b) Grimaldi is entirely shadow-filled, creating a 'notch' in the Moon, while Lohrmann, Hevelius, and Cavalerius are prominently displayed below Grimaldi on this photograph taken by the author using his 0.46 m reflector on 1985 January 5^{d} 20^{h} 23^{m} UT (when the Sun's selenographic colongitude was 67°.8). The camera, fitted with a 58 mm lens, was hand-held to a 9 mm Orthoscopic eyepiece (EFR = f/36) for the 1/125 second exposure on *Fuji* HR1600 film.

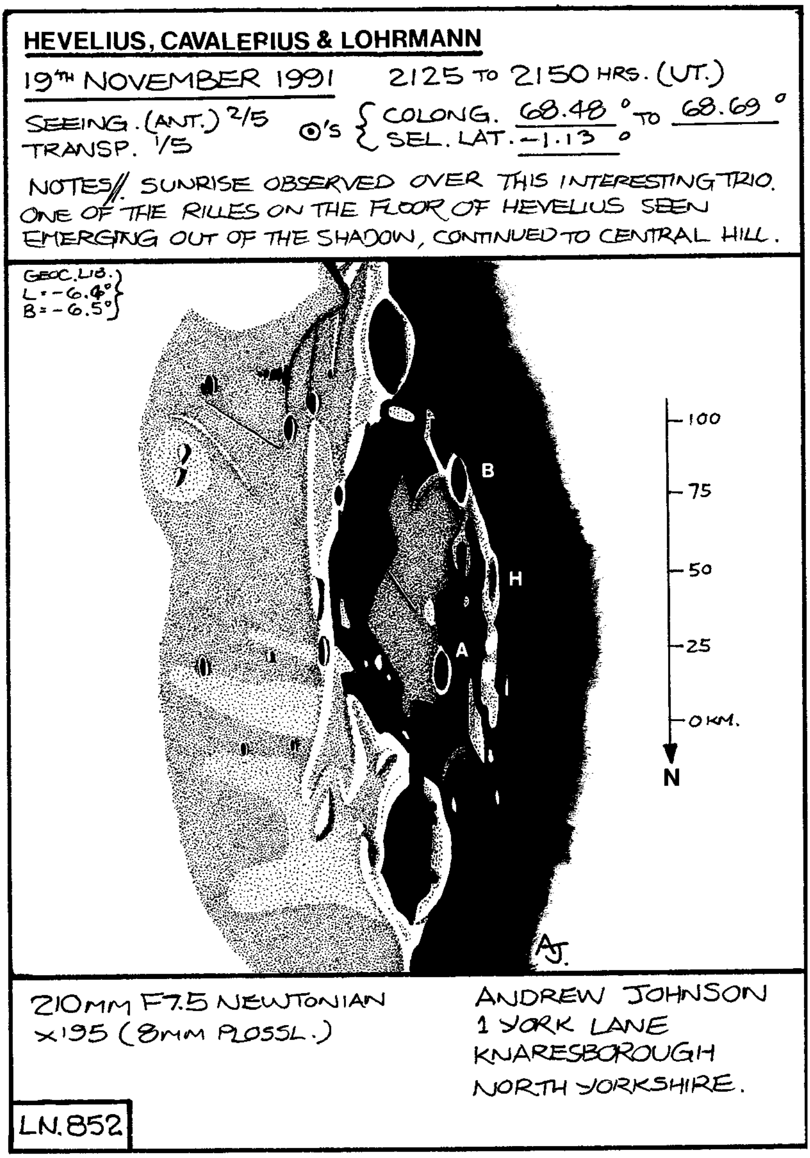
Figure 8.20(c) shows a detailed study of Hevelius, together with Lohrmann and Cavalerius, made by Andrew Johnson. Hevelius is a magnificent crater, 120 km in diameter, with some terracing and much fine detail visible in its somewhat irregular walls. It can be said to represent an example of a formation intermediate in type between the 'saucer-shaped' and 'walled-plain' craters. It is, though, rather closer to being of the 'walled-plain' variety than the other.

The floor is convex as is evident in Figure 8.20(b). The walls vary in height around the crater but typically soar up to about 1.8 km above the floor. The crater has a central mountain, as well as other floor details such as rilles and small craters. Hevelius is named after Johann Hewelcke, a seventeenth century Danzig astronomer and selenographer, and the crater is called "Hevel" on old maps.

Lohrmann is a 34 km diameter crater which seems to sit uneasily between Hevelius and Grimaldi. It has a rather hummocky floor and a central mound.

Figure 8.20 (*cont.*)
(c) Hevelius (largest crater), Lohrmann (above Hevelius) and Cavalerius, drawn by Andrew Johnson.

(c)



North of Hevelius, and just intruding into it, is the 64 km diameter Cavalerius. That Cavalerius is more youthful than Hevelius is evident both in its crisper appearance and in the fact that it is obviously Cavalerius which has intruded across the rim of Hevelius and not the other way round.

There is, though, some slumping of the rims of both at their intersection. In the case of Cavalerius the slumping is slight. In the case of

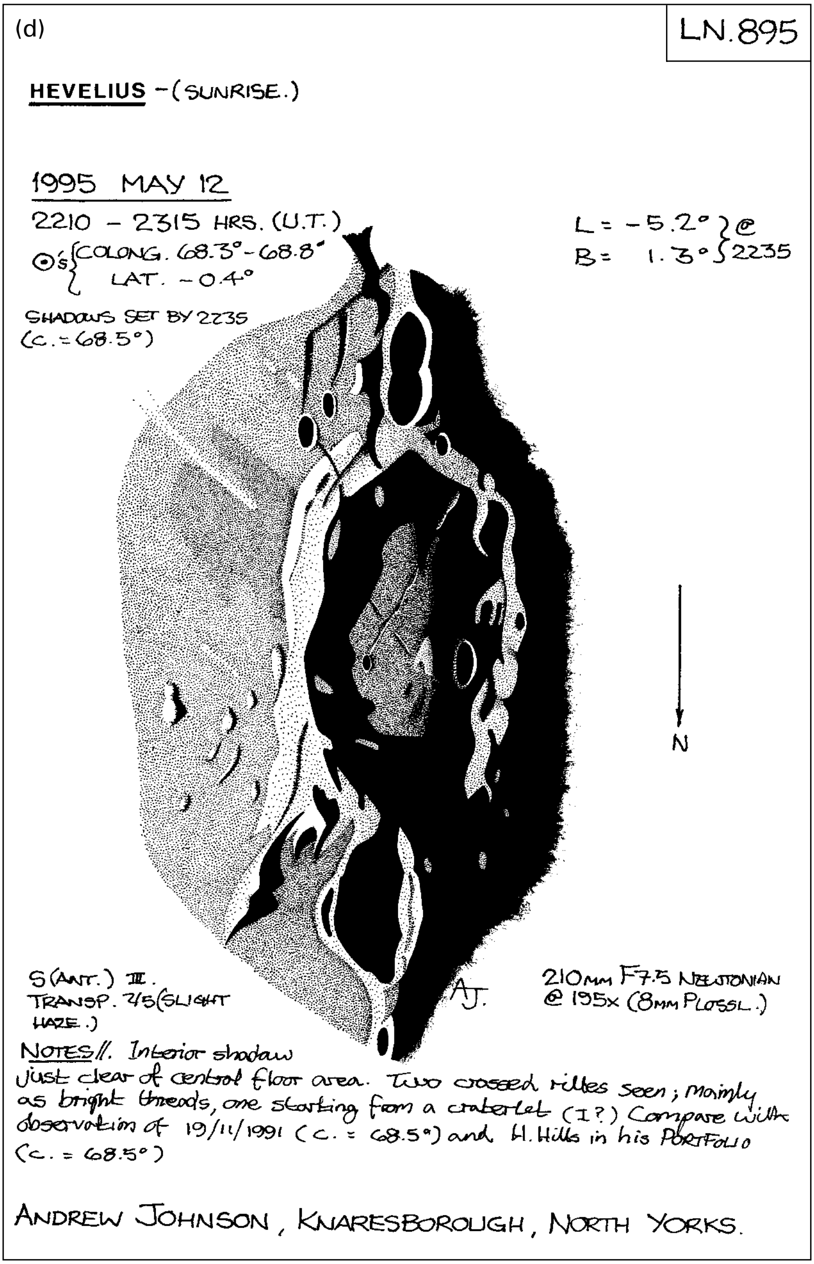


Figure 8.20 (*cont.*)
(d) Hevelius, with Lohrmann and Cavalerius, drawn by Andrew Johnson. Note the differences to the drawing in (c), largely the result of the different libration.

Hevelius it is considerable. Also the ground outside Hevelius in which Cavalerius was formed is lower, anyway, that the rim of Hevelius. This creates the illusion of a deep channel apparently joining Hevelius to Cavalerius when the formations are close to the terminator. Even the low-resolution view of the arrangement in Figure 8.20(b) shows this effect well. The exaggerated effect persists to quite a high Sun-angle because the rim of Hevelius just east of the point of intersection casts a long shadow down into Cavalerius.

Similar is the so-called 'Miyamori Valley'. This is an apparent chasm extending from Lohrmann south-westwards to the major crater Riccioli. Again it is an exaggerated effect for the most part generated by the shadows cast by the rather linear NNE section of the outer ramparts of Grimaldi. Any real valley is much less deep and well defined, being at most some low ground that threads between assorted hummocks and craters. Figure 8.20(e) shows a study of it by Roy Bridge. Notice how the shadow fades away, like the grin of a Cheshire cat, at the eastern end of the 'valley' as the terminator moves westwards. This sort of sequence drawing is highly instructive.

Figure 8.20(f) shows the area under higher Sun. The 'valley' has all but

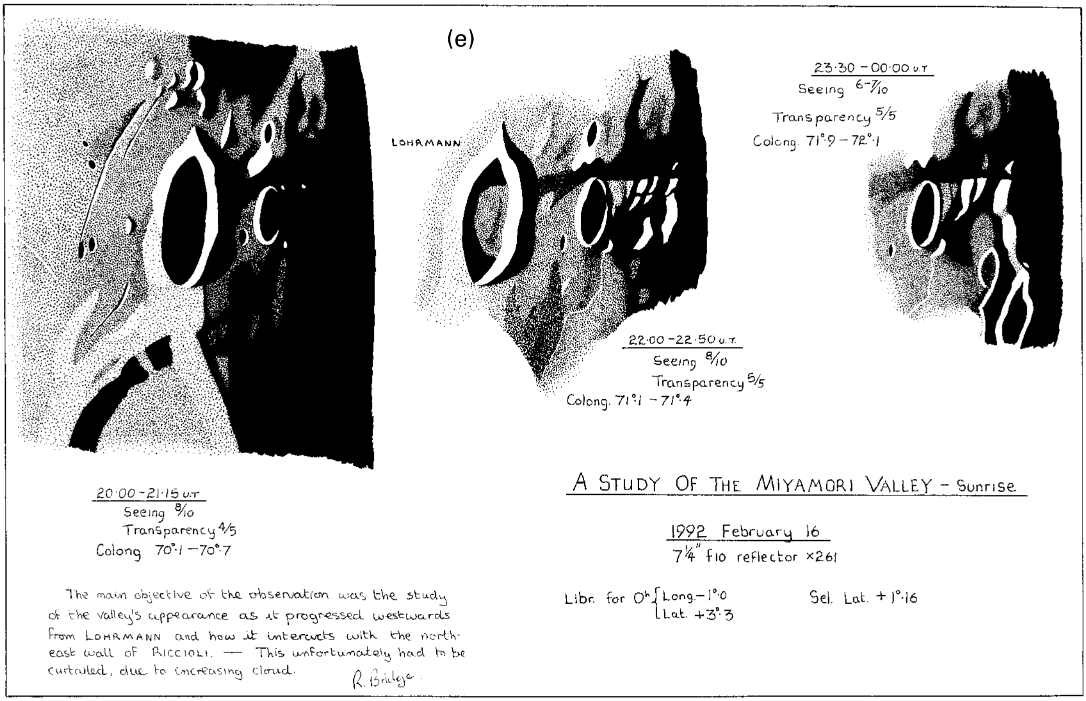
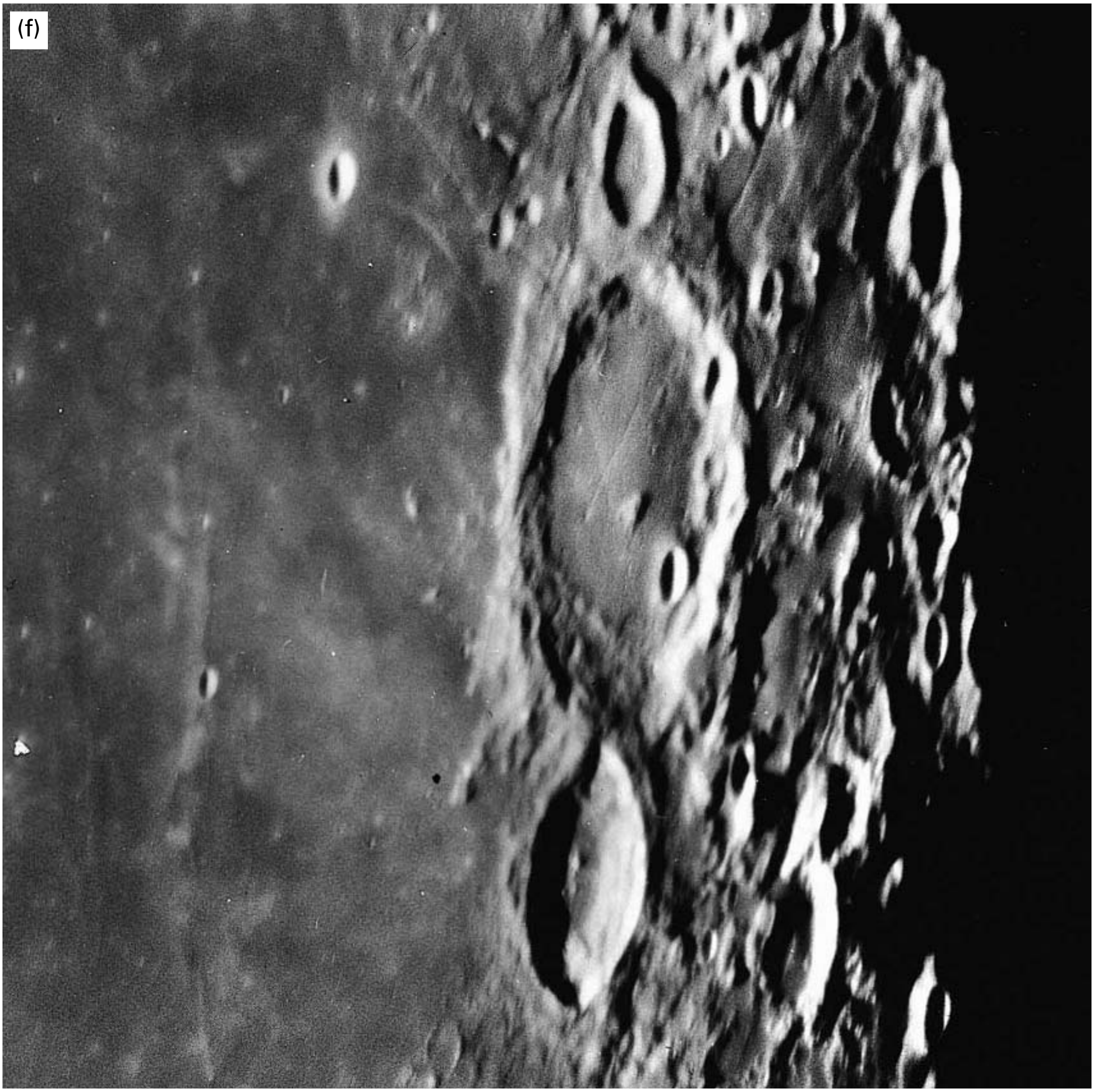


Figure 8.20 (*cont.*)
(e) The 'Miyamori Valley', drawn by Roy Bridge.



disappeared. However, some arcuate rilles are now in evidence curving westwards away from Hevelius.

Being so close to the western limb of the Moon, the appearance of the formations can alter quite significantly because of the effect of libration in longitude. Compare Figure 8.20(c) with Figure 8.20(d), which is another drawing by Andrew Johnson. Here the values of the Sun's selenographic colongitude are very similar and yet there are significant differences in the way Andrew has represented the features – in large part caused by the difference in the librations.

Figure 8.20 (*cont.*)
(f) Portrait of Hevelius, Cavalerius and Lohrmann, made using the 1.5 m reflector of the Catalina Observatory on 1966 February 4^{d} 06^{h} 53^{m} UT, when the Sun's selenographic colongitude was 74°.2. (Courtesy Lunar and Planetary Laboratory.)

Figure 8.20 (*cont.*)
(g) Grimaldi (centre) dominates this Catalina Observatory photograph, taken just 10 minutes after the one shown in (f). (Courtesy Lunar and Planetary Laboratory.)

South of Lohrmann, and with a tract of rough and cratered ground separating the two, is the great 'walled-plain' Grimaldi. Completely in shadow in Figure 8.20(b), the floor of this crater is just beginning to receive the rays of the rising Sun in Figure 8.20(a). Figure 8.20(g) shows the formation (together with Lohrmann and the southern part of Hevelius) in full sunlight.

That Grimaldi is much larger than Hevelius is very obvious. However, the exact size of Grimaldi is a little problematical. The very dark, lava-flooded, floor of the formation is roughly 140 km in diameter but, as can be seen from the photographs, is rather irregular in outline. Look carefully and you will see that the rough surrounds of the flood-plain climb upwards and form a vague crater rim (more obvious to the north and west) of diameter exceeding 220 km. There are even, in places on the Moon, faint traces of a secondary concentric ring at nearly twice the radius of the first. Clearly the impactor that created Grimaldi packed quite a wallop!

Occasional bright flashes and patches of colour and apparent mistiness have been reported from time to time on Grimaldi's lava-flooded floor and many small craters, mounds, spots, streaks and wrinkle ridges provide an endless source of study for the telescopist.

8.21 HORTENSIUS [6°N, 332°E] (WITH ASSOCIATED LUNAR DOMES)

Hortensius is a fairly unremarkable crater, 15 km in diameter, situated in the Oceanus Procellarum just west of the great crater Copernicus. It has a sharp rim and is quite deep for its size. Rim to lowest point in the bowl-shaped depression measures nearly 2.9 km. The real point of interest lies on the mare just to the north of the crater: several of the raised mounds known as lunar domes.

Most casual observers of the Moon never get to see lunar domes. They are invariably small and elusive, only showing up well at low Sun-angles. Small-scale maps, and even some of larger sizes, do not show the location of these intriguing formations. The domes near Hortensius are notable in that their location is easily defined. Also they are at their most evident close to the time of first quarter Moon, the most popular time for lunar observing (they are again evident at last quarter Moon, of course, but far fewer amateurs are out with their telescopes in the small hours of the morning to observe the Moon).

As far as advice about locating the domes goes, I can do no better than to refer you to Figure 8.21. On it you will see part of Copernicus to the far left of the photograph, and so can gauge the scale. Upper right you will see Hortensius and just below Hortensius you should be able to make out a cluster of blister-like mounds. They are the lunar domes.

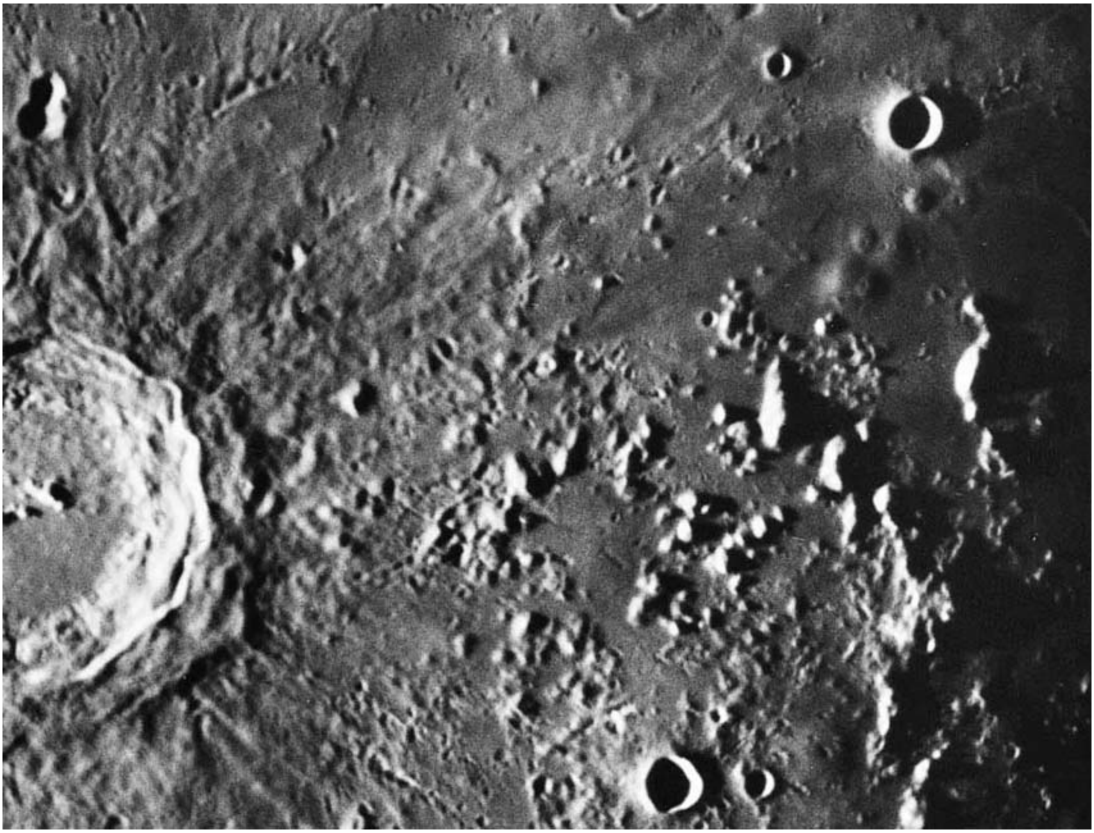


Figure 8.21 The subject of this photograph, Hortensius and its associated lunar domes, has been placed near the upper-right corner in order to show their location with respect to the nearby major crater Copernicus (partly shown on the left). Photograph taken with the 1.5 m reflector of the Catalina Observatory on 1967 January 21^{d} 02^{h} 44^{m} UT, when the Sun's selenographic colongitude was 31°.4. (Courtesy Lunar and Planetary Laboratory.)

Historically, the proponents of the endogenic origin theory of lunar craters used the domes to support their views. The domes, to them, were blisters that had failed to burst (on the mud-bubble theory of crater formation) and so were examples of the crater-formation process 'caught in the act'. We can dismiss this theory in the light of modern evidence but the question still remains: what are they and how do they fit into the scheme of things lunar? Here opinions vary.

As is so often the case about features and processes on the Moon, various authorities tend to give the impression that things are very 'cut-and-dried' and they usually give very definite explanations. The trouble is, you then read what another authority says on the same subject, presented with equal certainty, and yet differing from the explanation of the first one!

Some experts say that lunar domes are just mountains. Others, probably the majority, say that domes are volcanic swellings of the crust caused by a magma build-up from below. Others compare them to earthly cinder-cones and say they are true volcanoes.

I tend to side with the opinion that they are true volcanoes, though I don't agree with the cinder-cone interpretation. Many of them have what appear to be calderas situated at their summits. In fact, most of the Hortensius domes have summit craters; I think too many for chance impacts to be responsible. I cannot help wondering about the outpouring of low-viscosity lavas that flooded the great lunar basins. In particular, I wonder about the sites of the eruptions. There is strong evidence that the major lava flows originated from long fissures near the peripheries of the basins. However could there have been other vents further in? It is certain that the lavas did not switch off suddenly. Evidence for successive lava flows abound on the lunar maria. The vents which ceased eruption early were undoubtedly 'levelled over' with mare lavas but what of those that were last to finish? Maybe the last vestiges of volcanism brought to the surface rather less-fluid lavas – viscous enough to build up some vertical structure around the caldera? Certainly the impact melts that would have pooled inside the basins might provide the source of higher-viscosity lavas.

If you will indulge me while I build on my speculations, perhaps the domes have some connection with the newly formed mare striving to achieve isostatic equilibrium. This is the theoretically expected process of slight sinking of the layers of mare basalts after solidification. The cause for this is the higher density of the basalt compared to that of the bedrock. There is some evidence that this isostatic levelling process actually occurred on the Moon, in the form of faulting and apparent tide-marks at the basin boundaries, etc. As the solidified 'seas' sank they inevitably squeezed down on the layers below. Perhaps the domes resulted as a little of the more viscous sub-mare lavas escaped through fissures?

I must emphasise that this idea is not the slightest bit 'official'. It is merely the result of my musings and may be completely wide of reality – as indeed may be many of the current 'official' ideas on the subject. If only one thing can be taken as certain, it is that everybody cannot be right!

A lot of questions, with no universally agreed answers. Are the domes really primarily up-lift features but with internal fissures creating lava vents that open out at the peak in many cases? Maybe they instead represent the last vestiges of the ancient lunar volcanism? I wonder. I expect the definitive answer will have to wait until lunarnaut geologists conduct seismic sounding experiments (setting off small percussive charges and monitoring the resultant shock waves) at dome sites in future decades.

The lunar domes are as interesting as they are a challenge to observe.

There are many more examples elsewhere on the Moon, a number of them in the same general area as Hortensius. You will find domes very hard to see in all but the lowest angles of illumination. Also they are a test for good optics and good observing conditions. Image contrast is of prime importance. If you observe with a large-aperture reflector, perhaps one of the popular 'Dobsonian' telescopes, and can't detect domes when you think they should be visible, you might like to try masking the aperture with an off-axis hole. Despite the reduction in light-grasp you might find that the increase in contrast is enough to reveal the domes you could not see before. This technique is especially useful if the atmospheric conditions and/or the telescope optics are of indifferent quality. Happy dome hunting!

8.22 HUMORUM, MARE [CENTRED AT 24°S, 321°E] (WITH DOPPLEMAYER, GASSENDI, GASSENDI A, VITELLO)

Mare Humorum (Sea of Moisture – a rather inappropriate name, that!) might be one of the smaller of the lunar 'seas', its diameter averaging 400 km, but I think that it is certainly one of the most interesting. It is pictured in Figure 8.22(a), a photograph taken by the 1.5 m reflector of the Catalina Observatory on 1967 February 22^{d} 03^{h} 35^{m} UT, when the Sun's selenographic colongitude was 61°.

The mare basalts fill the very ancient basin. In fact the Humorum Basin is probably one of the earliest of them, at nearly 4.2 billion years old. This is evident by the total absence of any identifiable ejecta pattern, obliterated by the subsequent impacts and other events which have moulded the lunar surface.

By contrast, the surface of the mare appears to be one of the youngest of the great 'seas'. This is implied by the crater-record and is consistent with the results gained by the *Apollo* missions concerning the relative youthfulness of the westernmost of the lunar mare flood-plains. It is probable that the final significant eruptions of mare basalts that covered the Humorum Basin occurred not much more than 3 billion years ago. So, Mare Humorum is both one of the oldest and one of the youngest of the Moon's great 'seas', depending on whether we are talking about the basin or the lava flood-plain!

You might be wondering how the age of the mare can be gauged from the craters on it. To understand that, remember how the meteoritic bombardment of the Moon was severe early in its life and dwindled, both in the sizes of the impactors and the frequency of impacts, with time. From widespread studies of the numbers and sizes of craters on the Moon, taken together with certain well-established age benchmarks obtained by

Figure 8.22 (a) Mare Humorum. The largest crater (at the bottom of the photograph) is Gassendi. Details in text. (Courtesy Lunar and Planetary Laboratory.)

laboratory measurements of lunar samples brought to Earth, planetologists are in a position to gauge the age of a given surface on the Moon. Crudely put, if a given area of surface contains lots of large craters then it is old. If a greater fraction of the area is weighted to smaller craters then it is young. By making painstaking counts of craters and measurements of their sizes scientists can quite reliably determine the age of particular surfaces, such as the maria, on the Moon.

I find it difficult to believe that the Humorum Basin, along with the other western basins, remained completely 'dry' while the basins on the Moon's eastern hemisphere were busily filling with basaltic lavas; the site of the action only to switch to the Moon's western hemisphere when things

Figure 8.22 (*cont.*)
(b) A low Sun-angle over the Mare Humorum reveals low-relief features such as the wrinkle ridges on the mare and the graben on the junction between it and the Palus Epidemiarum (towards the upper left). Details in text. (Courtesy Lunar and Planetary Laboratory.)

had quietened down in the east. I think it much more likely that the lava flooding started in the west at more or less the same time as in the east. However, I think that it **continued for longer** in the west.

If that is the correct scenario then certain consequences must follow. For one thing, the basalt lavas of the western 'seas' must have a greater tendency to overflow the basin rims (given the finite depth of the basins) and spread over a much greater area of the Moon's surface. Look at any photograph of the full Moon and you will see that is indeed the case. Not only is a much greater area of the Moon's surface covered by dark mare material but the edges of the lunar seas are much less well defined by their parent basin rims.

Figure 8.22 (*cont.*)
(c) Southern section of the 'shore' of the Mare Humorum. The well-formed crater on the left of the group is Vitello. To the lower right of Vitello is the largest crater of the group, Dopplemayer. Details in text. (Courtesy Lunar and Planetary Laboratory.)

The westernmost half of the Mare Imbrium spills into the Oceanus Procellarum, which itself merges with the Mare Cognitum and Mare Nubium. Even the Humorum Basin wall is breached to the north-east and here the Mare Humorum spills into the Mare Nubium, and again to the south-east where the flood-plain extends into the Palus Epidemiarum (the ill-defined mare area south of the Mare Nubium), which itself curves round the area outside the south-western periphery of the Mare Humorum.

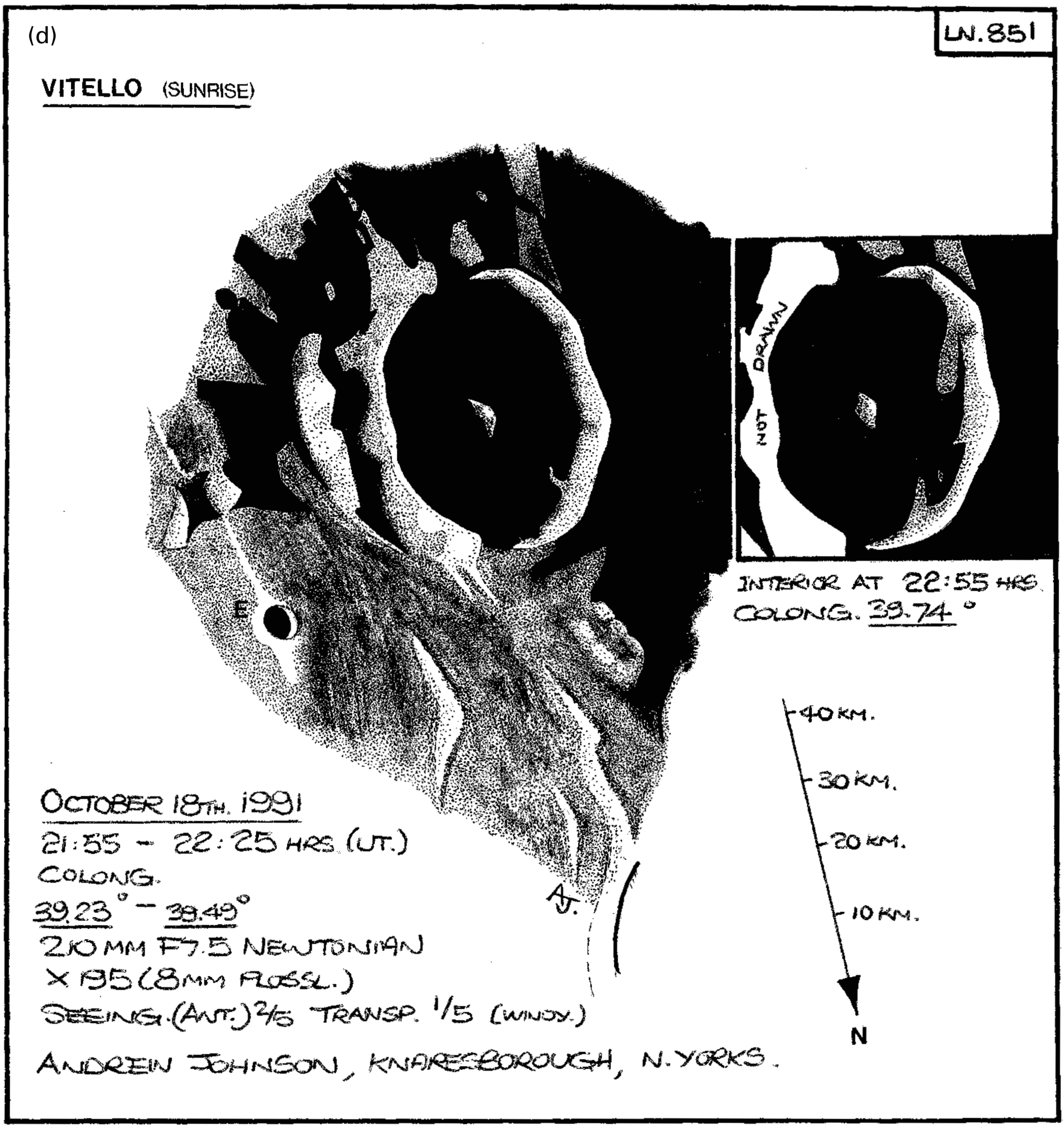
I would conjecture that future lunarnaut surveyors will find that the western seas are composed of a number of sheet-like strata, and will find fewer strata and generally thinner coverings to the basins in the east of the Moon.

As far as an answer goes as to why the crust should be thinner to the west of the Earth-facing meridian, well, maybe it has to do with the "Gargantuan Impact" originally proposed by Dr Peter Cadogan. On his theory the Oceanus Procellarum is really the lava in-fill of a 2400 km diameter basin that resulted from a colossal impact in Pre-Nectarian times. Here, though, I cannot claim to be on anything but thin ground, if you will excuse the pun!

As has already been said, there is a paucity of large craters actually on the Mare Humorum but there are some beautiful examples of craters situated around the periphery of the mare that post-date the creation of the basin and yet pre-date the lava flooding.

Again, this provides proof of a substantial interval between the two episodes. If you doubt this, then consider how these craters could survive the event that created the basin. They couldn't. The craters must have been formed after the basin. Then take a close look at the craters and you

Figure 8.22 (*cont.*) (d) Vitello, drawn by Andrew Johnson.



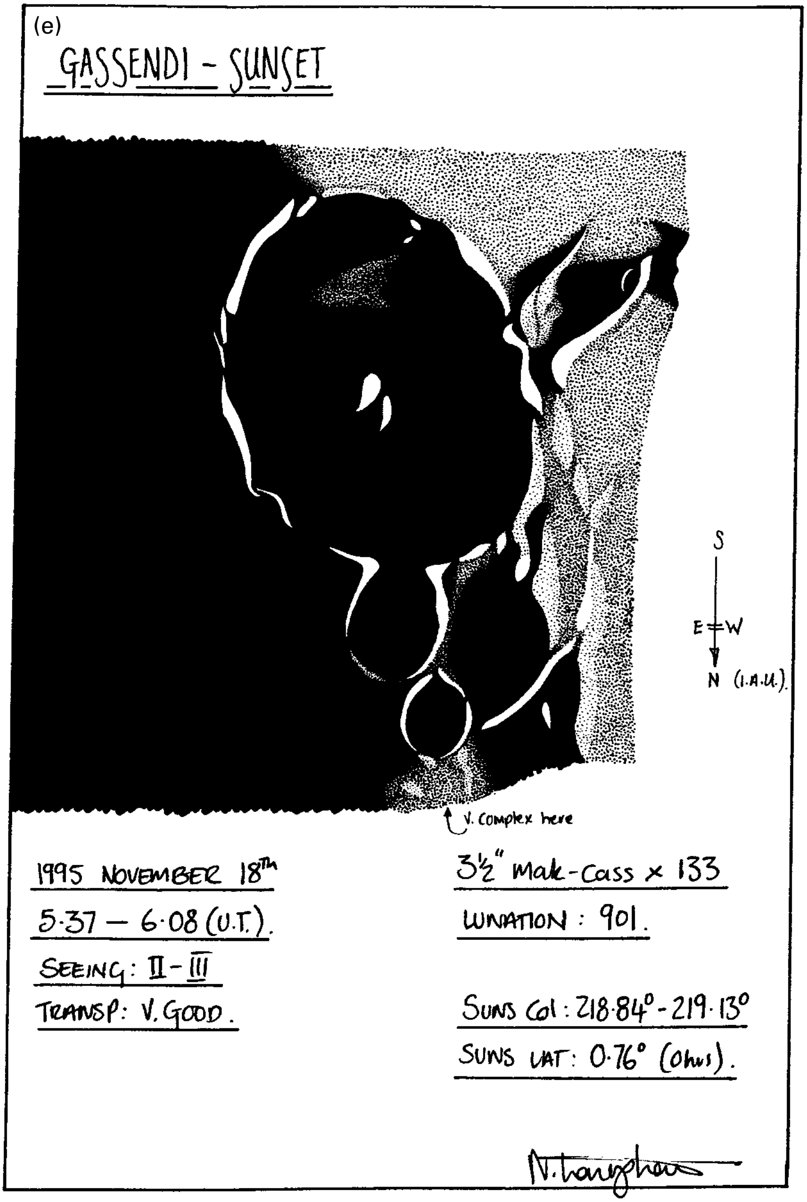


Figure 8.22 (*cont.*)
(e) Sunset over Gassendi, drawn by Nigel Longshaw.

will see that in many cases the mare basalt has intruded into them, typically breaching the walls that face in to the mare, and partially flooding their interiors. Obviously the flooding came after the craters were formed – and hence the interval between the basin creation and the flooding with mare basalts.

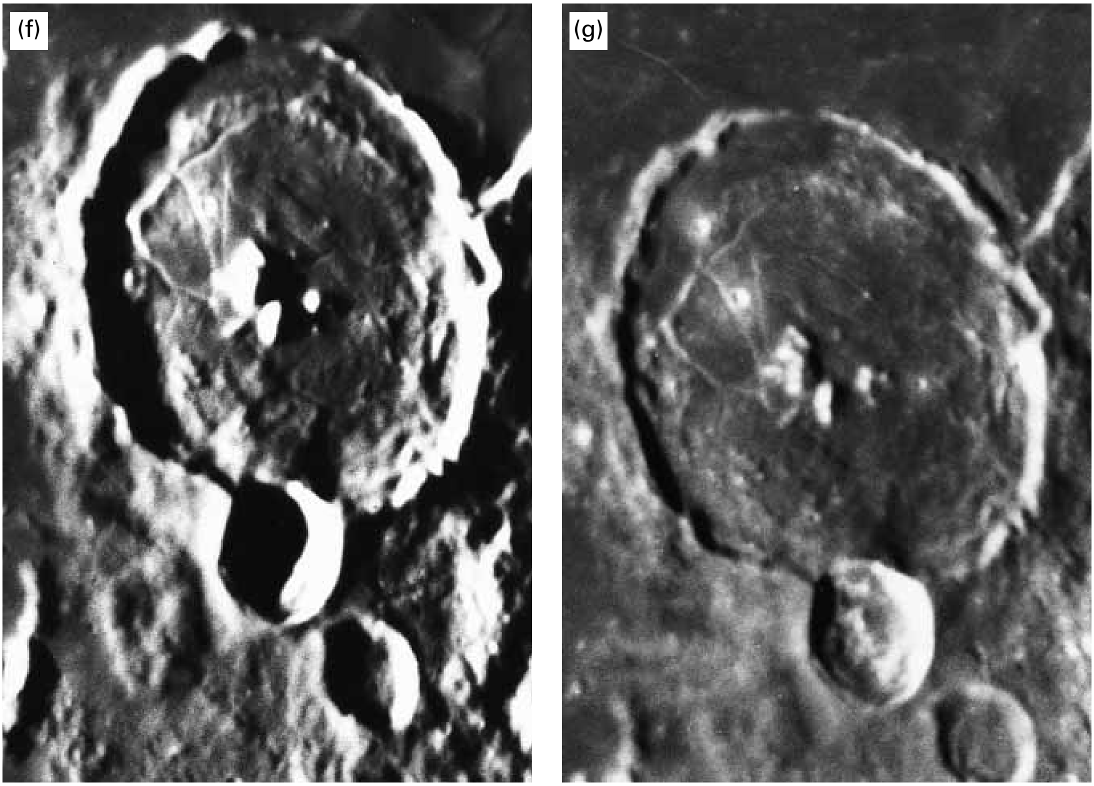


Figure 8.22 (*cont.*)
(f) Gassendi at colongitude 48°.7. Details in text. (Courtesy Lunar and Planetary Laboratory.)
(g) Gassendi at colongitude 61°.0. Other details in text. (Courtesy Lunar and Planetary Laboratory.)

As always, a low Sun-angle reveals details of small vertical relief. Figure 8.22(b) is another photograph taken with the 1.5 m Catalina Observatory telescope, this time on 1966 December 23^{d} 04^{h} 54^{m} UT when the Sun's selenographic colongitude was 39°.9 and the terminator bisected the Mare Humorum. Several roughly concentric wrinkle ridges show up under this lighting. These are thought to be the result of compressional forces.

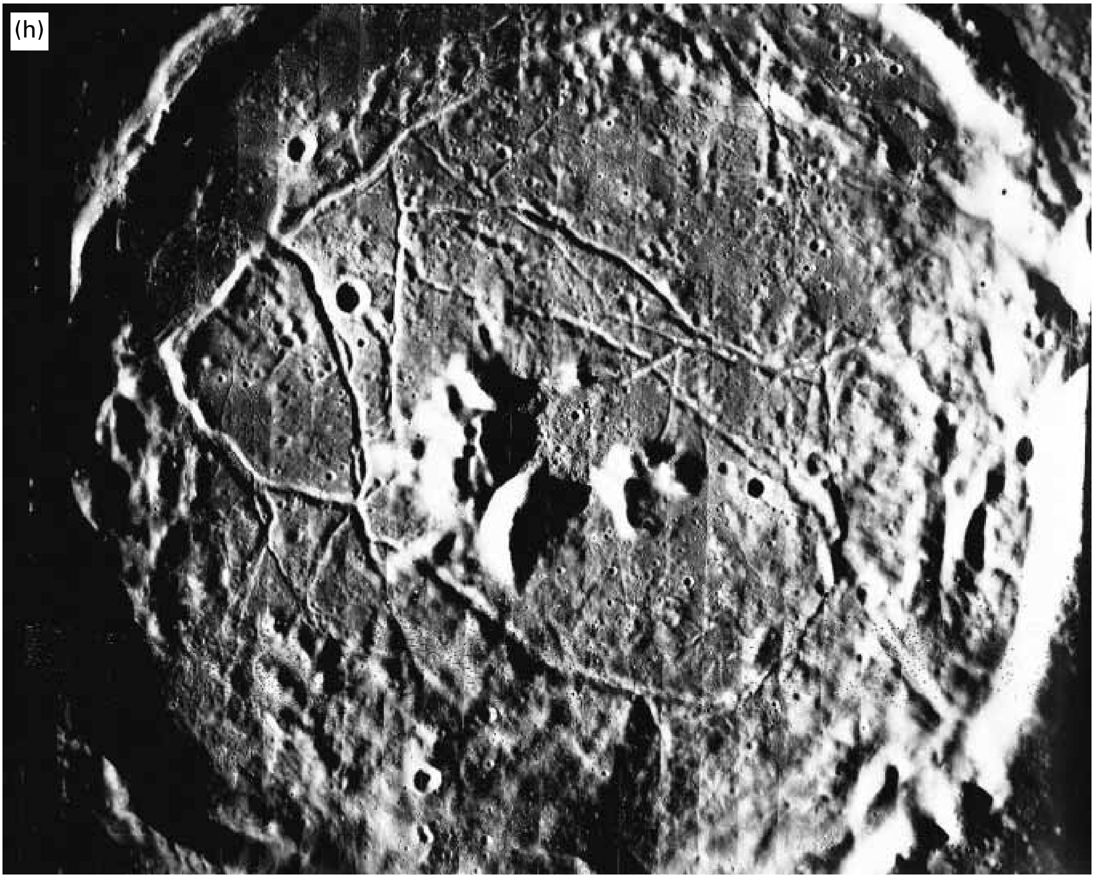
Further out, crossing the junctions of the Mare Humorum and Palus Epidemiarum and Mare Nubium, are several, also roughly concentric, graben. Each is of the order of 55 km wide and extends several hundreds of kilometres in length. These slumped features are thought to be the result of crustal stretching. Notice how they even carve their way through the mountainous regions and the oldest of the craters (but not the youngest examples).

The cluster of craters at the southern periphery of Mare Humorum are particularly beautiful. Figure 8.22(c) shows the group. It is an enlarged portion of Figure 8.22(a). The easternmost of the main craters, and the least degraded, is Vitello. Vitello is 45 km across and 1.7 km deep in its complex interior. It has a central hill and the interior shadows are far from regular when the Sun is low, as can be seen in the fine study by Andrew Johnson presented in Figure 8.22(d).

To the west of Vitello is the remnant of a large lava-flooded crater, with another partial ring, again completely flooded, abutting to its south-west. In effect, these form 'bays' in the Sea of Moisture. Just to the north-west of these and, at 64 km diameter, the largest of the formations pictured in Figure 8.22(c) is Dopplemayer. It has been flooded and eroded and yet its lofty central mountain soars about 760 m above the rippled floor of the crater.

It is Gassendi, though, which is the real jewel of the Mare Humorum. Spanning both 'shore' and 'sea' on the northern sector of the mare this 110 km diameter 'ring-plain' formation appears like a black lake at the times when the morning and the evening terminator just reaches it (see Figure 8.22(e)). With the Sun at a higher angle, the interior is seen to be

Figure 8.22 (*cont.*)
(h) *Orbiter V* photograph of Gassendi. (Courtesy NASA and Professor E. A. Whitaker.)



highly complex. Figure 8.22(f) shows a photograph of it taken with the 1.5 m Catalina Observatory telescope on 1966 April 2^{d} 08^{h} 12^{m} UT when the Sun's selenographic colongitude was 48°.7. Figure 8.22(g) shows it under a higher Sun (selenographic colongitude 61°.0). In fact, Figure 8.22(g) is an enlarged portion of part of Figure 8.22(a). You might notice how the relative prominence of the interior features has altered quite considerably over what is a relatively small change of lighting angle. This, in addition to the overall complexity of the formation, led to the selenographers of old varying quite considerably in the way they represented the crater. Inevitably, this led to debates about possible physical changes to the crater during the lifetimes of the observers – an idea now long abandoned, I hasten to add.

The walls vary in height around the crater, being highest on the west. An average height for them is about 1.8 km above the crater floor. The crater Gassendi A (33 km diameter, 3.6 km deep) intrudes into Gassendi to the north. Gassendi A is rather hexagonal in outline and has a complex interior. The southern section of the wall of Gassendi is highly eroded and even gives the impression of having been melted down by the lavas of Mare Humorum. The mare materials have clearly entered the crater here. The average hue of the floor of Gassendi is lighter than that of the Mare Humorum, except for the smooth crescent-shaped sector originating at the wall breach, which is of the same shade.

The crater floor is of the order of 600 m higher than the average level of the outer surrounds and is criss-crossed by a remarkable network of rilles. Many of these are visible in quite small telescopes (80–100 mm aperture) under suitable conditions of lighting. For a really detailed view of Gassendi take a look at the *Orbiter V* photograph shown in Figure 8.22(h).

As well as having a network of rilles over it, the floor is also rather rough and hummocky and there is an impressive central mountain complex. This is really the remnants of a central ring, as is evident in Figure 8.22(h). The tallest of the central peaks soars to above 1 km in height.

Gassendi is one of the Moon's 'hot spots' of Transient Lunar Phenomena, with many reliable reports of bright flashes and red glows seen in the crater. Significantly it turns out that it is also one of the sites of enhanced radon emission.

What story does the craggy face of Gassendi have to tell? Has the interior been pushed upwards by forces from below? What are the order and the time-scales of the events that have led to the Gassendi we see today?

8.23 HYGINUS, RIMA [CENTRED AT 8°N, 6°E] (WITH HYGINUS, RIMAE TRIESNECKER, TRIESNECKER)

The current thinking about rilles is that they are of two distinct types, each with a different mechanism of formation. *Sinuous rilles* are thought to have

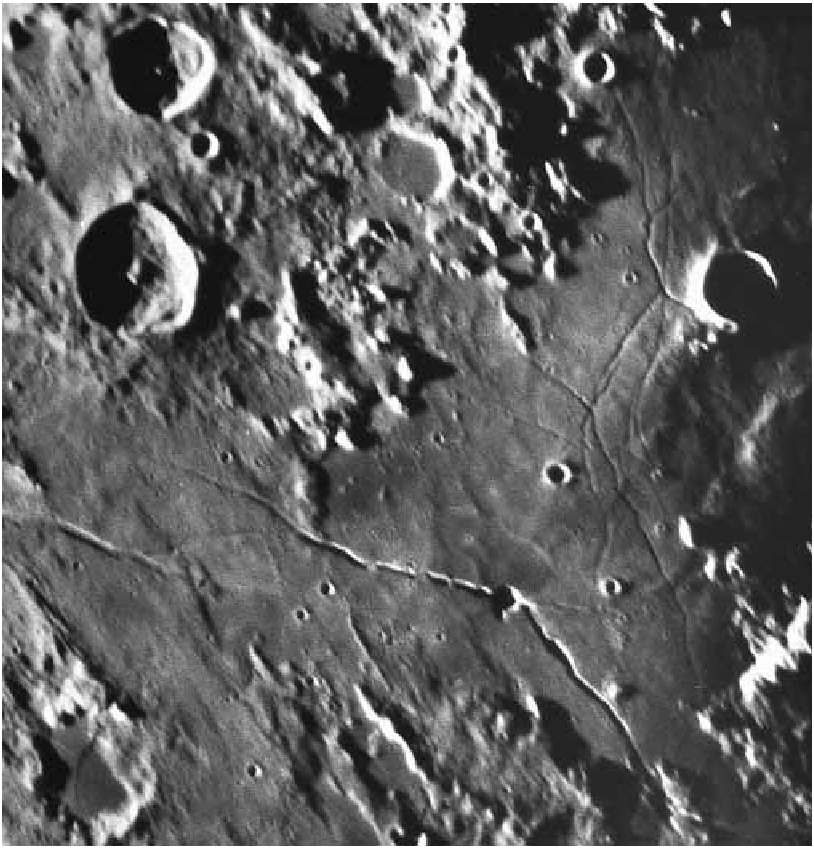


Figure 8.23 Triesnecker and its associated rilles (upper-right) and Rima Hyginus (extending from middle left to lower right) photographed using the 1.5 m reflector of the Catalina Observatory. At the time of the exposure, 1966 May 27^{d} 03^{h} 56^{m} UT, the Sun's selenographic colongitude was 356°.8. (Courtesy Lunar and Planetary Laboratory.)

been formed by running lava. Possibly the lava cut across the surface of the mare (they are peculiar to maria), or maybe it cut a tunnel just under the surface – the roof of the tunnel collapsing at a later date. They are characteristically about 1–2 kilometres wide (but wider examples exist, such as Vallis Schröteri) and they tend to snake about in the same manner as rivers do here on Earth.

The other type are the *linear rilles*. These tend, as their name suggests, to be somewhat straighter. Any changes of direction are rather more angular than is the case for the sinuous rilles. They also tend to be wider, typically 5–60 km, and can cross mare and highland boundaries. They are evidently lineaments where the ground to either side has been pulled apart slightly, creating slumped channels.

We call any channel of this sort a graben. Rima Ariadaeus, discussed in Section 8.6, seems to be of this type, and the arcuate rilles on the junction between the Mare Humorum and Palus Epidemiarum (see Section 8.22) even more definitely so.

Look at Figure 8.23 and you will find examples of both types of rilles. This Catalina Observatory photograph is of the region of the Moon extending from the Sinus Medii (at upper right) to the Mare Vaporum (lower left). Near the upper right of the frame is the 26 km diameter crater Triesnecker. It is itself an interesting object, 2.7 km deep and with a central mountain complex. However, it is the system of rilles extending from its eastern flank that grab the attention. These are the Rimae Triesnecker. They seem to be of the sinuous variety.

Crossing much of the frame from the lower right to the middle left of Figure 8.23 is the very much more prominent Rima Hyginus. At the extreme left of the photograph you will see the 'tail end' of another rille running parallel to the eastern end of the Rima Hyginus. This is the Rima Ariadaeus already referred to, and discussed more fully in Section 8.6.

Notice how a small crater (it is 10 km across) is situated at the sharp bend in the rille. This is the crater Hyginus. It is deeper than the rille and extends to a depth of about 770 m. Look carefully at the section of the rille to the east (left in the photograph) of Hyginus and you will see further, though much smaller, craters threaded along it like pearls on a necklace. High-resolution images from space probes reveal even more of the crater-chain appearance of Rima Hyginus. Other linear rilles show a similar structure.

It is not easy to understand exactly how these craters fit into the scheme of things. Are they also collapse features? Could at least some of the 'linear rilles' have been created in the same way as the sinuous rilles, except that the underground channels were much wider. Perhaps there was extensive lava flowing in thin sheets underneath the freshly solidified surfaces of the mare? Perhaps the roof falling in at widely spaced intervals creates crater chains? (Please note, I am here just referring to the small craters associated with rilles. I am not seeking to revive the spent arguments about the creation mechanisms of the Moon's major craters!) If the roof-falls occur closer together do they then form rilles of the Hyginus type? What about the crater Hyginus, itself, though? It is much deeper than the rille of which it seems to be such an important part.

If I seem to have posed a lot of questions to which you think that we ought to have definite answers by now, then I can only say that many experts differ in their interpretations of the rilles – and a few openly say that they are not at all sure of the mechanisms that have created these intriguing features.

The Ariadaeus, Hyginus and Triesnecker rille systems are visible with quite small-aperture telescopes near the times of first and last quarter Moon. I heartily commend you to seek them out and ponder on their significance for yourself.

8.24 IMBRIUM, MARE [CENTRED AT 35°N, 345°E] (WITH ARCHIMEDES, ARISTILLUS, AUTOLYCUS, BIANCHINI, HELICON, MONTES JURA, PROMONTORIUM HERACLIDES, PROMONTORIUM LAPLACE, SINUS IRIDUM, TIMOCHARIS)

The eastern edge of the Mare Imbrium (Sea of Rains) begins to come into sunlight about a day before first quarter Moon. At first quarter the area takes on a grand spectacle, as the photograph by Tony Pacey in Figure 8.24(a) shows. However, the nature of this important feature is probably best appreciated at a lunar age of about 10–11 days. Figure 8.24(b) is a photograph I took under just such lighting and conditions. I used my 18¼-inch (0.46 m) reflector to image the Moon directly onto HP5 film (processed in 'Celer Stellar' developer) in the camera mounted at the telescope's Newtonian focus (no eyepiece). Hence the effective focal ratio (EFR) is simply the focal ratio of the telescope (f/5.6).

If my choice of film seems odd to you, the reason is that I had wanted to use image projection to a high effective focal ratio. Hence the high-speed film I had loaded into my camera. As it was, the night turned out to be totally unsuitable, with poor transparency and very bad atmospheric turbulence, so I contented myself with a couple of low-resolution photographs of the Moon. The 1/500 second exposure was made at 1978 July 15^{d} 21^{h} 23^{m} UT, when the Sun's selenographic colongitude was 25°.3.

Figure 8.24(b) shows the outline of the circular Mare Imbrium very well, only the westernmost extremity of it lying over the dark side of the terminator. This basalt-filled basin is a whopping 1250 km in diameter. Only the Oceanus Procellarum has a greater area of mare-type basalt and the Imbrium Basin is the largest that is clearly identifiable as such on the Moon today. The impactor that created the basin also created ejecta and a pattern of ridges and linear faults radial to it that can be discerned (if you know what to look for) covering a large part of the Moon's visible face. Some of these have been featured in other sections in this chapter.

Several of the *Apollo* missions have obtained samples which included those identified as Imbrium impact ejecta (and *Apollo 15* actually landed on the periphery of the Mare Imbrium). It is from the laboratory analysis of these samples that a fairly precise date has been determined for the basin-creating impact. The results indicate that it happened 3.85 billion years ago, the uncertainty being plus or minus 0.05 billion years. This is one of the primary benchmarks that has been used to build up our picture of the sequence of events which sculpted the surface of the Moon that we see today. Actually, the Imbrium Basin is the youngest of the really large basins on the Moon's Earth-facing hemisphere. The Orientalis Basin is the only large one that is younger, but very little of it shows on the Earth-facing hemisphere.

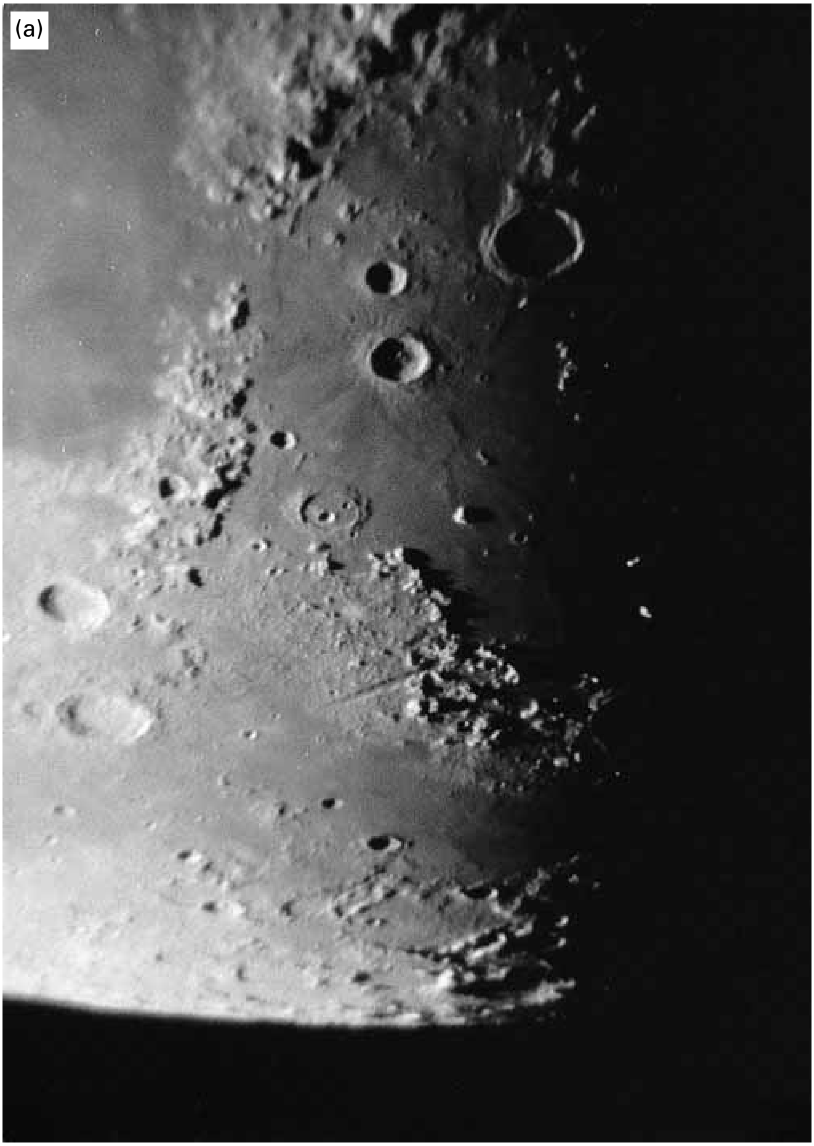


Figure 8.24 (a) Sunrise over the Mare Imbrium photographed by Tony Pacey on 1987 April 6^{d} 20^{h} 00^{m} UT (approx.). He used his 10-inch (254 mm) reflector, with eyepiece projection onto *Ilford* FP4 film for this 0.25 second exposure.

The age of the surface covering of the Mare has been determined mainly by the method of counting the numbers of craters of specific sizes, keyed with the determined ages of the *Apollo 15* rock samples. That and spectrophotometric studies (reflectance at specific wavelengths) has shown that episodes of lava flooding occurred from 3.7 to 3.2 billion years ago. The lavas that form the major part of the visible surface of the Mare Imbrium are taken to be about 3.3 billion years old.

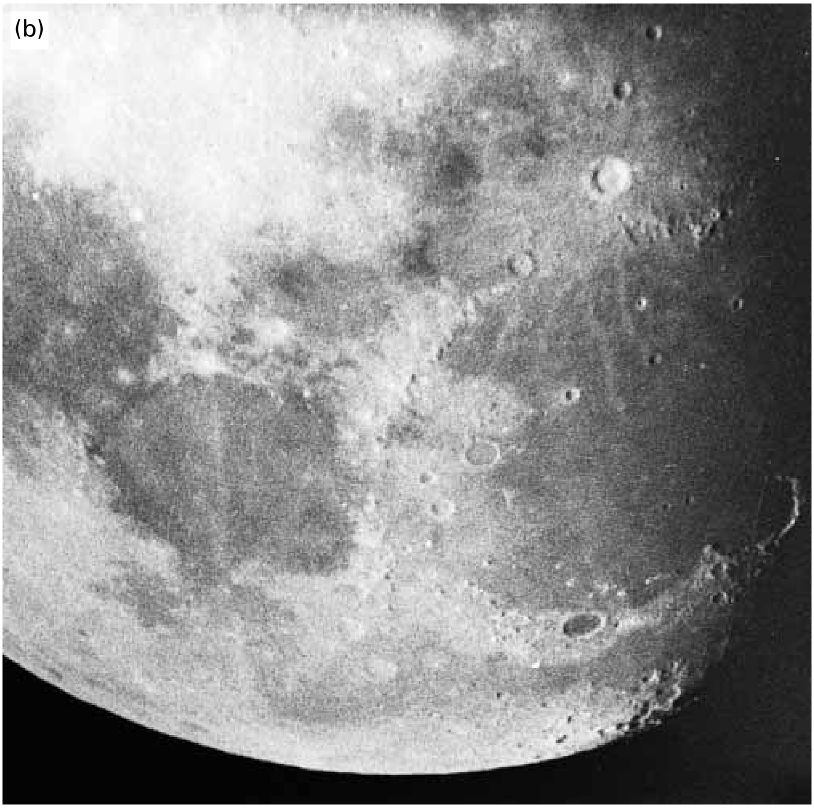


Figure 8.24 (*cont.*)
(b) The circular outline of the Mare Imbrium is evident in this photograph by the author. Details in text.

Some of these lava flows are visible as areas of slightly differing hue, even to the observer using simple eyeball-to-eyepiece methods. You might like to try looking for these yourself.

As always with lunar maria, a low Sun-angle shows up many wrinkle ridges and a peppering of small craters also covers the mare, though most are beyond the powers of amateur-sized telescopes and normal backyard observing conditions. See what examples you can find.

Figure 8.24(c) shows the south-eastern sector of the mare, while Figure 8.24(d) shows its north-eastern sector. Both are photographs taken with the 1.5 m reflector of the Catalina Observatory in Arizona. Figure 8.24(c) was taken on 1967 January $20^{d}\ 01^{h}\ 46^{m}$ UT, when the Sun's selenographic colongitude was 18°.5 (morning illumination) and Figure 8.24(d) was taken on 1966 September $6^{d}\ 10^{h}\ 44^{m}$ UT, when the colongitude was 167°.3 (late afternoon).

The spectacular Montes Apenninus defines the south-eastern boundary of the mare (see Figure 8.24(c)). These are chiefly blocks of lunar crust which have been violently uplifted by the Imbrium impact event. This mountain range is discussed in more detail in Section 8.5, earlier in this

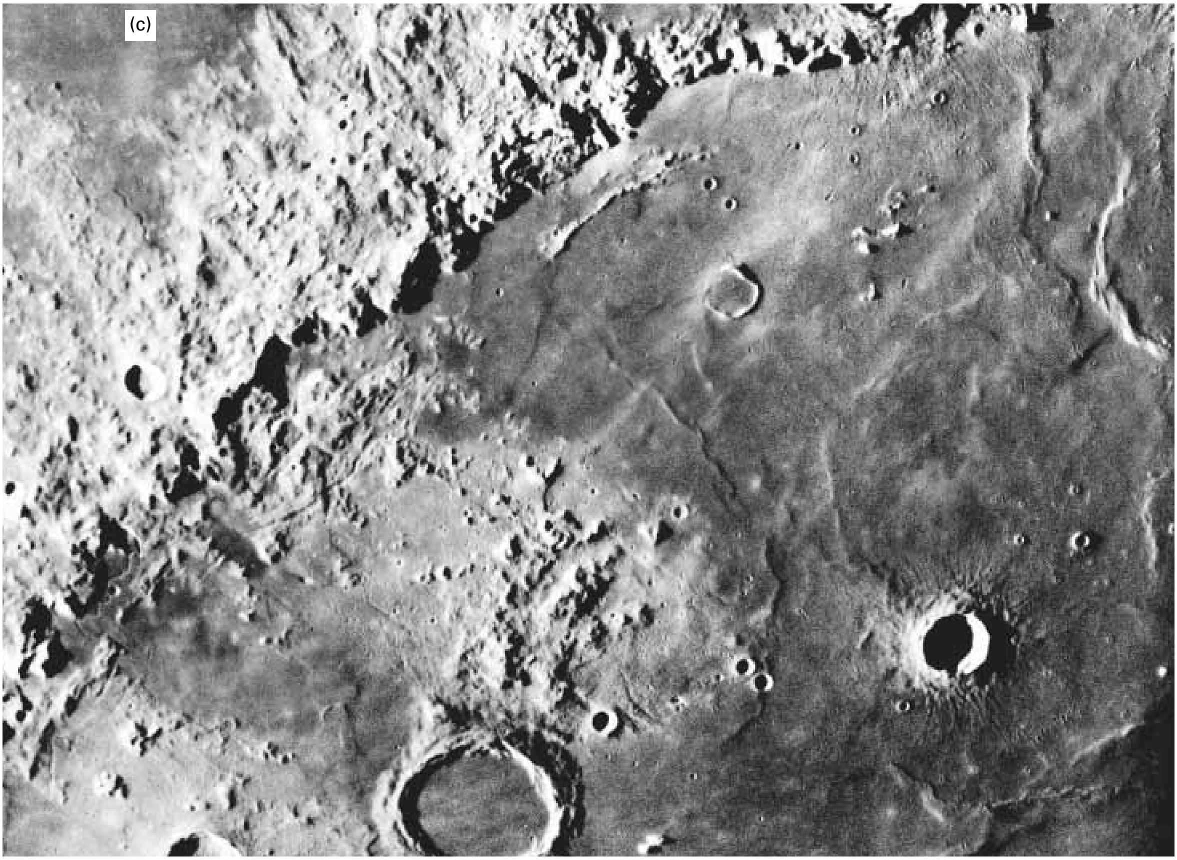


Figure 8.24 (*cont.*)
(c) South-eastern Mare Imbrium, bordered on the left by the Montes Apenninus. The largest crater (at the bottom of the photograph) is Archimedes. The crater to its left is Autolycus and that to its right is Timocharis. Further details in text. (Courtesy Lunar and Planetary Laboratory.)

chapter, together with the crater Eratosthenes, which marks the northernmost point of the Apennine range. To the west of Eratosthenes lies a further, smaller, range of mountains, the Montes Carpatus, with the major crater Copernicus just to their south (see Section 8.13).

The major part of the eastern boundary of the old basin is marked by the Montes Caucasus, another uplift-created mountain range. Between the Montes Apenninus and the Montes Caucasus there is a breach in the mountains where mare lavas have flowed to connect the Mare Imbrium with the adjacent Mare Serenitatis. Figure 8.24(a) shows this particularly well.

Along the north of the Mare Imbrium lies another mountain range, the Montes Alpes (discussed along with the Vallis Alpes, in Section 8.3). You will

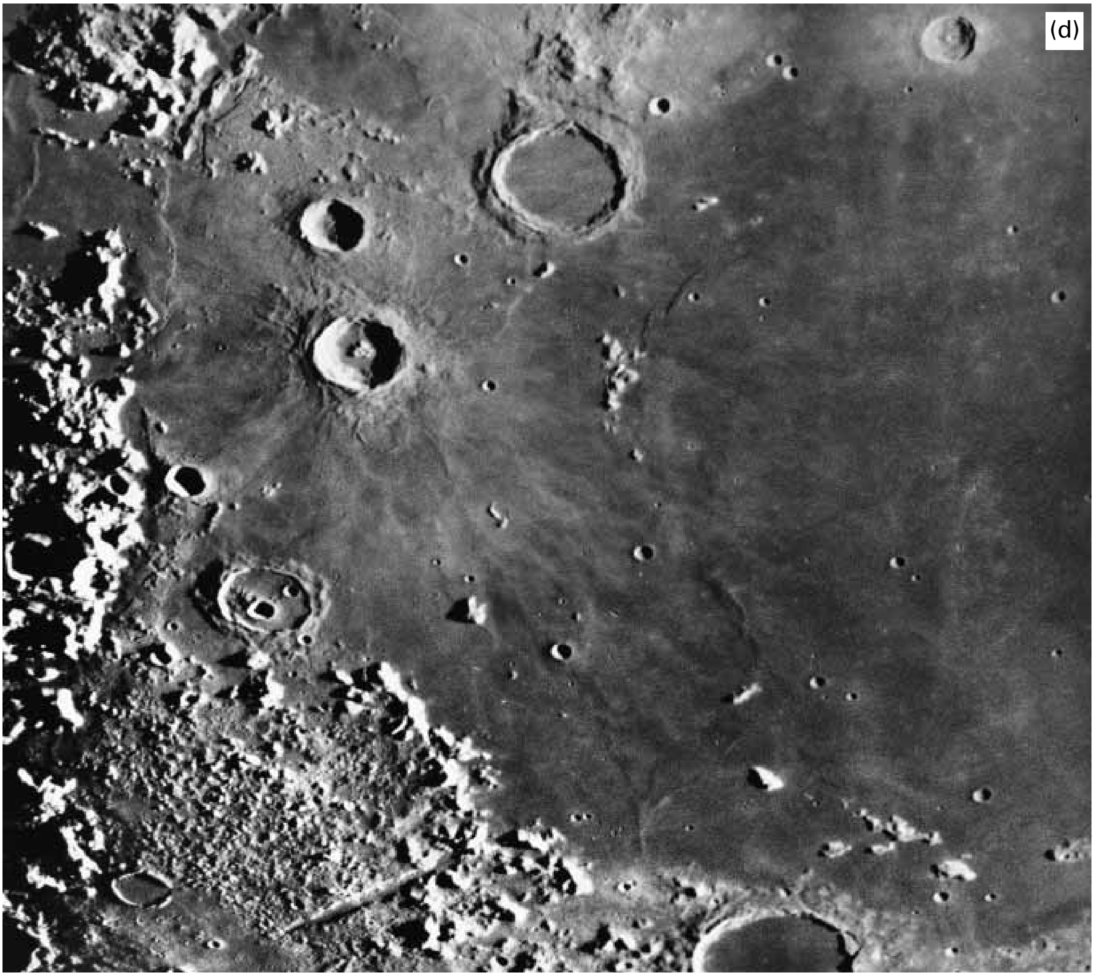


Figure 8.24 (*cont.*)
(d) North-eastern Mare Imbrium, bordered on the left by the Montes Caucasus, and on the lower left by the Montes Alpes. Further details in text. (Courtesy Lunar and Planetary Laboratory.)

notice that the innermost boundary of this mountain range is also concentric with the mare but it lies along an arc of smaller radius than the Montes Carpatus, Apenninus, and Caucasus. Actually the Imbrium Basin was a 'multi-ring' basin. The outermost ring is defined by the mountain ranges previously mentioned while the Montes Alpes is the surviving part of the middle one of three original rings of uplifted lunar crust. All that survives of the innermost ring is a few isolated mountains that poke up through the lava flood-plain. I will leave you to obtain a map of the mare (I recommend using a plan-view) and identify, and plot, the vestiges of the rings for yourself.

There is almost no sign of any remaining ring-relics along the westernmost boundary of the Mare Imbrium. Here it simply merges with the vast

Figure 8.24 (*cont.*)
(e) Archimedes (the largest crater), Autolycus (upper-left crater), and Aristillus (lower-left crater). Enlarged portion of Figure 8.24(d). (Courtesy Lunar and Planetary Laboratory).

expanse of the Oceanus Procellarum. Examine the area at full Moon and you will see clear indications that the darker Imbrium lavas have overflowed into the slightly lighter Procellarum lavas, rather than the other way round.

In the bay at the southern extremity of the Montes Alpes and the northernmost section of the Montes Caucasus is situated the interesting crater Cassini. This crater and its environs are discussed in detail in Section 8.11.

The prominence of the largest crater on the mare, the 83 km diameter Archimedes, is such as to be a 'focal point' of the mare even though it is positioned considerably off-centre. Figure 8.24(e) (which is an enlarged part of Figure 8.24(d)) shows it very well. Clearly the impact that created the crater happened after the Imbrium Basin was formed (it could not have survived the Basin-forming event) but before the mare flooding episode (the mare lavas remain undisturbed right up to where the crater emerges from the mare). It also indicates the shallowness of the mare flood-plain. Most of this form of crater exists as a depression below the surface of the surrounds (there are plenty of examples all over the Moon to bolster this assertion). Yet the rim still rises up to nearly 1.9 km above the flood-plain in places. Notice, also the hummocky tract of ground extending southwards towards the Montes Apenninus and how the mare lavas have interacted with it – a further indication of the shallowness of the lunar 'sea'. Even at the centre

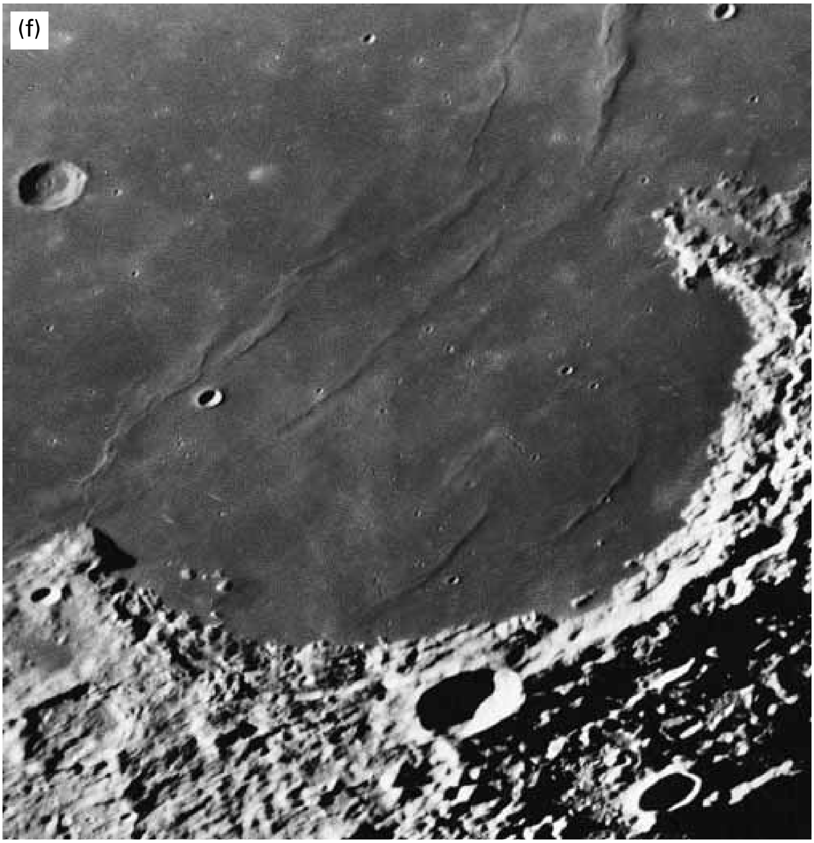


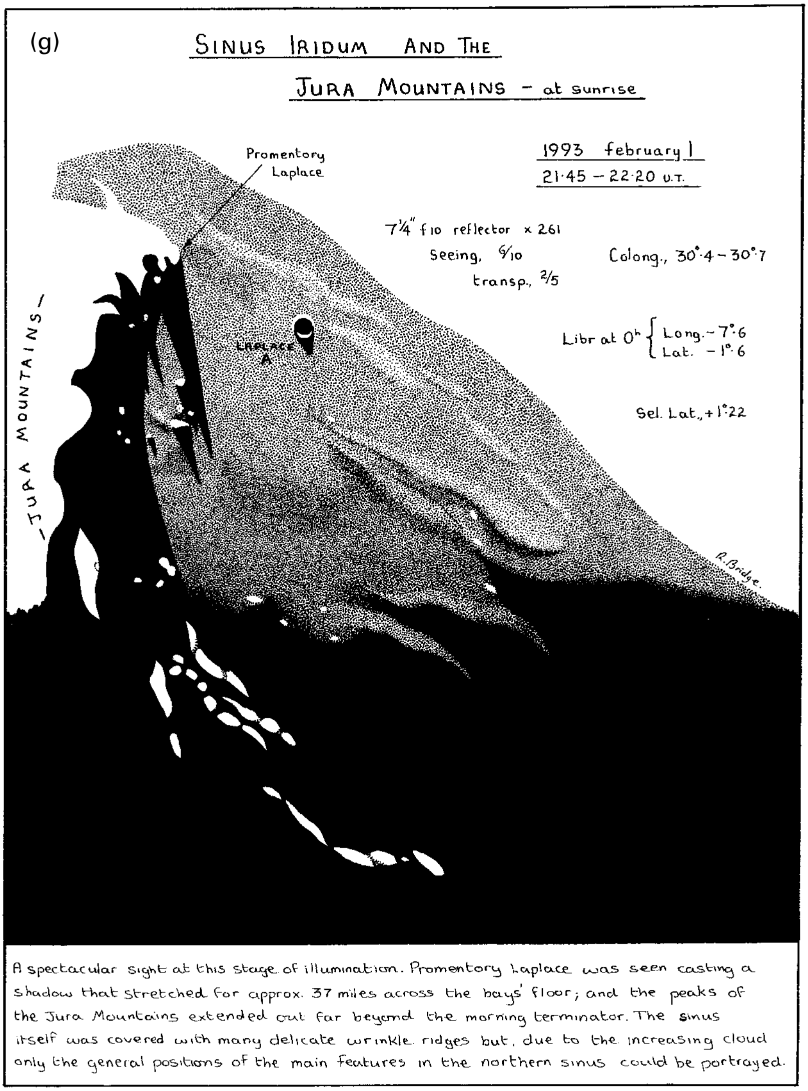
Figure 8.24 (*cont.*)
(f) Sinus Iridum, bordered by the Montes Jura. Details in text. (Courtesy Lunar and Planetary Laboratory.)

of the Imbrium Basin, the depth of mare basalt is probably no greater than 1.5 km.

The fact that Archimedes has been filled in with mare-type lava almost to the level of the Mare Imbrium surrounds (actually, about 200 m below) is interesting. I estimate that the lava-filling inside the crater must extend to around 2 km depth, deeper than the extreme depths of almost all of the Moon's 'seas'!

Though the crater superficially has a bland appearance, there are some delicate features to discern in Archimedes. The easiest of these is the spire-like shadows cast by the crater rim across the floor when the Sun-angle is low. These are instructive as they are a magnified (though distorted) profile of the rim itself. The next easiest to discern is a faint pattern of east–west bands covering the floor of the crater. They are most obvious under a high Sun. What do you think caused the pattern? Hardest to see are some very tiny craters within Archimedes. They are best under a low Sun but also need a good telescope and fine seeing conditions. The ones I have seen most

Figure 8.24 (*cont.*)
(g) 'The Golden Handle' effect. South is to the right in this drawing by Roy Bridge.



often are a pair close to the north-west rim. I find I can discern some others but only rarely. How many can you see?

The next major crater to the west of Archimedes (to the right of Archimedes on Figure 8.24(c), both craters being near the bottom of the photograph), is the 35 km diameter Timocharis. It is 3.1 km deep, with terraced walls rising to a sharply defined rim. It has a faded ejecta pattern which becomes most prominent near full Moon. At these times the crater also takes on a rather 'mist-filled' appearance, the same mirage that afflicts Eratosthenes.

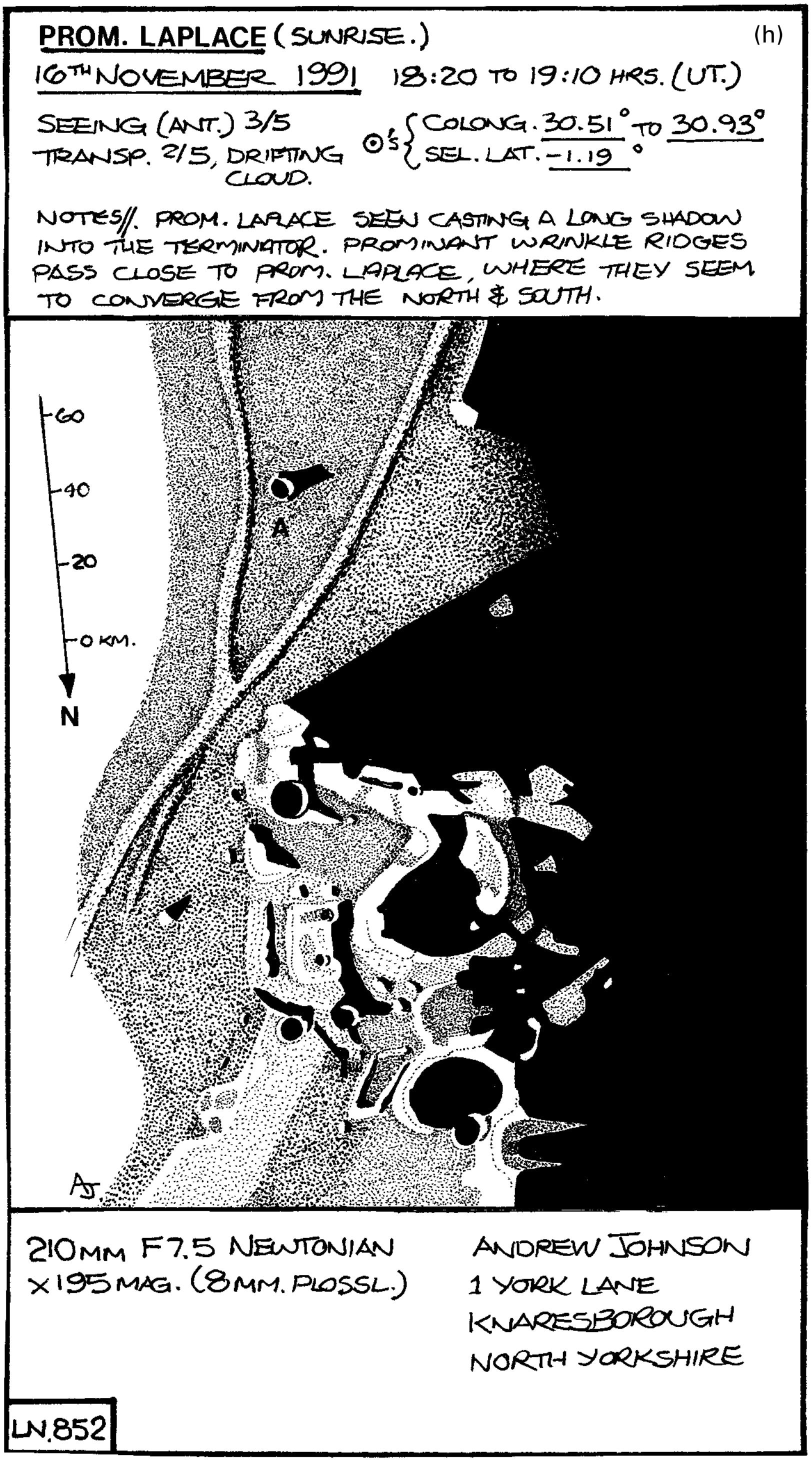


Figure 8.24 (*cont.*)
(h) Promontorium Laplace, drawn by Andrew Johnson.

The first major crater to the east of Archimedes is Autolycus. This is 39 km in diameter and 3.4 km deep. It has a ray system which is fainter than that of Timocharis, with a gentler interior slope and wider terraces. To the north of Autolycus is the larger, 55 km diameter, Aristillus. It is 3.6 km deep and also has significant interior terracing. Its ray pattern is the most prominent of the three craters. The prominent triple mountain peaks rise to almost 1 km above the crater floor. All three of these craters have raised outer slopes and ejecta patterns splashed across the mare, so they were obviously formed **after** the mare-flooding episode.

At the western end of the Montes Alpes there is a bay, the Sinus Iridum (Bay of Rainbows), the bordering mountain range being named Montes Jura (the Jura Mountains). This bay merges with the Mare Imbrium at the junction between it and the Oceanus Procellarum. Obviously the Jura Mountains are the surviving remnants of the uplifted crust defining another impact basin, of about 250 km diameter, which overlapped the Imbrium Basin. Which, though, came first? The answer is not at all obvious but planetologists consider the wide tract of light-coloured, hummocky, terrain along the northern 'shore' of the Mare Imbrium and extending to the Jura Mountains and a little beyond to have been created contemporaneously with the Imbrium impact. If this is correct then it follows that the Iridum Basin was formed after the Imbrium Basin (can you see why?).

Figure 8.24(f) shows the Sinus Iridum in full morning sunlight. It is another Catalina Observatory photograph, this one taken on 1967 January 22^{d} 03^{h} 31^{m} UT, with the Sun's selenographic colongitude 43°.9. The cape at the eastern end of the Montes Jura has been named Promontorium Laplace (Cape Laplace). That at the western end is Promontorium Heraclides (Cape Heraclides). The large (39 km diameter) crater in the hinterland mid-way between the capes is called Bianchini. The crater at the top left of Figure 8.24(f) is Helicon. It has an unusual structure, 25 km in diameter with a single interior terrace in the 1.9 km high walls above the flooded crater floor. Helicon actually resides beyond the boundary of the Sinus Iridum, on the Mare Imbrium. Many wrinkle ridges cross the floor of the Sinus Iridum. Some of these are roughly concentric to the Iridum Basin, others to the Imbrium Basin. The junction between the two is the most wrinkled part of all.

At the times when the terminator bisects the Sinus Iridum, part of the Montes Jura are in full sunlight, and the rest of the range pokes up into the sunshine, producing an effect called "The Golden Handle". I captured this appearance in the photograph presented as Figure 8.24(b). A more detailed view is provided by Roy Bridge in his drawing, which is shown in Figure 8.24(g). Figure 8.24(h) shows a more detailed view of the Promontorium Laplace at local dawn, as drawn by Andrew Johnson.

Lastly, I should mention the 'Great Black Lake' crater Plato which is situated at the north point of the Mare Imbrium. It is important enough to demand a section all of its own. You will find details of it and some of the nearby features on the Mare Imbrium, such as Mons Pico and Piton, in Section 8.33 further on in this chapter.

8.25 JANSSEN [45°S, 42°E] (WITH FABRICIUS, METIUS, RHEITA, VALLIS RHEITA)

The crater-ridden south-eastern highlands of the Moon can be a highly confusing place to find one's way around. Figure 8.25(a) is a wide-field view of this portion of the lunar disk, taken with the 1.5 m reflector of the Catalina Observatory in Arizona. The exposure was made at 1966 June 24^{d} 03^{h} 39^{m} UT, the Sun's selenographic colongitude being 339°.8 at the time.

Look to the left of centre on Figure 8.25(a) and you should be able to discern the outline of one of the most important formations in this area of the Moon. This is the crater Janssen (not to be confused with Jansen – a small crater in the Mare Tranquillitatis!). Figure 8.25(b) is an enlarged portion of the same photograph, in which Janssen nearly fills the frame.

Janssen's hexagonal outline is a mighty 190 km in diameter. It is clearly an extremely old structure, having been extensively modified and covered in craters large and small. The largest of the intruding craters, at 78 km diameter, is Fabricius. This is sited in Janssen's north-east sector. Notice the partial inner ring, concentric with the terraced walls of Fabricius. Also of note is the rille (judging by the look of it, a graben) that curves from the south-south-west rim of Fabricius right across the floor of Janssen to its far wall. The whole interior of Janssen has the decidedly 'tortured' appearance of a lunar formation of the greatest antiquity. You will find endless hours of interest in the study of this one feature alone.

Adjoining Fabricius to its north-east is the somewhat larger (88 km diameter) crater Metius. Though part of it is seen in Figure 8.25(b), it is seen fully in Figure 8.25(c), another enlarged portion of the same Catalina Observatory photograph.

Metius has a much more 'smoothed down' appearance than Fabricius, especially in its floor. Undoubtedly this has much do with the shaking Metius received during the impacts that created the craters around it, especially Fabricius which clearly post-dates it. Figure 8.25(a) shows that many of the old impact-craters share the same eroded characteristics in this region of the Moon. Going further north-east there is another old crater, Rheita. This is 70 km in diameter and its general form seems to be something of a cross between that of Fabricius and that of Metius (but more like that of Metius).

Figure 8.25 (a) The south-eastern highlands of the Moon. Note the hexagonal form of the giant crater Janssen, just to the left of the centre of the photograph, and the gorge-like Vallis Rheita, close to the left. Details in text. (Courtesy Lunar and Planetary Laboratory.)

However, the main interest here is not Rheita but rather the enormous gorge-like valley its western rim intrudes into. This remarkable formation dominates Figure 8.25(c).

Depending on where you define the beginning and end of the valley to be, it is about 180 km long and is about 25 km wide along much of its length. Best seen two or three days after full Moon, it resembles a line of craters, all overlapping and with the walls between them broken down.

Both camps of crater creationists (impact and volcanism) claimed this feature as definite proof of their ideas. To the 'volcanists' the valley

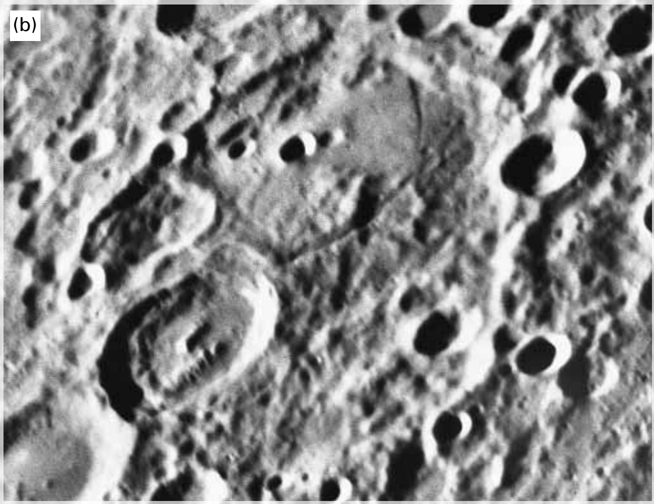


Figure 8.25 (*cont.*)
(b) Close-up of Janssen. This is an enlarged portion of (a). The crater Fabricius is in the lower-left part of Janssen. (Courtesy Lunar and Planetary Laboratory.)

Figure 8.25 (*cont.*)
(c) Close-up of Vallis Rheita. The crater Rheita intrudes into the lower end of the valley. Upper right of Rheita, and on the other side of the valley, the largest crater is Metius. Adjoining Metius, and to the upper right of it, is the crater Fabricius. Part of Janssen is also shown in this enlarged portion of (a), which also overlaps with the view shown in (b). (Courtesy Lunar and Planetary Laboratory.)

represented a chain of calderas aligned over a massive fault. Meanwhile the 'impactists' thought that the Vallis Rheita, and a few other examples of the same type of formation, were created by blocks of material ejected from the mare basins when they were formed.

It now seems pretty certain that the 'impactists' have got it right. The closest mare is Mare Nectaris and there are a number of less prominent valleys in the area which are radial to it. You might like to examine Figure 8.25(a), or better still use your telescope to observe the region. How many valleys can you find?

The commentators I have read who make reference to the creation of Vallis Rheita all say that the ejecta from the Nectaris Basin event is responsible. However, Vallis Rheita seems to lie at a slightly different angle to the valleys I can identify as being radial to the Mare Nectaris. I, at least, think that the impact event that created the Mare Imbrium is the culprit for this particular 'scar' on the lunar surface. Certainly the alignment seems to better fit the centre of the Mare Imbrium, rather than the centre of the Mare Nectaris.

I think that the Moon-shaking Imbrium impact of 3.85 billion years ago caused some huge blocks of material to be blasted from the site into ballistic trajectories. If I am right, one meteor-like collection of these splattered across the Moon, like a blob of paint from a flicked paintbrush, to create the valley. Hence the valley is really a secondary impact feature!

8.26 LANGRENUS [9°S, 61°E] (WITH ANSGARIUS, HOLDEN, KAPTEYN, KÄSTNER, LAMÉ, LOHSE, LANGRENUS A, LA PÉROUSE, VENDELINUS)

The splendid crater Langrenus is situated on the eastern shore of the Mare Foecunditatis. It is large and looks imposing when the terminator is nearby. It also has a bright interior and so readily stands out under a high Sun. In fact, Langrenus is striking whenever it is sunlit (see Figure 8.26(a)).

It is a prominent member of 'the Great Eastern Chain' of craters, the most southerly member of which is Furnerius. Going northwards from Furnerius, first comes Petavius (Furnerius and Petavius are detailed in Section 8.17), then Vendelinus (see Figure 8.26(b), where it is pictured with Petavius) and then Langrenus (see Figure 8.26(c), where Vendelinus and Langrenus are pictured together). The more northerly members of the 'chain' are the Mare Crisium (see Section 8.14) and Endymion (see Section 8.15).

The details for Figures 8.26(a) and (b) are given in the accompanying captions. Figure 8.26(c) is a Catalina Observatory photograph, taken with the 1.5 m reflector, on 1966 May 6^{d} 08^{h} 12^{m} UT. At the time of the exposure the selenographic colongitude was 103°.4.

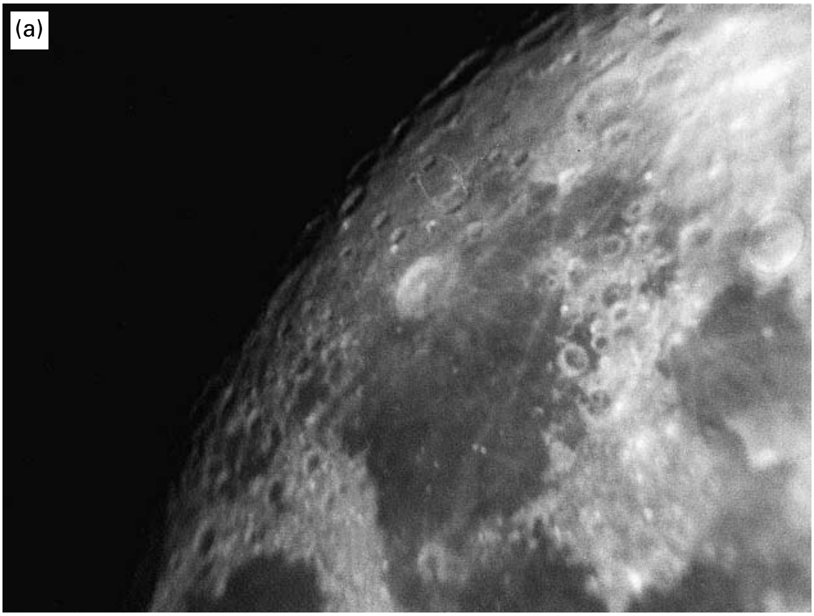


Figure 8.26 (a) General area of Langrenus (south is diagonally towards the upper right in this view). Photograph taken by the author, using his 0.46 m reflector, on 1977 August $29^d\ 22^h\ 33^m$ UT, when the Sun's selenographic colongitude was 85°.3. Eyepiece projection was used (EFR = f/17) for the 1/30 second exposure on FP4 film, developed in *Microphen.* (b) Vendelinus (lower formation) photographed, with Petavius, by Tony Pacey on 1992 January 21^d $23^h\ 55^m$ UT, when the Sun's selenographic colongitude was 103°.6. Tony used eyepiece projection on his 10-inch (254 mm) Newtonian reflector to produce an EFR of about f/50. A ½ second exposure was given on FP4 film.

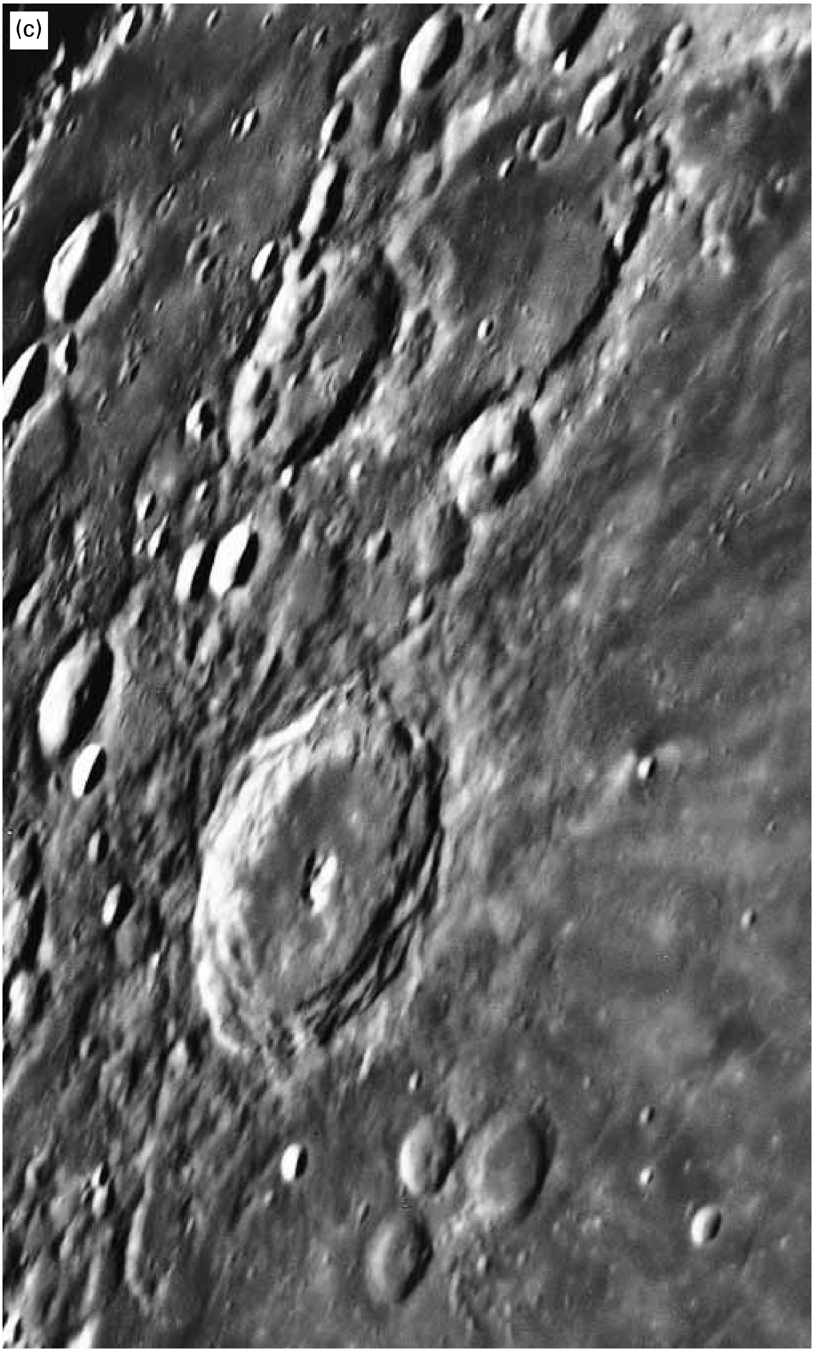


Figure 8.26 (*cont.*)
(c) Langrenus (lower crater) and Vendelinus (the large, less well-defined formation in the upper part of the frame). Details in text. (Courtesy Lunar and Planetary Laboratory.)

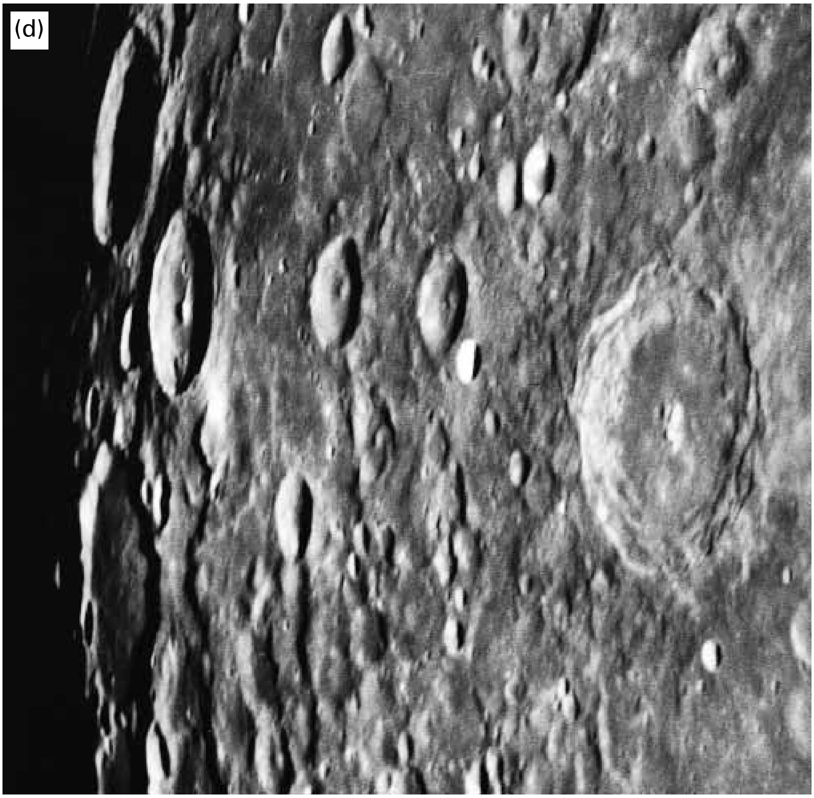


Figure 8.26 (*cont.*)
(d) Area extending eastwards from Langrenus. Going increasingly left from the top of Langrenus are the major craters: Langrenus A, Kapteyn and La Pérouse. To the upper left of La Pérouse is the larger crater Ansgarius. To the lower left of La Pérouse is the old 'walled-plain' Kästner. Further details in text. (Courtesy Lunar and Planetary Laboratory.)

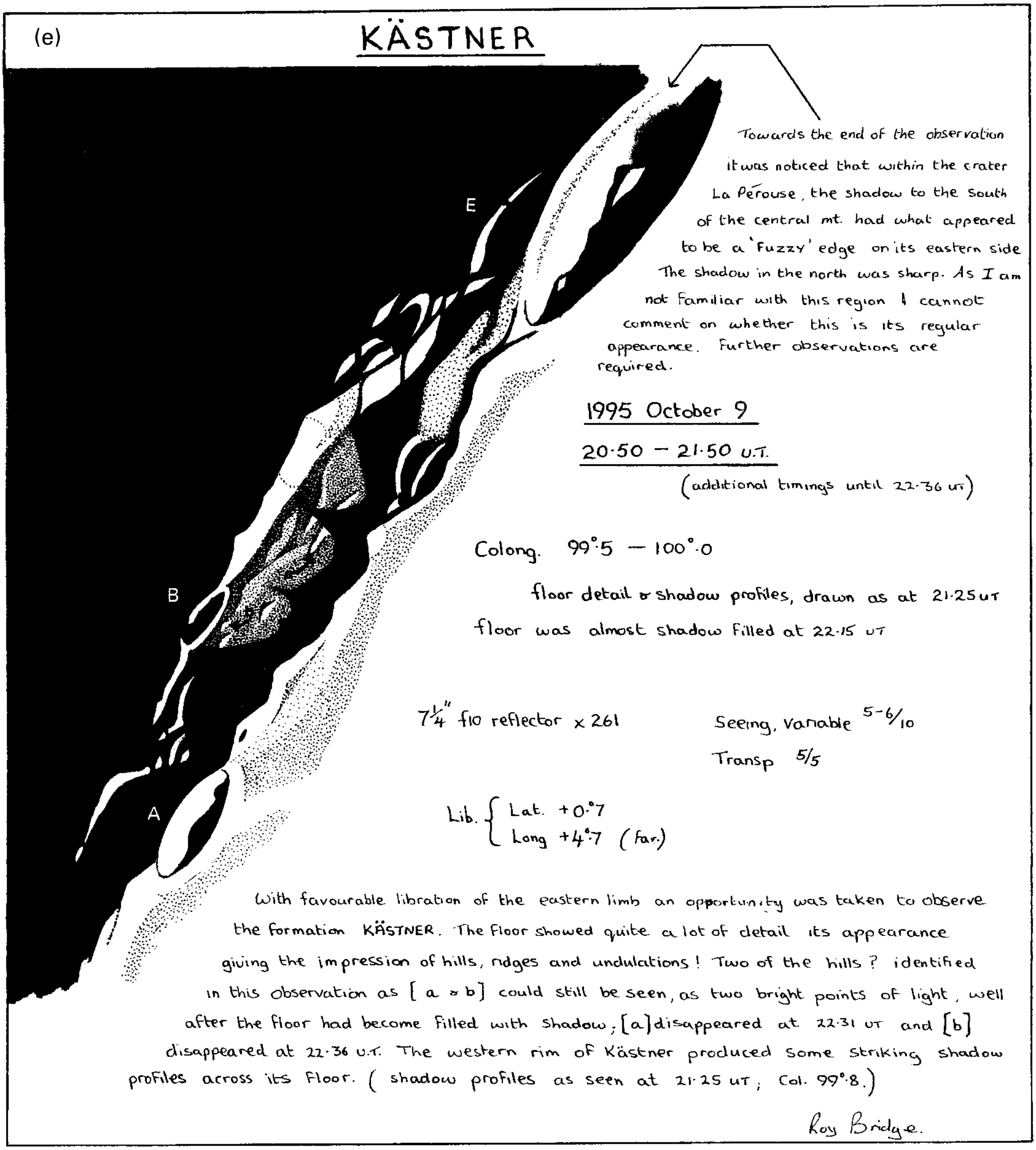
Langrenus's roughly terraced walls rise to about 2.7 km above the hilly floor. Rim-to-rim it spans a diameter of 132 km. The walls may look much higher than 2.7 km, in relation to the crater's diameter, but this is an illusion caused by a combination of our foreshortened view of the crater and the very gentle slope of the inner terraces. Owing to the interior slope, the main floor arena of the crater spans about 87 km, much smaller than its rim-to-rim diameter. The prominent and somewhat oddly shaped central mountain rises up to about 1 km above the crater floor.

There is much fine detail in the interior of Langrenus, and in the complex outer ramparts, to intrigue the observer equipped with even a quite small telescope. This is especially so as the appearance of the crater changes quite dramatically as the Sun rises over it. Figure 8.26(d) shows a view of the crater at a colongitude of only 6°.1 different from that in Figure 8.26(c), and yet the visual differences are obvious.

At high Sun angles I find that the interior of Langrenus takes on a distinctly yellowish-brown tint, compared to its surrounds. To see the colour clearly I use a magnification of no more than ×144 on my 18¼-inch (0.46 m) reflector. Can you see any colour tint inside Langrenus through your telescope?

Vendelinus is a very different type of formation to Langrenus, as is clearly shown in Figure 8.26(c). In fact, you may find it quite difficult to make out Vendelinus from the general confusion of lumps, bumps and smaller craters. This feature really only looks distinctive under a low Sun.

Figure 8.26 (*cont.*)
(e) Kästner, drawn by Roy Bridge.



First take a look at the small-scale image of it in Figure 8.26(b) and you should then be able to trace its outline in the much more detailed view presented in Figure 8.26(c). This 147 km diameter 'walled-plain' is clearly very old. Indeed, one could argue that it has just begun to lose its identity as a crater in its own right. Even if you think that is an exaggeration, you must surely agree that Vendelinus is a crater in an advanced state of ruin.

The largest crater to intrude into it (on its north-east portion) is the 84 km diameter Lamé. This creates the large 'notch' in the outline of Vendelinus which is so very apparent in Figure 8.26(b), Lamé here being filled with shadow. The other two sizeable craters which encroach onto the rim of Vendelinus are Holden to the south-east and Lohse to the north-west. These have diameters of 47 and 42 km, respectively. As is the case with Langrenus, there is much fine detail within Vendelinus for the enthusiast to study. The different characters of these lunar neighbours are as instructive as they are interesting.

Figure 8.26(d) is already referred to as providing another view of Langrenus. It is another Catalina Observatory photograph, this time taken on 1966 April 6^{d} 08^{h} 00^{m} UT when the Sun's selenographic colongitude was 97°.3. It shows the area eastwards of Langrenus. Take a line from the top of Langrenus, on the photograph, and extend it to the left and it will cut through three sizeable craters. The first is Langrenus A (diameter 42 km). Then comes Kapteyn (diameter 49 km). The last is La Pérouse (diameter 78 km). Notice the evolution of the forms of these craters going from the smallest. To the south-east (upper left in the photograph) is the even larger (94 km diameter) Ansgarius. To the north-east of La Pérouse is another ancient 'walled-plain' type of crater, the 119 km diameter Kästner. Roy Bridge has made a fine drawing of Kästner, along with La Pérouse, and this is presented in Figure 8.26(e).

This has been something of a 'whistle-stop tour' of the complex environs of the grand crater Langrenus. In truth, one could spend a lifetime making a study of any chosen small part of it!

8.27 MAESTLIN R [4°S, 319°E] (WITH MAESTLIN)

Just 120 km south-south-west of Kepler, Maestlin R is normally camouflaged by Kepler's rays. However, at low angles of illumination Kepler's rays vanish and features of small vertical relief become prominent. Maestlin R is an arc of isolated peaks, the only remains of an ancient crater that was all but obliterated about 3.2–3.8 billion years ago when the lavas that formed the vast expanse of the Oceanus Procellarum flowed across the lunar surface.

The remnants of the crater rim span about 60 km. Figure 8.27(a) shows an excellent drawing of it made by Roy Bridge. The small crater shown on

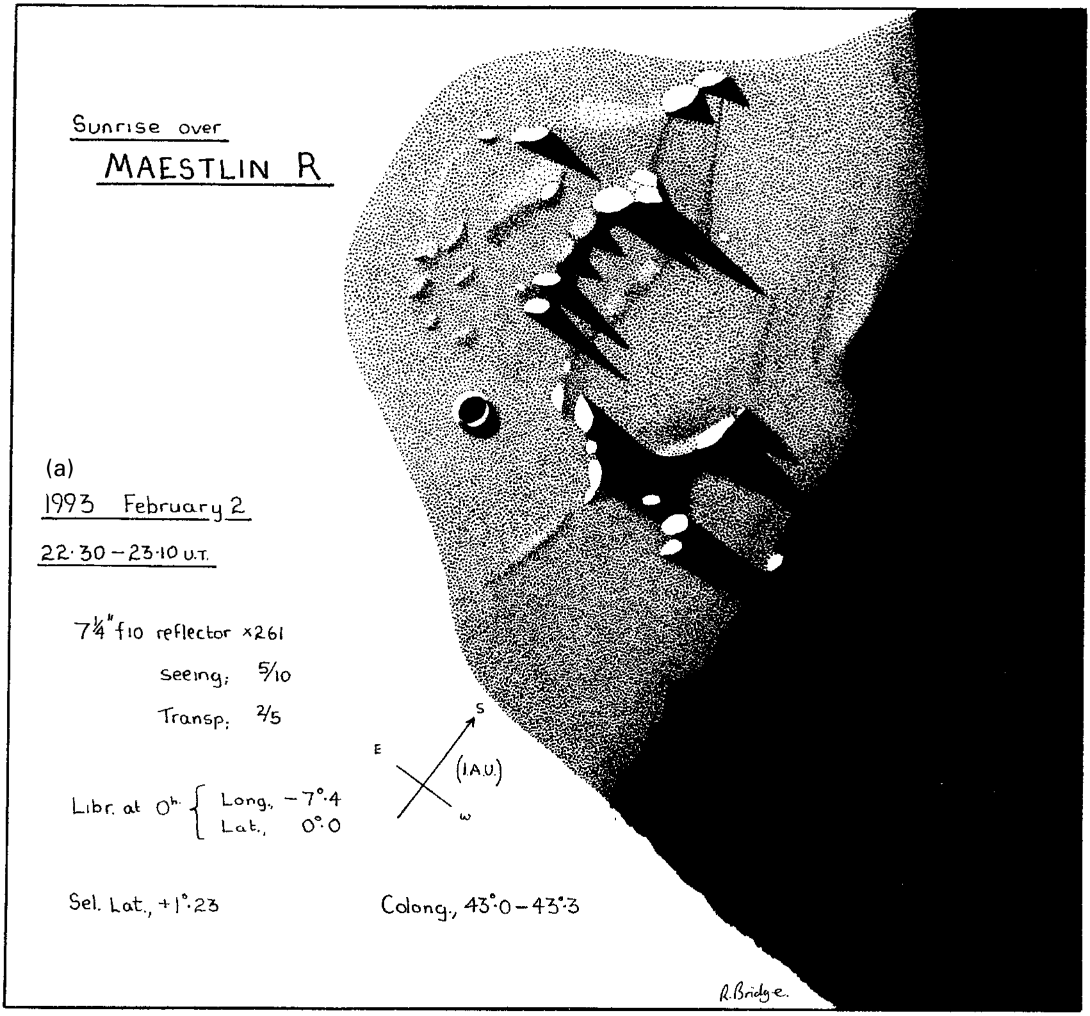


Figure 8.27 (a) Maestlin and Maestlin R, drawn by Roy Bridge. Note the north–south orientation of this drawing.

the drawing is Maestlin. It is rather dish-shaped, being 7.1 km in diameter and 1.6 km deep.

The main reason I selected this formation as one to feature is not so much the formation itself but rather that Roy Bridge has made a superb sequence drawing of sunrise over it. This is shown in Figure 8.27(b). Sequence drawings like these are highly instructive. Unless you happen to have a space probe fitted with high-resolution radar-ranging equipment that you can put into lunar orbit, this technique is the most sensitive available to you for detecting small variations of surface height. Appearances change rapidly at the terminator, as Figure 8.27(b) shows very well. Combined with drawings made on other dates, sunrise and sunset sequences can be used to generate extremely detailed profiles of lunar

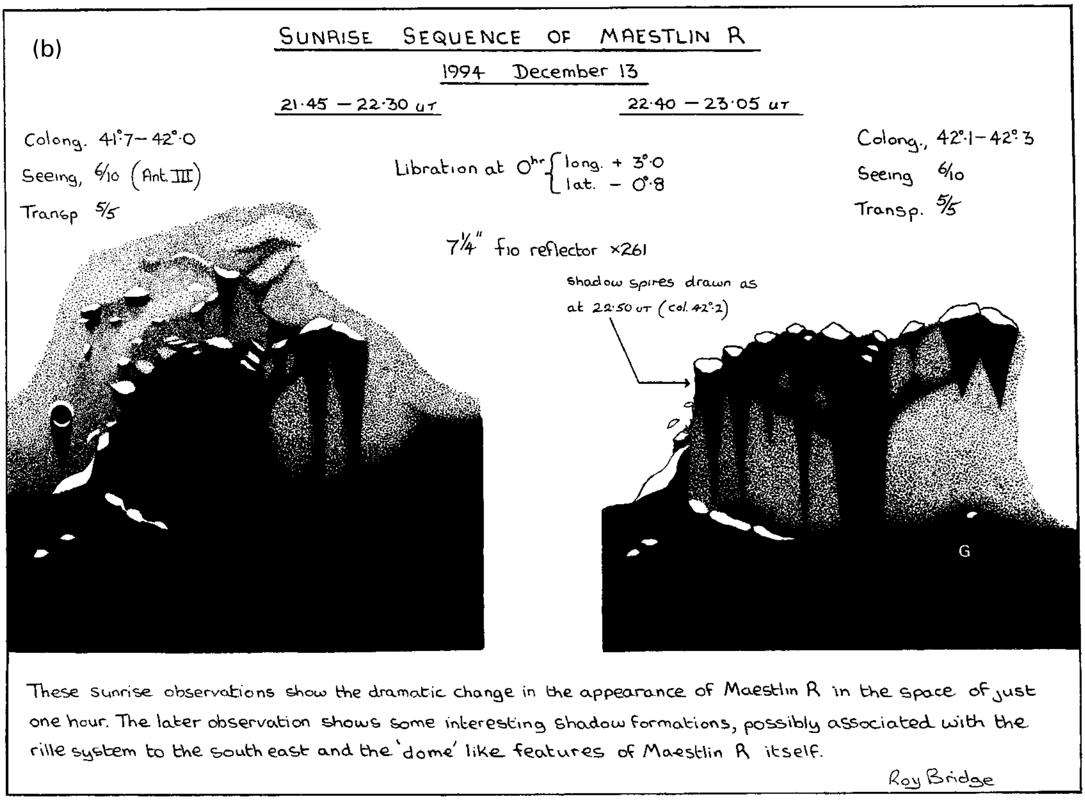


Figure 8.27 (*cont.*)
(b) Sunrise sequence of Maestlin R, drawn by Roy Bridge. The orientation of this drawing can be ascertained by comparing it to the drawing shown in (a).

surface topography. For instance, the drawings in Figures 8.27(a) and (b) can be used in this way. I will not pretend that your results will be cutting-edge science and that the professional planetologists will be waiting with bated breath for your publications. However, as with all your topographic studies of the Moon, **you** will get to know parts of the Moon in intimate detail.

8.28 MESSIER [2°S, 48°E] (WITH MESSIER A)

Not far from the crater Langrenus, just a little further north and quite close to the western shore of the Mare Foecunditatis, is situated one of the Moon's real oddities: the pair of craters Messier and Messier A. You might just be able to make them out on Figure 8.26(a), back in Section 8.26 dealing with Langrenus. Figure 8.28(a), presented here, shows them in much greater detail. This photograph was taken with the 1.5 m reflector of the Catalina Observatory on 1966 April 6^{d} 08^{h} 00^{m} UT, when the Sun's selenographic colongitude was 97°.3.

The eastern (left in the photograph) crater of the pair is Messier. It is rather oval, being elongated in the east–west direction, with dimensions of about 9 km × 11 km.

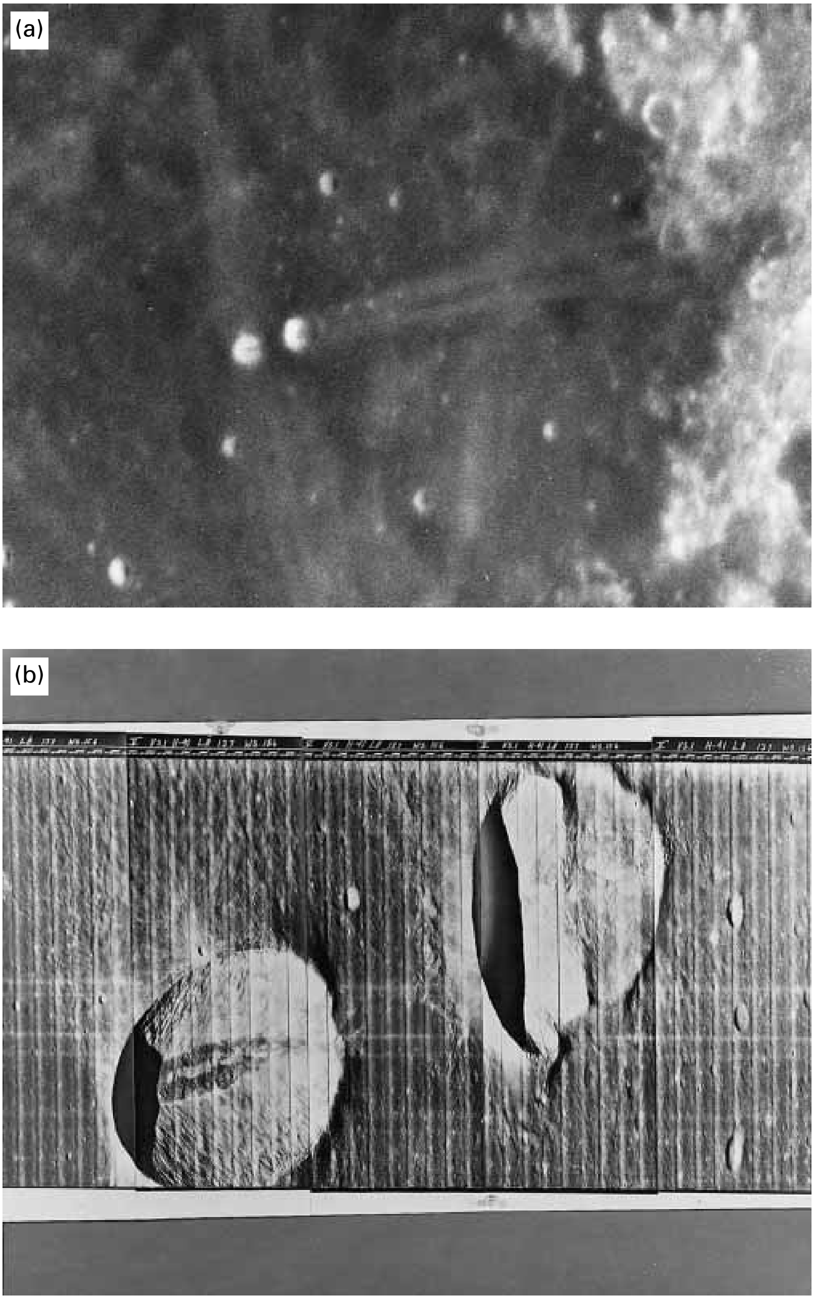


Figure 8.28 (a) Messier and Messier A. The western shore of the Mare Foecunditatis is visible on the right of the photograph. Details in text. (Courtesy Lunar and Planetary Laboratory.) (b) *Orbiter V* view of Messier and Messier A. (Courtesy NASA and Professor E. A. Whitaker.)

Messier A, which used to be called Pickering (I think that it is a pity the name was changed), is rather oddly shaped. The eastern (Messier-facing) side of it is flattened, while the western rim is much more pointed in form. In fact, the crater rim forms the same profile as a hen's egg! It is about 13 km across at it's widest part and is of similar east–west length to Messier. Both craters have highly reflective interiors with dark streaks extending westwards from the central regions up their west walls. There seems to be a thin ridge of raised ground extending from the west rim of Messier to the east rim of Messier A. Figure 8.28(b), an *Orbiter V* photograph, shows the craters in more detail.

Even more weird are the two rays which extend, comet-like, westwards from Messier A. The rays are very prominent under a high Sun. A 60 mm refractor will easily show them at these times. Remarkably the rays stay quite prominent even at very low Sun angles, unlike most other lunar ray systems.

Many of the observers of yesteryear suspected both long- and short-term changes in Messier and its companion. Certainly they can change in relative prominence during the lunation but all these changes are purely optical effects. However, there is one real mystery which surrounds this pair – how were they formed? On this there is no universal consensus. It seems certain that both are the result of a very low-angle (probably about 5°) impact of material striking the lunar surface from the east but was it a case of 'one lump or two'?

Did the impactor hit the Moon to form Messier, bouncing and finally dropping again to form Messier A? Or were there two impactors, perhaps two fragments of a comet, flying side by side? Nobody really knows for sure. The bright interiors and surviving ray pattern must mean the craters were formed in the last few hundred millions of years – why not seek them out yourself and ponder on how they were created.

8.29 MORETUS [71°S, 354°E] (WITH CYSATUS, GRUEMBERGER, SHORT)

Moretus stands like a sentinel at the gateway to the Moon's south polar region. It is a magnificent crater, 114 km in diameter, with beautifully sculpted interior terraces. At the centre of the large, arena-like, floor a central mountain mass rises to a height of about 2.1 km.

Moretus is pictured in Figure 8.29, which is a Catalina Observatory photograph. It was taken on 1967 January 20^{d} 01^{h} 52^{m} UT, when the Sun's selenographic colongitude was 18°.5. As the photograph shows, there are signs of another crater on the southern slopes of the interior. Oddly, all that shows are a series of mountain peaks. Could this be a case of a meteor having struck almost immediately after the great impact which created

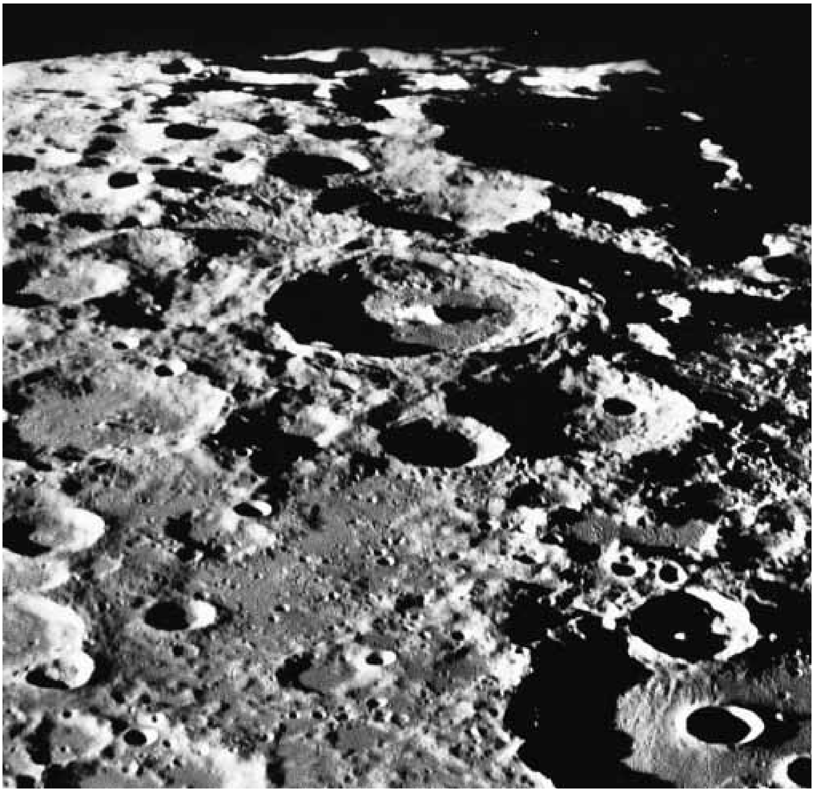


Figure 8.29 Moretus is the large crater in the upper-middle of this Catalina Observatory photograph. The formation in the lower-right corner is actually part of the crater Clavius. Details in text. (Courtesy Lunar and Planetary Laboratory.)

Moretus itself? My thinking is that the interior of Moretus would still have been largely molten and suffering the aftershocks of the primary impact, so preventing the second crater from fully forming.

The large crater, actually 94 km in diameter, immediately to the north-west of Moretus is called Gruemberger. It is obviously older than Moretus, its outline being much more eroded and its floor more extensively cratered. To the north of Moretus, also encroaching into Gruemberger, is the much fresher looking Cysatus. Cysatus, of diameter 49 km, has a finely terraced interior and a very low central mountain. South of Moretus is the 71 km diameter crater, Short.

The western extremity of the crater Moretus lies on the Moon's central meridian – latitude 0° (and 360°) E. That, together with the convergence of the terminator, enables one to deduce the direction of the lunar south pole. Of course, whether one can see it or not depends on the libration. I wonder how long it will be before a lunarnaut makes the trek and is first to stick a flag in the Moon's most southerly location?

8.30 NECTARIS, MARE [15°S, 35°E] (WITH BEAUMONT, FRACASTORIUS, PICCOLOMINI, ROSSE, RUPES ALTAI)

Mare Nectaris is a somewhat undistinguished looking basalt flood-plain in the Moon's south-eastern quadrant, adjoining the Mare Tranquillitatis. With the names meaning 'Sea of Nectar' and 'Sea of Tranquillity' this region of the Moon certainly sounds delightful!

The region is pictured in Figure 8.30(a). As can be seen from the photograph, Mare Nectaris is somewhat irregular in outline, though its nature as a lava-filled basin is not too hard to imagine. Its diameter averages about

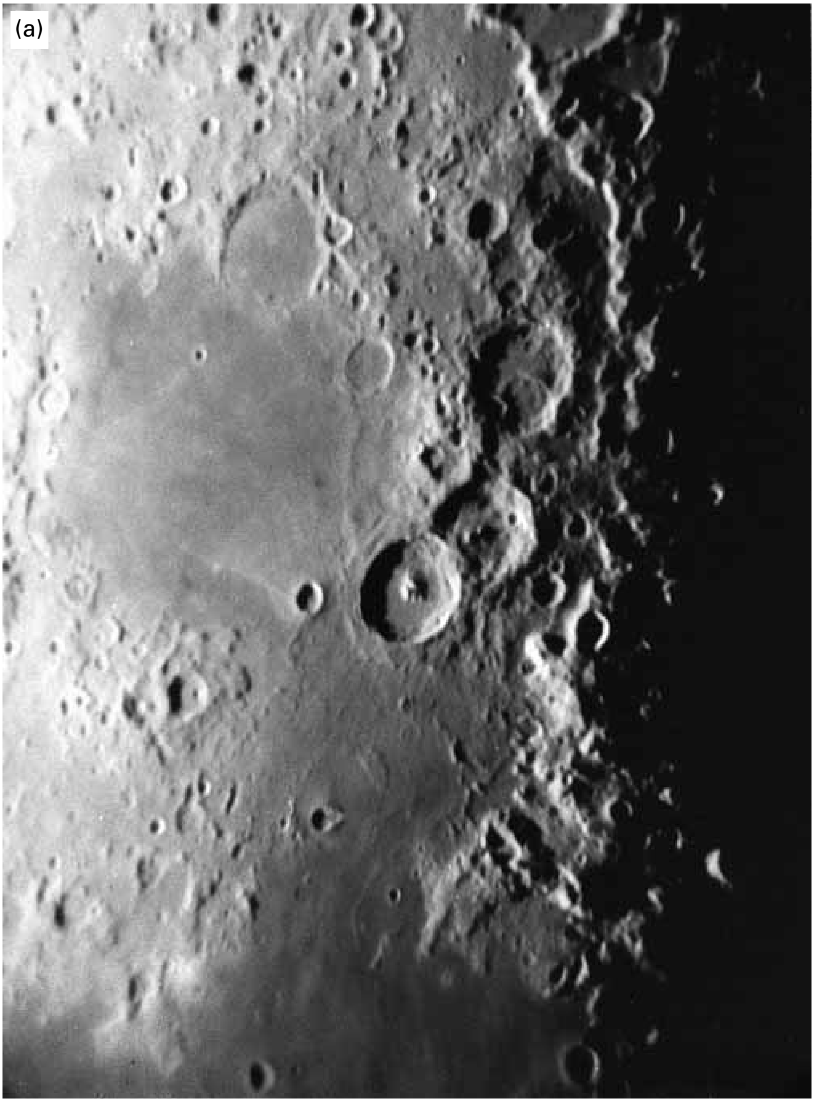


Figure 8.30 (a) The smooth grey plain in the upper-left part of this photograph is the Mare Nectaris. The rugged mountain range (really an escarpment) to the right of the photograph is known as the Rupes Altai. The three major craters to the left of the mountain range are Catharina (upper), Cyrillus (connected to Catharina) and Theophilus (overlapping Cyrillus). Photograph taken by Tony Pacey, using his 10-inch (254 mm) Newtonian reflector on 1991 March 21^{d} (time only approximately known – circa. 20^{h} 00^{m} UT). He used eyepiece projection and a 1 second exposure on T-Max 100 film, processed in HC110 developer.

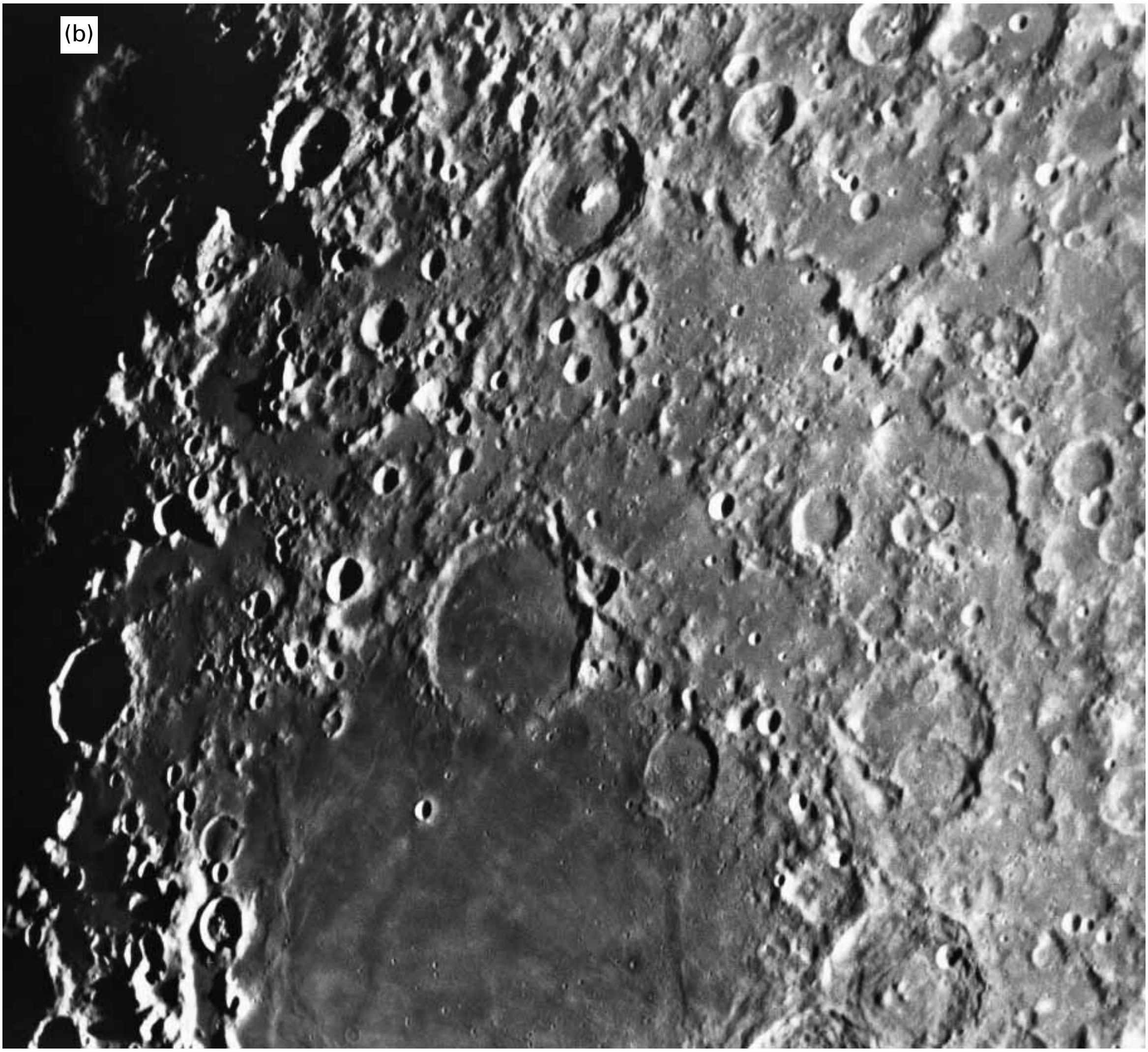

(b)

Figure 8.30 (*cont.*)
(b) Wide-angle view encompassing the southern half of the Mare Nectaris and the Rupes Altai. The dominant crater at the top of the photograph is Piccolomini. The flooded, incompletely enclosed, crater at the top of the mare is Fracastorius. The crater Catharina and part of Cyrillus can be seen to the lower right. Photograph taken with the Catalina Observatory 1.5 m reflector on 1965 November 12^{d} 10^{h} 31^{m} UT, when the Sun's selenographic colongitude was 134°.3. (Courtesy Lunar and Planetary Laboratory.)

350 km. The craters Catharina, Cyrillus, and Theophilus are identified on the photograph but a detailed discussion of these is reserved to Section 8.44, as is the small crater Mädler just to the east of Theophilus.

The *Apollo 16* Lunar Excursion Module touched down in the hinterlands approximately 300 km west of Theophilus. The rock samples collected were found to be very complex. In many cases the origins of the samples could not be determined with absolute certainty. This is particularly so in the case of Nectaris Basin ejecta. Bearing that in mind, planetary scientists have assigned an age of 3.92 billion years to the Nectaris Basin. Even if the sample identifications are correct, then the analytical techniques used still give an uncertainty of plus or minus 0.05 billion years for the result.

The interval between the formations of the Nectaris and Imbrium basins is now defined to be *Nectarian Period* in the chronology of the Moon. Officially the age range this represents spans 3.92–3.85 billion years. This was a time of heavy bombardment – a real lunar 'Blitzkrieg'. During the Nectarian Period a dozen other basin-forming impacts occurred, together with many of the larger, and now degraded, craters and some light plains formed by basin ejecta and a general heavy reworking of the Moon's regolith.

Also very evident on Figure 8.30(a) is a vast mountain range (more accurately described as an escarpment) encircling the mare to the south and west. This is the Rupes Altai, actually the surviving section of a ring that must have surrounded the Nectaris Basin until soon after its formation. The Nectaris Basin was a multi-ring structure. The best-preserved example of this type of formation is the larger and younger Mare Orientalis, situated on the Moon's western hemisphere and mostly on the hidden side.

Figure 8.30(b) shows the southern section of the Mare Nectaris in more detail. Notice also that the lighting is from the opposite direction. The major part of the Rupes Altai is also shown. Figure 8.30(c) is an enlarged section of (b), concentrating on the Rupes Altai. The whole escarpment spans about 500 km and follows a curve of radius approximately 480 km centred on the Mare Nectaris. The reason this formation is really best described as an escarpment, rather than a mountain range, is that the peaks are elevated to very little above the ground to the west. However, the ground falls away sharply on the side facing into the Mare Nectaris, the average drop being about 1.8 km.

It seems that the Rupes Altai is much more a slump-fault than a range of uplifted crustal blocks, as is the case for the Montes Apenninus, bordering the Imbrium Basin.

The formation is striking even through a small telescope when seen at lunar ages of around 5½ days and 19 days, though it rapidly loses its distinctiveness when the terminator moves away from the area. As you might be able to discern in Figure 8.30(b), there are distinct traces of the continuation of the ring beyond the southernmost point and round to

Figure 8.30 (*cont.*)
(c) Enlarged portion of (b) showing the Rupes Altai. Piccolomini is mostly hidden beyond the top-left corner and Catharina is to the lower right. (Courtesy Lunar and Planetary Laboratory.)

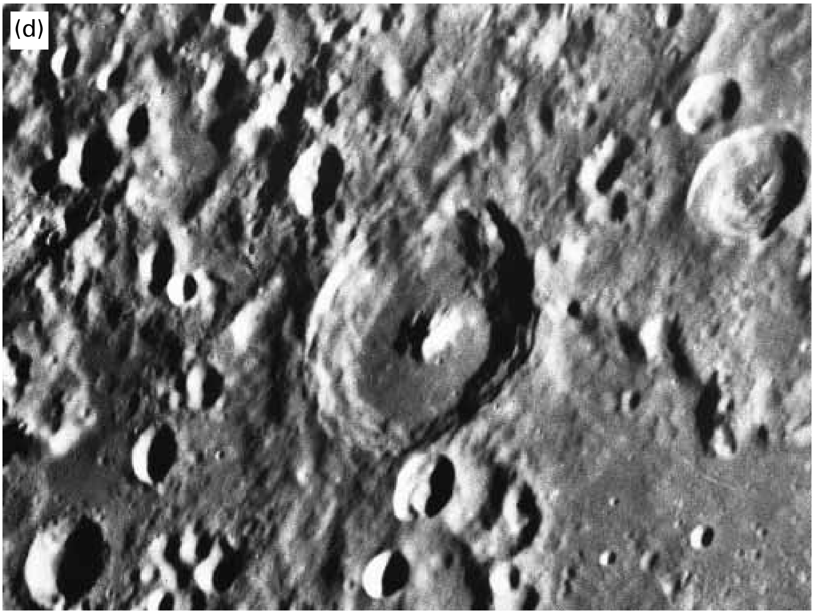


Figure 8.30 (*cont.*)
(d) Enlarged portion of (b) centred on Piccolomini. (Courtesy Lunar and Planetary Laboratory.)

the east of the Mare Nectaris but these are much less obvious than the Rupes Altai proper.

The southern portion of the Rupes Altai terminates in a beautifully sculpted large crater (shown in Figure 8.30(b)). This is the 89 km diameter Piccolomini. Figure 8.30(d) is another enlargement from (b) and is centred on Piccolomini. The walls of the crater rise to nearly 4.5 km above the significantly convex floor. The walls have very fine interior terraces which are noticeably smoothed by erosion and landslips. The northern half of the outer slopes are also rippled with slumps running parallel to the crater rim. The complicated central mountain mass also shows evidence of landslips and much of the floor of the crater is also quite well smoothed. Most remarkable of all, though, is the intrusion into the crater of the external terrain to the north of it. Indeed, the terrae seem almost to have 'poured' into the crater over its northern rim and even 'flowed' some way onto the crater floor. Clearly, Piccolomini has been subject to some very significant seismic shaking since its creation. A truly remarkable object.

The lava flooding that created the mare is thought to have occurred about 3.7–3.8 billion years ago. One of the casualties of these floods was the crater Fracastorius. This 124 km diameter crater is pictured, along with the southernmost section of the Mare Nectaris, in Figure 8.30(e). This is an enlargement of yet another part of Figure 8.30(b). Notice how the northern wall of the crater has been largely eliminated by the lavas. It seems that this section has been more than just buried. Rather, much of the original crater wall has been melted and washed away.

Figure 8.30 (*cont.*)
(e) Enlarged portion of (b) showing the southern sector of the Mare Nectaris. Fracastorius is in the upper half of the photograph. The much smaller, flooded crater Beaumont is to the right. The prominent small crater to the lower left of Fracastorius is Rosse. (Courtesy Lunar and Planetary Laboratory.)

The nearby crater Beaumont is a smaller-scale (53 km diameter) cousin of Fracastorius. In this case there is a small breach in the eastern section of the wall. The tiny craters that pepper the southern section of the Mare Nectaris, and the flooded floor of Fracastorius in particular, make an excellent test for observer, telescope and seeing conditions. How many can you see and record?

The small crater Rosse, 12 km in diameter and 2.4 km deep, situated on the Mare Nectaris about 70 km to the north of Fracastorius, should be easily visible in almost any telescope which can honestly sport the title 'astronomical'. It has a bright interior and is obviously quite 'fresh' by the standards of the local terrain.

All in all, this is a fascinating and highly complex area of the Moon.

8.31 NEPER [9°N, 84°E] (WITH JANSKY)

If you **really** want a challenge, try identifying and observing the crater Neper. It lies so close to the Moon's eastern limb that libration often conspires to remove it from view just when the lighting is suitable and the sky

Figure 8.31 (a) Neper is the large crater close to the limb of the Moon in this Yerkes Observatory photograph. (Courtesy Yerkes Observatory and Professor E. A. Whitaker.)

(b)

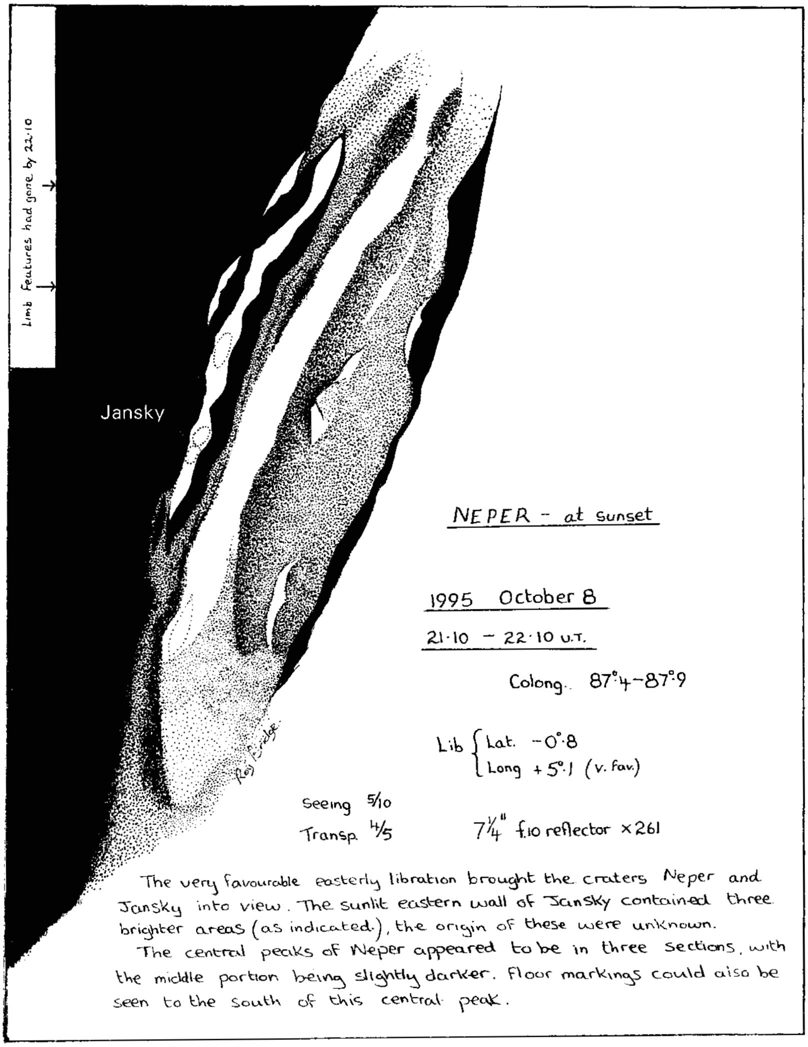


Figure 8.31 (*cont.*)
(b) Neper, drawn by Roy Bridge.

is clear and steady! Moreover, conditions will only be favourable just after full Moon. The only other time it is seen under a low Sun-angle is when the Moon is a very thin crescent. However, then the Moon is very close to the Sun in the sky. At those times you will only be able to see the Moon against a twilight sky. Even then, its altitude will be very low and the atmosphere is bound to be very unsteady. Figure 8.31(a) shows a view made under such conditions. You may think the photograph does not show very much, even though the libration was obviously rather favourable for observing this feature. In point of fact, it was taken with the largest refracting telescope in the world – the 40-inch (1.02 m) telescope of the Yerkes Observatory (unfortunately I do not have any further details) and getting a view of the crescent Moon as good as this is no mean achievement!

Neper is a great formation, 142 km in diameter, with terraced walls and a central mountain. Roy Bridge has made a superb drawing of this difficult feature and this is presented in Figure 8.31(b). This time the view is of local sunset over the crater. Roy even manages to show part of the large crater Jansky which lies **beyond** Neper and the easternmost part of which actually lies **beyond** 90°E. Jansky is 72 km in diameter.

8.32 PITATUS [30°S, 346°E] (WITH HESIODUS)

Pitatus is a beautiful flooded crater on the southern shore of the Mare Nubium. It is 105 km in diameter, and has highly eroded walls and a peculiarly offset central peak There are some ridges, hills, and rilles on its floor but all are very delicate objects requiring large apertures and steady seeing and, very importantly, just the right lighting to show them up. Figures 8.32(a) to (d) are a series of views at a range of lighting conditions. Figure 8.32(a) is a drawing by Andrew Johnson showing the formation at local sunrise (Sun's mean selenographic colongitude 14°.3 for the period of the drawing). Figure 8.32(b) is another Andrew Johnson drawing, this time made at a mean colongitude of 17°.9. Figure 8.32(c) is a Catalina Observatory (1.5 m telescope) photograph taken at a colongitude of 22°.6 and Figure 8.32(d) is another photograph taken with the same telescope when the Sun's selenographic colongitude was 39°.9. Notice the dramatic changes in the appearance of the formation.

The crater joined to the western flank of Pitatus, shown in Figures 8.32(c) and (d), is the 42 km diameter Hesiodus. The breach in the wall between these two lunar arenas would be a fascinating place for a lunarnaut to explore. I wonder who will be the first lucky person to trek between Pitatus and Hesiodus and when that journey will be made? In the meantime, there is much to interest and challenge the backyard telescopist in these particular lunar formations.

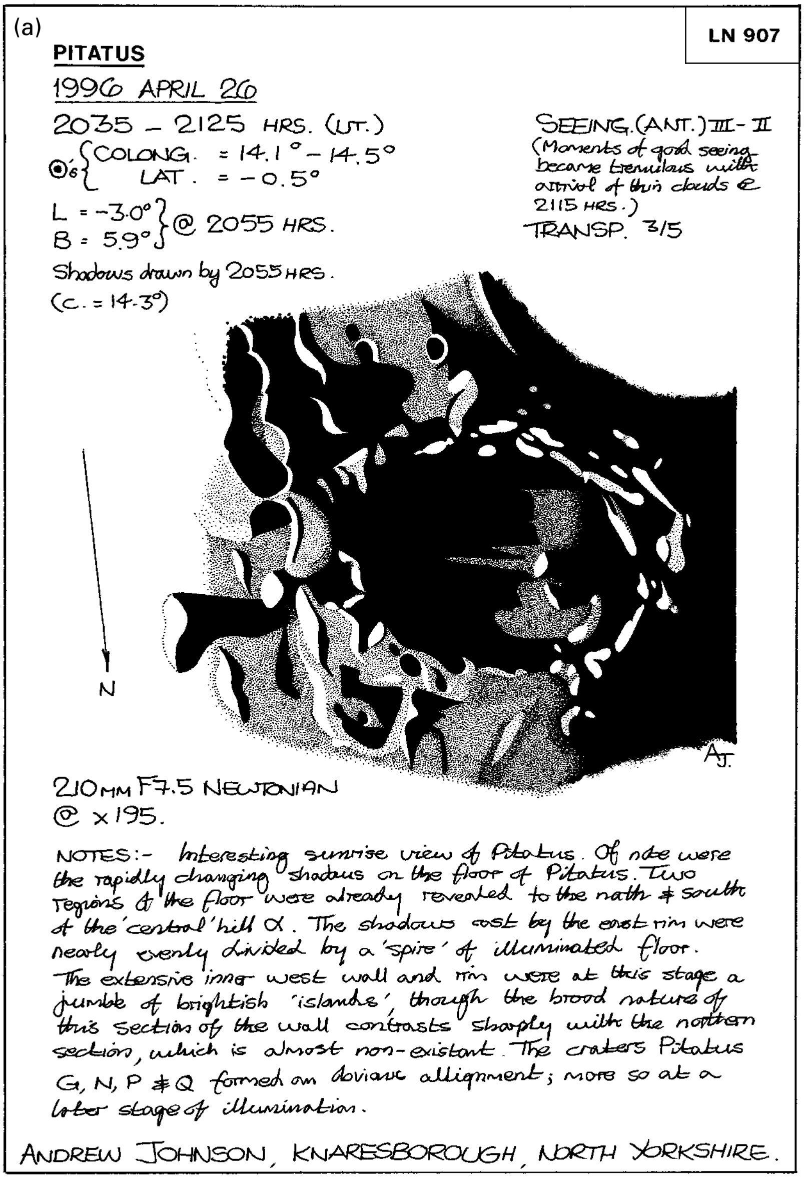
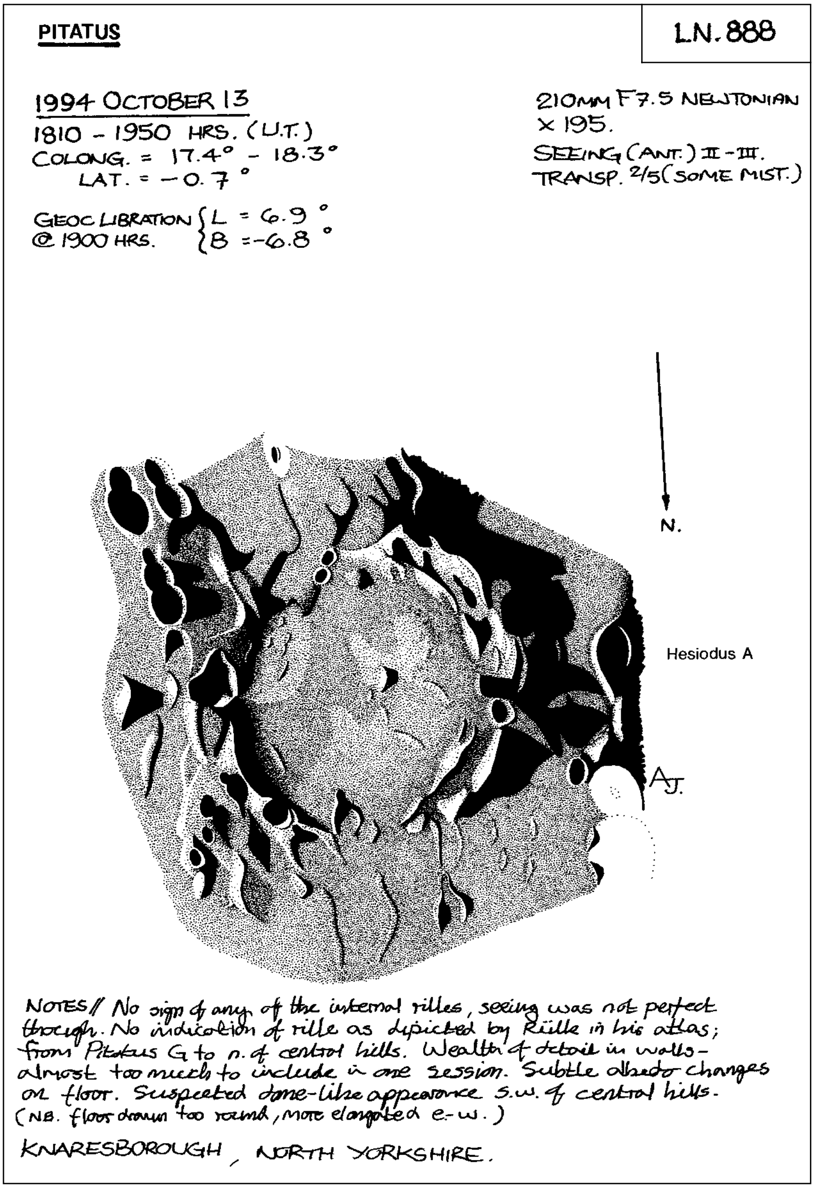


Figure 8.32 (a) Pitatus at a colongitude of 14°.3, drawn by Andrew Johnson.

Figure 8.32 (*cont.*)
(b) Pitatus at a colongitude of 17°.9, drawn by Andrew Johnson. Note Andrew's comments, especially that about the true shape of the crater.

(b)



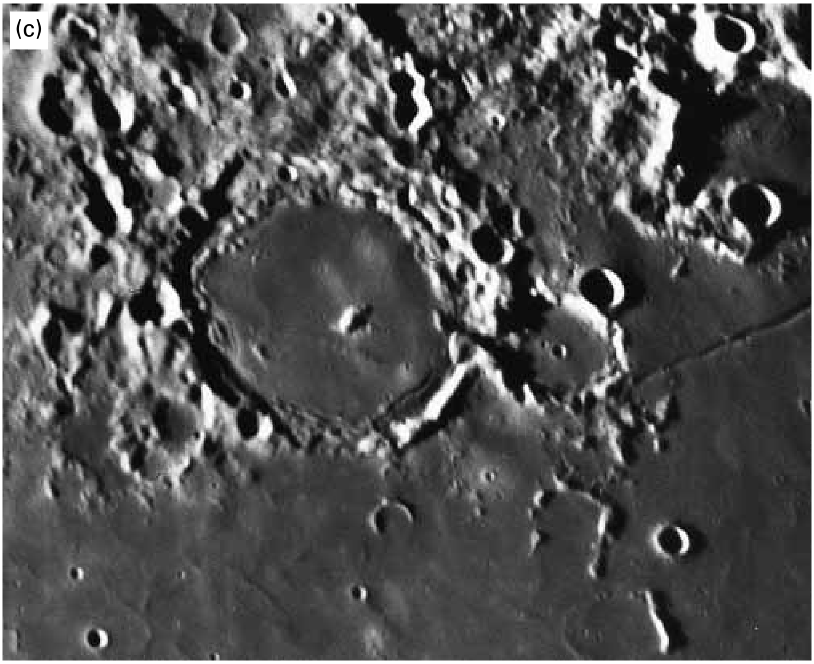


Figure 8.32 (*cont.*)
(c) Pitatus and Hesiodus. Catalina Observatory photograph, taken with the 1.5 m reflector on 1966 May 29^{d} 04^{h} 41^{m} UT, when the Sun's selenographic colongitude was 22°.6. (Courtesy Lunar and Planetary Laboratory.)
(d) Pitatus. Catalina Observatory photograph, taken with the 1.5 m reflector on 1966 December 23^{d} 04^{h} 54^{m} UT, when the Sun's selenographic colongitude was 39°.9. (Courtesy Lunar and Planetary Laboratory.)

8.33 PLATO [51°N, 351°E] (WITH MONS PICO, MONS PITON, PLATO A)

If any one formation on the Moon's surface is more popular, and consequently more observed, than any other, surely it must be the crater Plato. It is bathed in sunshine from first to last quarter Moon and, as Figure 8.33(a) shows, appears as a dark oval set into the bright strip of rough terrain betwixt the Mare Imbrium (Sea of Rains) and the Mare Frigoris (Sea of Cold). It certainly grabs the attention and Johannes Hevelius named it "The Great Black Lake".

Plato marks the northernmost termination of the Montes Alpes, described in Section 8.24, earlier in this chapter. These mountains are the surviving remnants of an inner-ring feature in the Imbrium Basin. Hence Plato is situated on the Basin shelf. Since Plato could not have survived the Basin-forming impact about 3.85 billion years ago, it must have been formed after that. Given it is clearly flooded with dark basaltic lava, that puts its age at no greater than 3.0 billion years **if** we are correct in our assertion that all the major lava upwelling on the Moon was over by then. Actually, there is some evidence that minor volcanic activity continued on the Moon for another billion years, though the evidence is strong that Plato was formed – and subsequently flooded – in the interval 3.85–3.00 billion years ago. Perhaps of significance is that the composition of Plato's lava is a little different to that of the nearby 'seas', as witness its somewhat darker colouration.

The foreshortening due to its location makes Plato appear oval. Really it is quite circular and regular in outline, spanning 100 km from rim to rim. The walls of this arena reach up to approximately 2 km above the level of the dark floor but the summit peaks are fairly jagged. This is shown to the most beautiful effect when the Sun-angle is very low over the formation. Very striking spire-like shadows then extend across the crater floor (see Figure 8.33(b)). When the crater is very near the terminator the shadows show changes that are apparent after just a few minutes observation.

In fact, the shadows can reach right across the floor from the wall casting them to the wall opposite. This is a consequence of the fact that Plato's floor is one of the flattest large areas on the Moon's surface.

Under close inspection (though only needing a small telescope for this) the walls of Plato shows considerable signs of slumping along its northern and western sections. Most obvious of these is the huge triangular block, known as Plato Zeta, which has broken away from the western wall and slumped inwards, leaving a canyon behind it.

As can be seen in Figure 8.33(a), a number of small craters are situated on Plato's dark floor. Their visibility is heavily lighting- and seeing-dependent. With Plato close to the terminator and in good seeing, I have used a

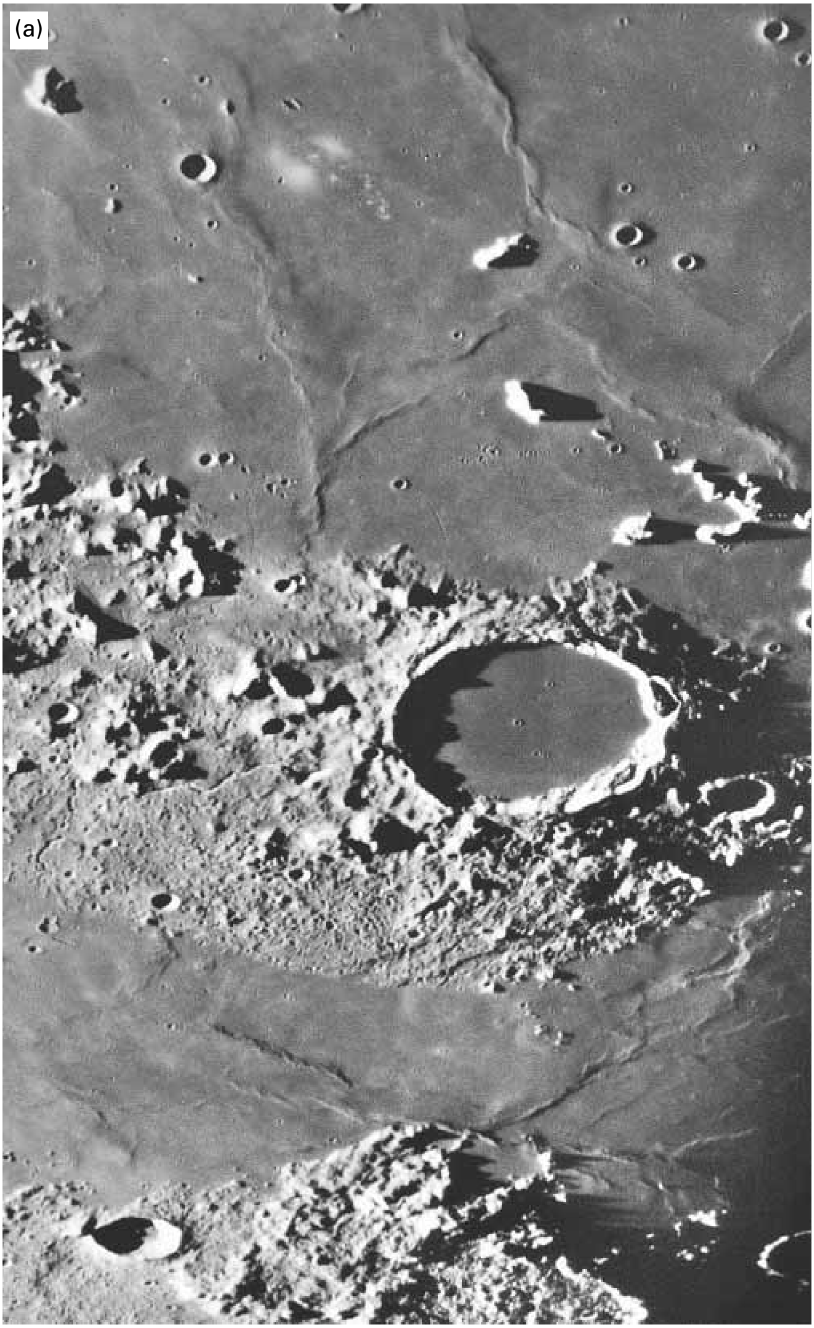


Figure 8.33 (a) The crater Plato (centre right) photographed with the 1.5 m reflector of the Catalina Observatory in Arizona, on 1967 January 20^{d} 01^{h} 45^{m} UT, when the Sun's selenographic colongitude was 18°.4. Part of the Mare Imbrium can be seen above Plato. Just above Plato is the outline of a 'ghost crater'. On the right side of it can be seen part of the Montes Teneriffe, while on the upper part of the ghost crater is situated Mons Pico. Mons Piton is in the upper-left corner of this frame. The crater Plato A is just to the lower right of Plato. (Courtesy Lunar and Planetary Laboratory.)

power of ×432 with my 18¼-inch (0.46 m) reflector and seen them as perfectly formed bowl-shaped craters with distinctive interior shadows, though these shadows are not as intensely black as elsewhere. The largest, which is just a little off-centre in Plato, is the easiest to see. It is about 3 km in diameter. The crater south-west of this and the pair (appearing as one in poorer seeing conditions) to the north-west of the near-central crater are significantly more difficult. There is a very much smaller crater close to Plato Zeta, which I have glimpsed only very rarely. You might be able to make it out in Figure 8.33(a). It is also well shown in Figure 8.33(c), another of Terry Platt's superlative CCD images. Terry's image is even more amazing when you consider that the lighting is rather higher than the ideal for viewing their crateriform aspect!

At higher Sun angles these craters usually appear as white disks. In bad seeing these white disks become white 'blobs' which fluctuate rapidly in visibility. On the worst nights they are completely invisible. Of course, it is the atmospheric turbulence which causes them to behave in this way. Even accepting that, a large folklore has been built up about apparently enigmatic variations in visibility of Plato's floor craters. Almost all of the major observers of the past have recorded instances when they considered the floor craters should be visible and yet are completely absent. Many report

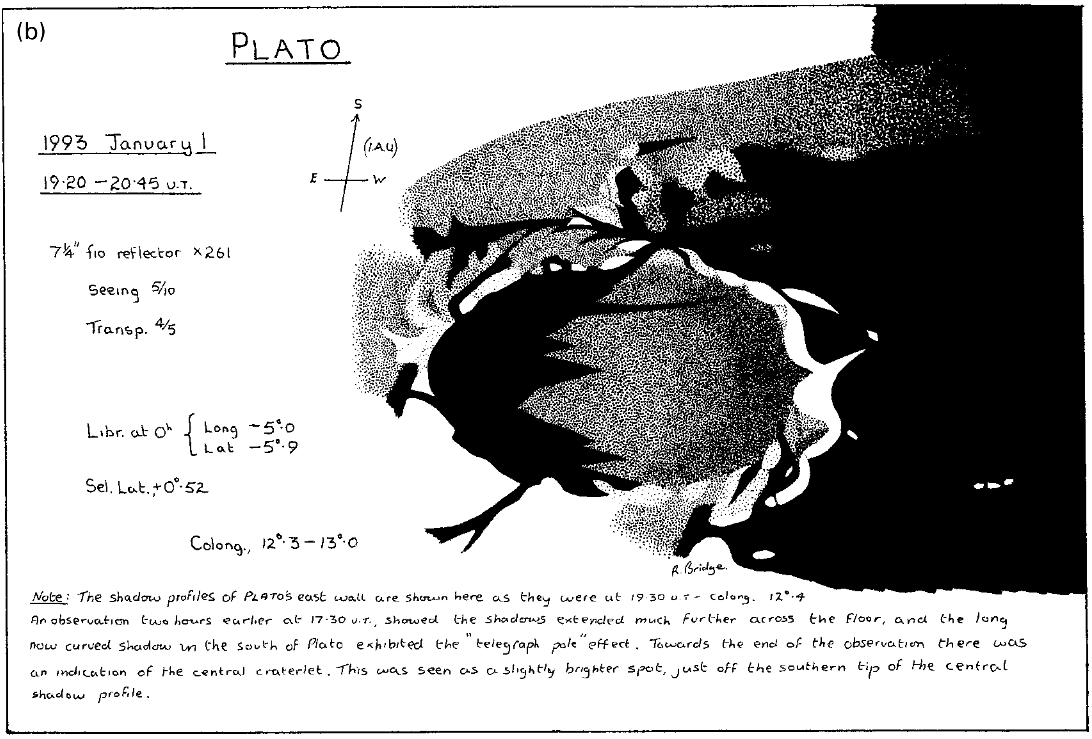


Figure 8.33 (*cont.*)
(b) Plato, drawn by Roy Bridge.

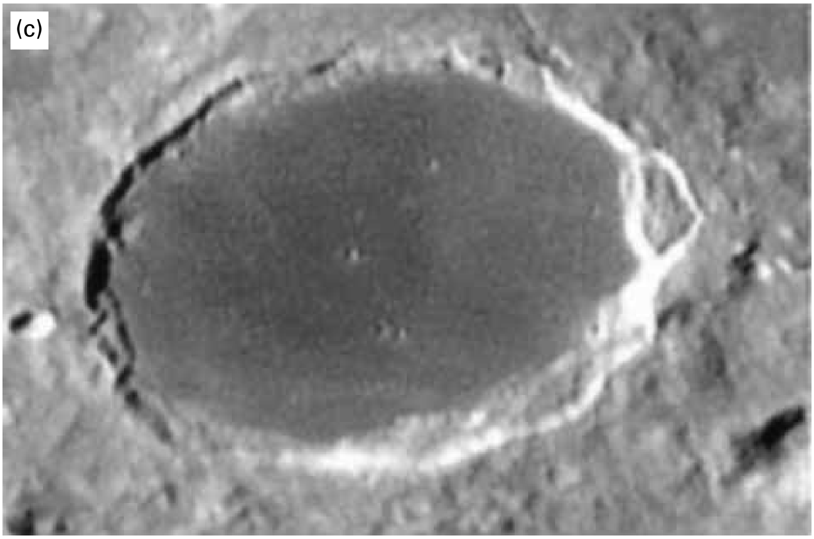


Figure 8.33 (*cont.*)
(c) Plato, imaged by Terry Platt using his 12½-inch (318 mm) tri-schiefspiegler reflector and *Starlight Xpress* CCD camera (other details not available). The author has applied slight image sharpening and brightness re-scaling.

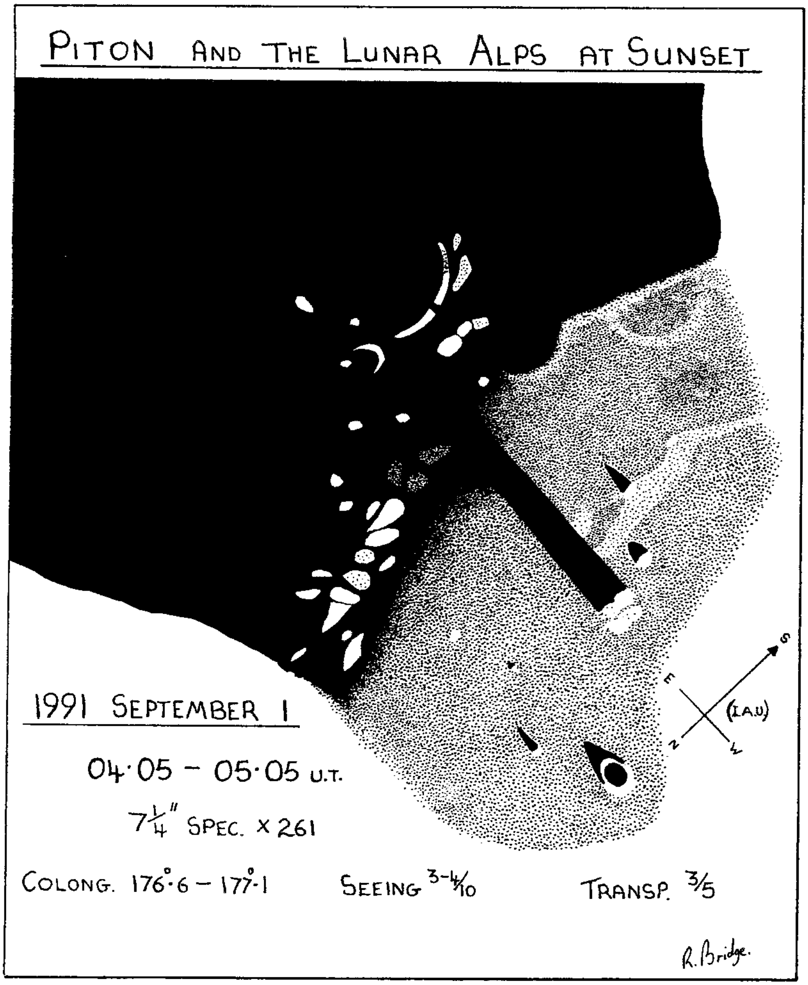
a fog-like veil extending over the crater floor and extinguishing the details of all it covers. In all the nearly 30 years that I have been observing the Moon, I cannot say with certainty that I have ever seen the craters much less distinct than I considered they should be for the given seeing conditions. However, I have seen the opposite effect on just a few very rare occasions. For instance, I have been perplexed to see the floor craters as bright white blobs (the near-central one by far the brightest) through my 6¼-inch (152 mm) reflector when all is fuzzy and violently rippling in ANT. V. seeing! Yet most other times they are invisible through telescopes small or large when the seeing is not quite as bad. Puzzling!

Plato is also a 'hot spot' for other types of transient phenomena. Flashes have been occasionally reported; also an apparent blurring of parts of the crater rim while other parts of the crater remain sharp and clear-cut. I have seen this effect myself. Coloured glows are sometimes reported extending along the crater rim. Again I can concur. However, the normal prismatic effect of the Earth's atmosphere can produce exactly these effects. The northern section of the rim of Plato then appears reddish-orange and the southern section appears blue. Is this the cause in every instance? I think so, though I did once see a red glow that seemed very different in colour and extent from the normal spurious colour (which was also present).

Is Plato occasionally the site of genuine TLP or are these variations just illusions, perhaps caused by the normal intertwining of seeing conditions and the complex interaction of sunlight with the formation? I think that is certainly the case in the vast majority of instances. Some people are very sure that is the case in **all** instances. In fact, they dismiss all suggestions of

Figure 8.33 (*cont.*)
(d) Mons Piton, drawn by Roy Bridge.

(d)



genuine TLP out of hand. I think there is a case for further study – the type of study that involves very careful monitoring of Plato through the telescope. I have more to say about TLP research in the final chapter of this book.

Another effect, that has long ago been demonstrated to be an illusion, is the apparent **darkening** of the floor of Plato as the Sun rises higher over it. Of course, the floor actually brightens with increasing Sun-angles. What is happening is that the rough surrounds of the crater brighten more rapidly than its smooth floor, so increasing the contrast. Various light spots and mottled patterns also appear towards local lunar noon (which is full Moon, as we see it from the Earth). A lighter sector in the south-west, covering about one-eighth of the total floor area, becomes especially apparent

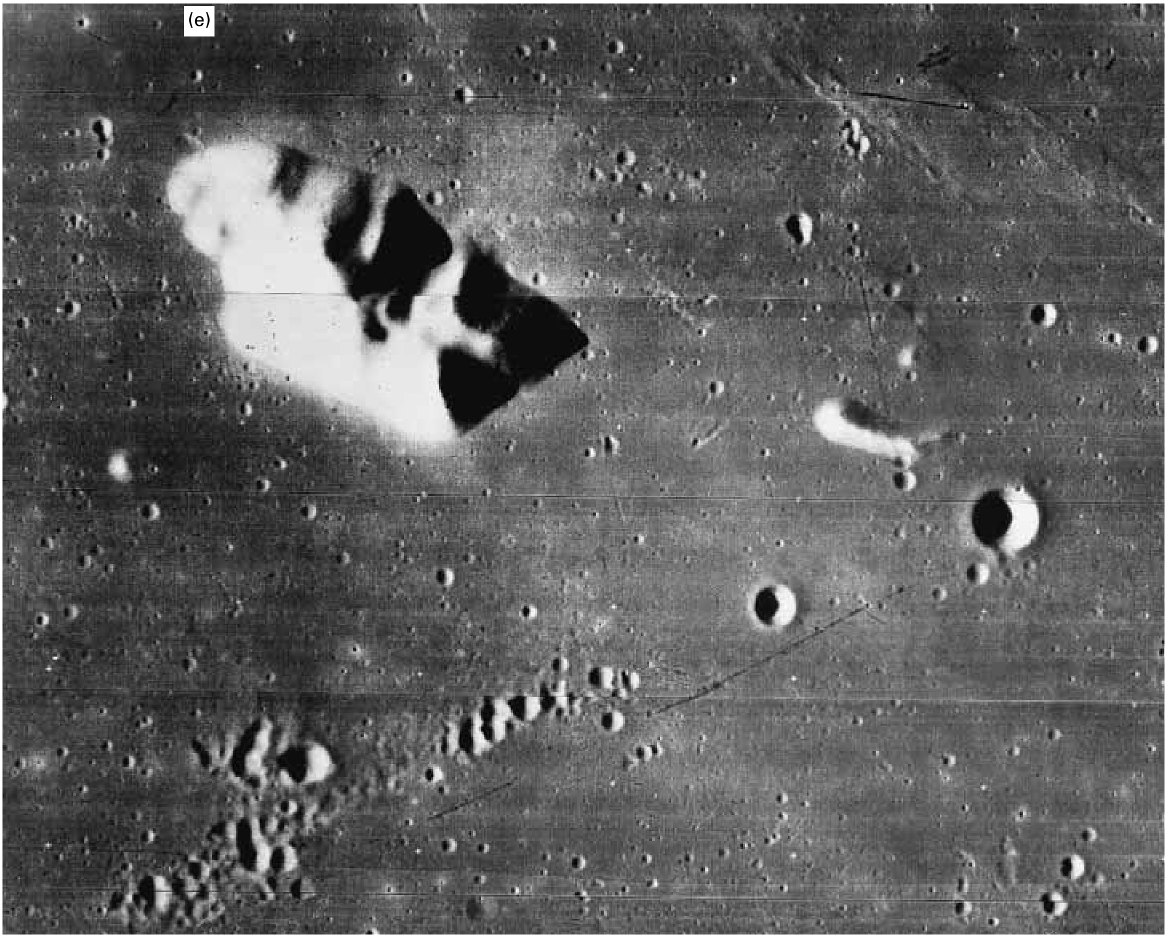


Figure 8.33 (*cont.*)
(e) *Orbiter IV* photograph of Mons Pico. (Courtesy NASA and Professor E. A. Whitaker.)

at these times – a frequent cause of "mists extending across the floor from the crater wall" reports from the uninitiated.

Plato's surrounds are very complex and the nearest sizeable crater is Plato A, 22 km across, situated about 20 km to the north-west of Plato. It is shown in Figure 8.33(a). A number of fissures cut through the hinterlands, most prominent of these being a rille extending eastwards from Plato (the western termination of which occurs a little east of the flanks of the crater).

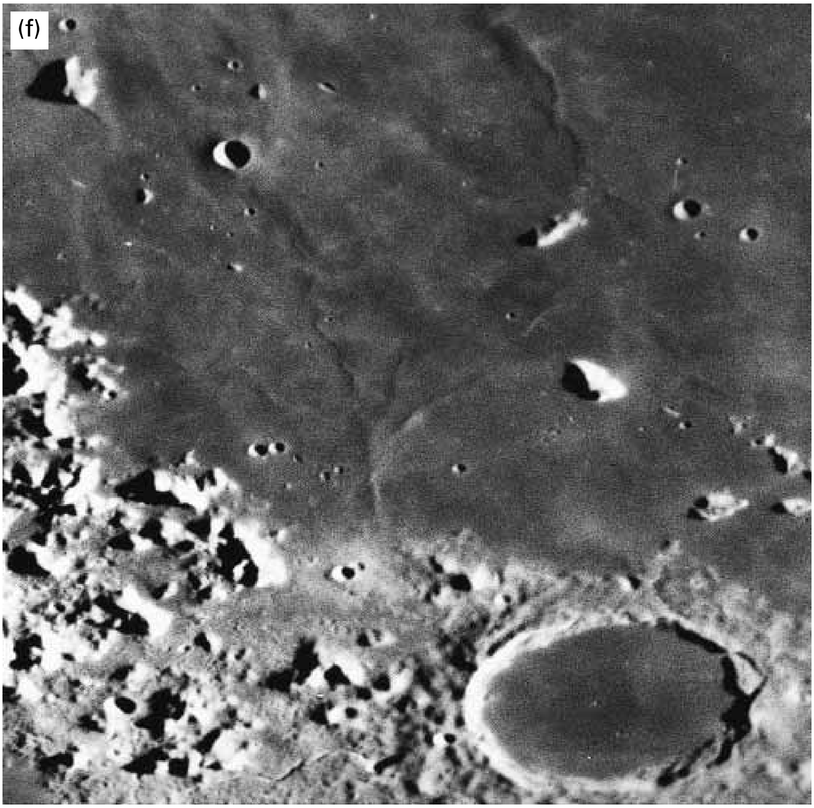


Figure 8.33 (*cont.*)
(f) Plato (lower right) to Mons Piton (upper left) photographed using the 1.5 m Catalina Observatory reflector on 1966 September 6^{d} 10^{h} 44^{m} UT, when the Sun's selenographic colongitude was 167°.3. (Courtesy Lunar and Planetary Laboratory.)

The strip of rough ground south of Plato is narrowed by the northern part of the outline of a 'ghost crater' extending southwards onto the Mare Imbrium. It is mostly visible as a slightly raised ridge in the mare, and is well shown as such in Figure 8.33(a) and in Chapter 5, Figure 5.3. The feature is approximately 115 km in diameter.

On the western flank of the ghost crater are a collection of mountain peaks, the Montes Teneriffe. These reach a height of approximately 2.4 km. The isolated peak on its southern rim is Mons Pico, also about 2.4 km high. It is a very reflective object and seems extraordinarily bright when the upper parts of it catch the sunlight and the immediate surrounds are in the darkness beyond the terminator. This mountain is also the source of various alleged changes and anomalous appearances, most probably all illusory. A remarkably straight line of craters cross the ghost crater a little to the north of Mons Pico.

There are various other isolated peaks poking up through the lavas of the Mare Imbrium. Some of these can be seen in Figure 8.33(a). One of the most notable is Mons Piton, visible in the top-left corner of the photograph.

It is 2.25 km high. This mountain is another source of reported changes and odd appearances. Figure 8.33(d) is a drawing of the area made by Roy Bridge (see also the drawing by Andrew Johnson, shown in Chapter 3, Figure 3.5). Figure 8.33(e) shows an *Orbiter IV* view of Mons Pico. Mons Pico and Piton are shown in Figures 8.33(a) and (f) where they are lit from opposite directions. Notice how their appearances differ between the two views. Is it any wonder that the visual observers of yesteryear considered the mountains subject to change!

8.34 PLINIUS [15°N, 24°E] (WITH DAWES, MENELAUS, PROMONTORIUM ARCHERUSIA, ROSS, MARE SERENITATIS, MARE TRANQUILLITATIS)

In the manner of an ancient gate-keeper, the crater Plinius stands close to the narrow intersection of the Mare Tranquillitatis with the Mare Serenitatis. It is shown, near the end of a lunar day, and still on guard, in Tony Pacey's excellent photograph, which is presented in Figure 8.34(a). Perhaps the smaller crater Dawes, standing a little to the north-east (left and slightly lower in the photograph) is an apprentice guard?

Plinius is actually situated just inside the Mare Tranquillitatis. The mountainous cape immediately west of Plinius is known as the Promontorium Archerusia, the name surviving from Hevelius's map. In his chart Hevelius named what we now call the Mare Tranquillitatis and Mare Serenitatis the Pontus Euxinus, meaning "Black Sea". Neither sea might actually be black, but there is certainly a very distinct colour difference between the two maria. Mare Tranquillitatis is clearly very much darker than Serenitatis and it is much bluer. In fact, I find that it takes on a very distinct Prussian blue tint when seen at low power through my telescopes (to repeat yet again, the real colours on the Moon are various shades of brown – but the eye averages the view as white, so producing apparent coloured tints in specific features. The colours themselves might not be true but at least they do indicate the colour **differences**).

Serenitatis, to me, has the faint greenish colour in common with the other lunar maria. I ought to repeat that experience has shown me that my eyes are more sensitive to colours than most (and to my regret I find that this heightened sense is dwindling with age) and you may well go to your telescope and fail to see any colours at all. Proper colorimetric studies do show that the Mare Tranquillitatis **is** much bluer than the other lunar maria. This is because the Tranquillitatis lavas are much richer in titanium than is the norm.

Figure 8.34(b) shows a wide-angle view encompassing both maria that I took myself. It was taken on colour film and even that shows the Mare Tranquillitatis as bluer than the other mare. It is a pity that it has to be

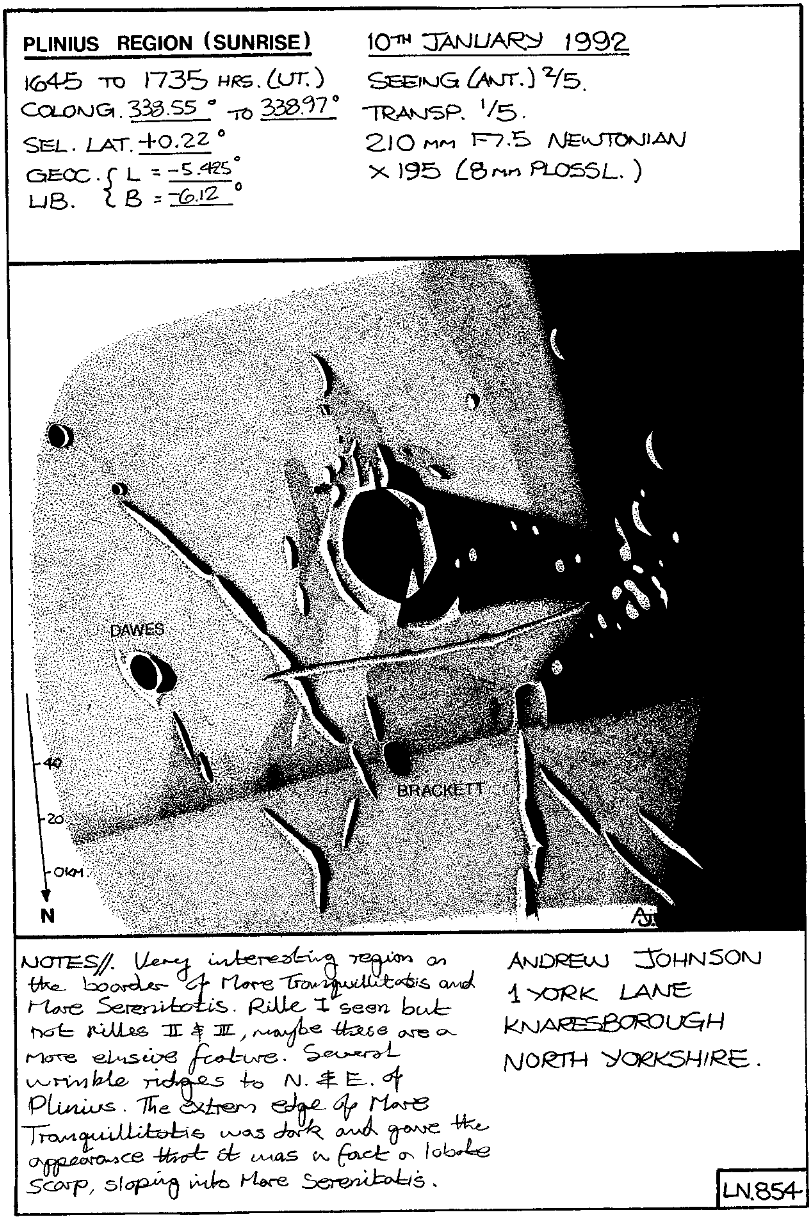
Figure 8.34 (a) Plinius (the large crater just below centre) and environs, photographed by Tony Pacey. He used his 12-inch (305 mm) reflector for this ½ second exposure on T-Max 100 film on 1992 September 16^{d} 23^{h} 55^{m} UT, when the Sun's selenographic colongitude was 139°.5.

Figure 8.34 (*cont.*)
(b) The two main dark areas close to the lunar terminator are Mare Tranquillitatis (upper) and Mare Serenitatis (lower). The small 'sea' attached to the south (top) of the Mare Tranquillitatis is the Mare Nectaris. Photograph taken by the author on 1992 September 14^{d} 22^{h} 46^{m} UT, when the Sun's selenographic colongitude was 114°.5. He hand-held his camera, fitted with a 58 mm lens, to a 44 mm Plössyl eyepiece (EFR = f/7.4) for a 1/1000 second exposure on *3M* Colourslide 1000 film.

reproduced in monochrome here. The Tranquillitatis Basin is probably the oldest of the large basins. Certainly it has a much less well-defined shape than most. It is also masconless. Could that mean the basin was formed at a time not long after the creation of the Moon, when all but an outer very thin crust was still molten? If so, the Tranquillitatis Basin probably dates back about 4.5 billion years!

Figure 8.34 (*cont.*) (c) Plinius and environs, drawn by Andrew Johnson.

(c)



The diameter of the Tranquillitatis flood-plain is very roughly 800 km, about 20 per cent larger than that of the Mare Serenitatis. In common with the other lunar maria, the lava flooding commenced about 3.9 billion years ago (less than a hundred million years after the formation of the Serenitatis Basin), and successive lava flows are evident on both maria. The last really significant lava eruptions probably occurred about 3.6 billion

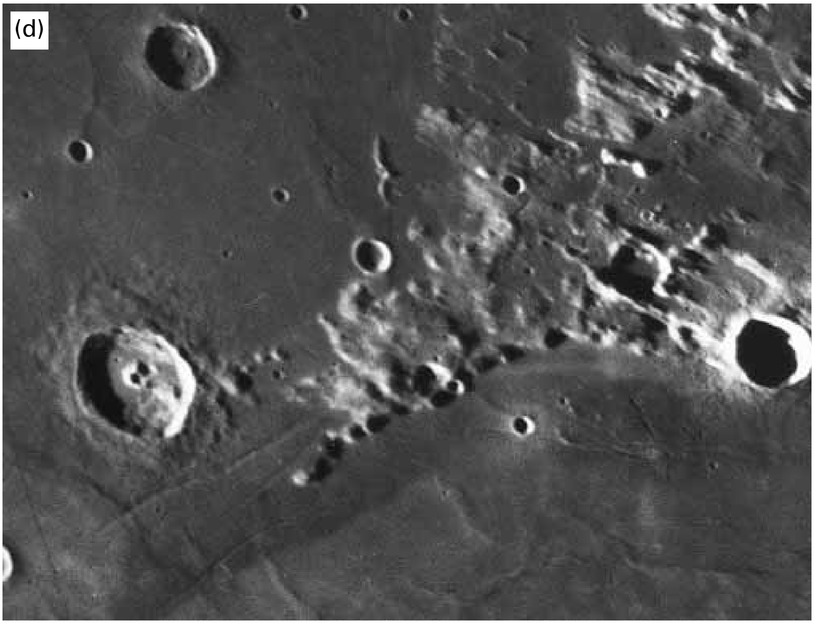


Figure 8.34 (*cont.*)
(d) Plinius (the large crater on the left), Ross (largest crater above Plinius) and Menelaus (large crater on the extreme right) photographed using the Catalina Observatory 1.5 m reflector on 1966 April 27^{d} 02^{h} 54^{m} UT, when the Sun's selenographic colongitude was 351°.0 (morning illumination). The cape to the right of Plinius is the Promontorium Archerusia. Notice the rilles extending from it and passing below Plinius. (Courtesy Lunar and Planetary Laboratory.)
(e) Plinius and environs, photographed using the Catalina Observatory 1.5 m reflector on 1966 September 4^{d} 10^{h} 38^{m} UT, when the Sun's selenographic colongitude was 142°.9 (afternoon illumination). Other details as for (d). (Courtesy Lunar and Planetary Laboratory.)

year ago. Interestingly, the same titanium-rich lavas that dominate the covering of the Mare Tranquillitatis also encroach onto the southern half of the perimeter of the Mare Serenitatis.

Figure 8.34(a) shows many of the wrinkle ridges on the mare superbly well. Figure 8.34(c) is a drawing of the region executed by Andrew Johnson. It is usual for compressional features on the lunar maria, particularly the wrinkle ridges, to be complemented with tensional faults around the peripheries. These mainly manifest as graben-type rilles. You might expect the junction between two maria to be especially rich in rilles – and you would be right! Rilles of the graben variety can, indeed, be found at the junction of the two maria and these are very well shown in Figures 8.34 (d) and (e), which are Catalina Observatory photographs.

The various illustrations accompanying this section show a day in the life of the crater Plinius. Figure 8.34(c) pictures the crater at sunrise, while Figure 8.34(d) reveals it later on in the local morning, Figure 8.34(e) shows it in the local afternoon, and Figure 8.34(a) shows it at sunset.

The crater is 43 km in diameter and has quite a sharp rim, 2.3 km above the hummocky floor. The interior walls are terraced and rather complex, the outer slopes also being complex and with some radial ridging. The central mountains are very peculiar and can give the impression of being a crater under some illuminations, such as that shown in Figure 8.34(d). Under a very high Sun the central peak becomes rather bright and five bright, rather fuzzy, streaks extend from the central peak up the interior terraces. This appearance reminds me of a spoked wheel.

To the north-east of Plinius, a little to the left and slightly below it on Figure 8.34(a), is the crater Dawes. This, another sharp-rimmed crater, has a diameter of 18 km. Dawes is also shown in Andrew Johnson's drawing (Figure 8.33(c)). The features on its floor are all of low height and so are rather difficult for the backyard telescope-user to appreciate. Approximately south of Plinius, and above it in Figures 8.34(d) and (e), is the 26 km diameter crater Ross. The photographs show the somewhat peculiar profile of this crater. Again referring to Figures 8.34(d) and (e), the large crater to the extreme right on the photographs is the 27 km diameter Menelaus.

Menelaus has spectacularly terraced walls which rise 3 km up to a sharply defined rim. The crater brightens considerably under increasing Sun-angles. Near full Moon it takes on the appearance of a brilliant white ring. It also has an asymmetric ray pattern, the chief component of which is a bright streak which bisects the Mare Serenitatis. Obviously the crater is no more than a few hundred million years old. The asymmetry of the ray pattern and the somewhat off-centre interior mountain complex suggest the impactor arrived at an angle to the surface from the south-east.

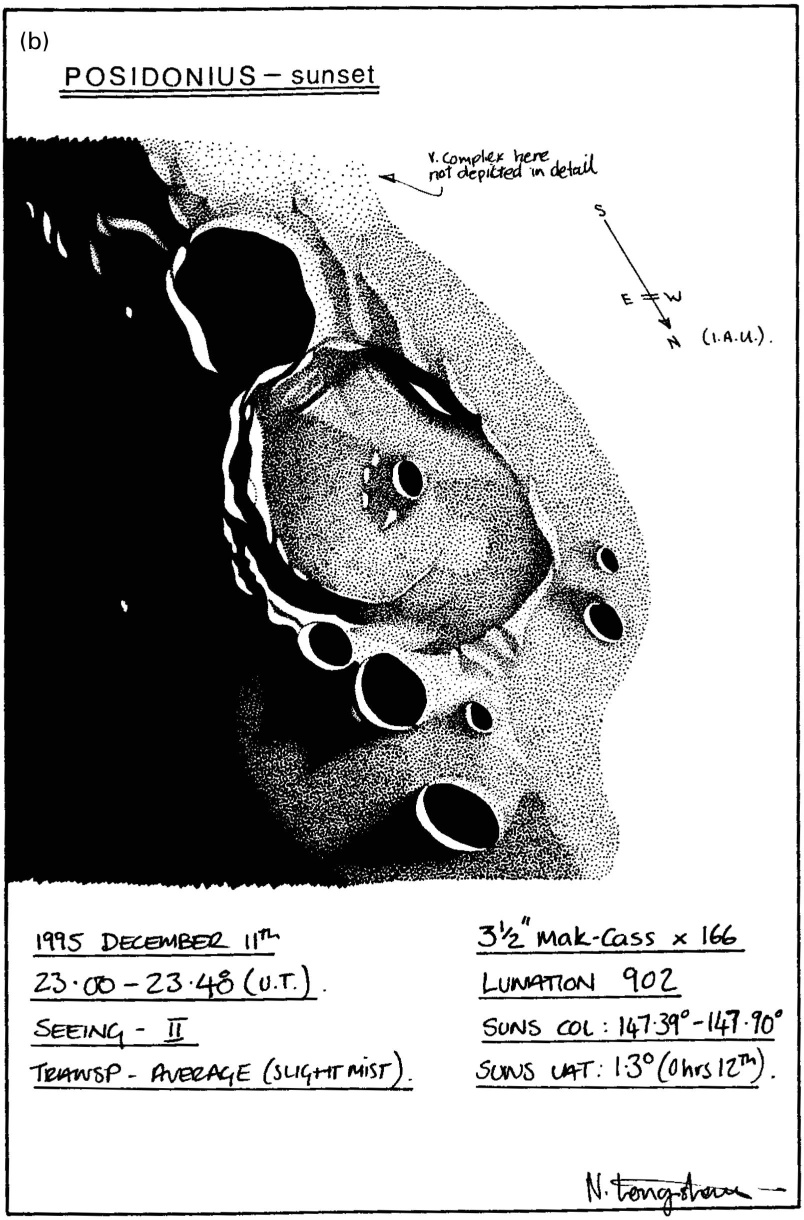
Another area of the Mare Tranquillitatis is discussed in Section 8.45. The next section details another part of the Mare Serenitatis.

8.35 POSIDONIUS [32°N, 30°E] (WITH CHACORNAC, DANIELL, LACUS SOMNIORUM, POSIDONIUS A)

The 100 km diameter crater Posidonius is situated on the eastern edge of the Mare Serenitatis (see the last section for more details of this mare) and at the southernmost junction with it and the inset Lacus Somniorum (Lake of Dreams). Figure 8.35(a) can be used to identify the crater. It appears in the extreme top-left corner of this photograph by Tony Pacey. It is also shown in the wide-angle view presented as Figure 8.34(b) in the last section. There it appears as the large white disk at the left-hand side of the Mare Serenitatis, and you can also see how it is positioned at the southernmost junction of the Sea of Serenity and the Lake of Dreams.

Figure 8.35 (a) Posidonius (crater in top-left corner) to the Moon's north pole, photographed by Tony Pacey. Details given in the main text.

Figure 8.35 (*cont.*)
(b) Posidonius (main crater) with Chacornac (adjoining Posidonius to the upper left) and Daniell (bottom crater), drawn by Nigel Longshaw.



Nigel Longshaw has made a drawing of Posidonius and this is shown in Figure 8.35(b). This drawing is already impressive to the casual glance. Look closely at the hand-written notes accompanying it and you will see that Nigel used a 3½-inch (90 mm) catadioptric telescope to make the observation! This puts the use of large-aperture telescopes into a proper perspective. It is the skill and application of the person behind the eyepiece that really counts.

Figure 8.35 (*cont.*)
(c) Posidonius with Chacornac and Daniell, photographed using the Catalina Observatory 1.5 m reflector. Details in text. (Courtesy Lunar and Planetary Laboratory.)

Figure 8.35(a), already referred to, shows the crater illuminated by the morning Sun. To obtain this photograph Tony Pacey used his 10-inch (254 mm) Newtonian reflector, with eyepiece projection (enlargement factor not given) onto T-Max 100 film, processed in HC110 developer. The ½ second exposure was made at approximately 20^{h} UT on 1991 March 21^{d}. The value of the Sun's selenographic colongitude was approximately 330° at the time.

Figure 8.35(c) is a photograph of Posidonius taken with the Catalina Observatory 1.5 m reflector on 1966 September 4^{d} 10^{h} 03^{m} UT. This time the crater is shown under late afternoon illumination, the colongitude now being 142°.6. Figure 8.35(b) shows the formation at sunset (details presented with the drawing).

If you get a feeling of *déjà vu* when looking at the illustrations accompanying this section, then look back to Section 8.22 and you will see why. The crater Gassendi seems, superficially at least, almost to be the twin of Posidonius. Gassendi is just 10 km larger in diameter and each formation has a smaller adjoining crater. In the case of Gassendi, it is Gassendi A. In the case of Posidonius, it is Chacornac. The main similarity, though, is in the interior structures of the craters. Both have hummocky and rille-ridden floors which give the impression of being pushed upwards by forces from below.

Since the craters are of similar size, one can assert that the incoming projectile was endowed with a similar amount of kinetic energy (which depends on both the speed and the mass of it), but can the locations of the two craters also be a factor in determining their final forms? Both craters lie on basin shelves: the Humorum Basin shelf in the case of Gassendi and the Serenitatis Basin shelf in the case of Posidonius. My speculation is that the particular subsurface structure that exists at a basin shelf lends itself to a Posidonius and Gassendi type of crater, given an impactor of similar energy.

Concentrating on the fine details of Posidonius, it has a somewhat west-of-centre crater on its floor. This is the 11 km diameter Posidonius A. On the east side of this crater is a little ring of mountain peaks. Nigel Longshaw's drawing (Figure 8.35(b)) shows them particularly well. Perhaps these are the surviving remnants of an old, now obliterated, crater? A further mountainous ridge encompasses much of the eastern half of Posidonius. Is this another old and wrecked crater? As Figure 8.35(c) shows very well, much of the floor of Posidonius within this arc is raised upwards. Also there is significant faulting at the interface between this raised ground and the rest of the interior of Posidonius. Clearly the history of this crater is not at all straightforward.

The surrounding walls of Posidonius vary considerably in height, being at their highest (of the order of 2 km) to the east. The largest crater adjoining Posidonius is Chacornac. It is 51 km in diameter. It has a very 'tortured' interior, though it does seem to have been formed after Posidonius. It is shallower than Posidonius, the lowest point near the centre being about 1.5 km below the level of the crater rim. As the illustrations all show, several craters lay on or just north of the northern half of the perimeter of Posidonius. The most interesting of these is Daniell, shown as the lowest crater rendered in Nigel Longshaw's drawing of the area (Figure 8.35(b)). Of course, all the craters in the area appear foreshortened from the Earth because of their position on the Moon's disk. Look carefully at the illustrations and you will see that Daniell is much more oval than the others. Actually it spans about 30 km in the (roughly) north–south direction but is only about 23 km wide measured (roughly) east–west! Daniell is about 2.1 km in depth. I will leave you to ponder on the events and processes which have led to the formation we see today.

8.36 PYTHAGORAS [63°N, 258°E] (WITH BABBAGE)

To find out if you can see Pythagoras, first locate the Sinus Iridum. Then look radially from it towards the limb of the Moon. If the area is in sunlight you will locate the crater Pythagoras very close to the lunar limb. The crater is best seen a day or so before full Moon. Before then it will not be sunlit. After that the higher Sun will cause the details to wash out, especially so since the sunlight will be coming from approximately the same direction

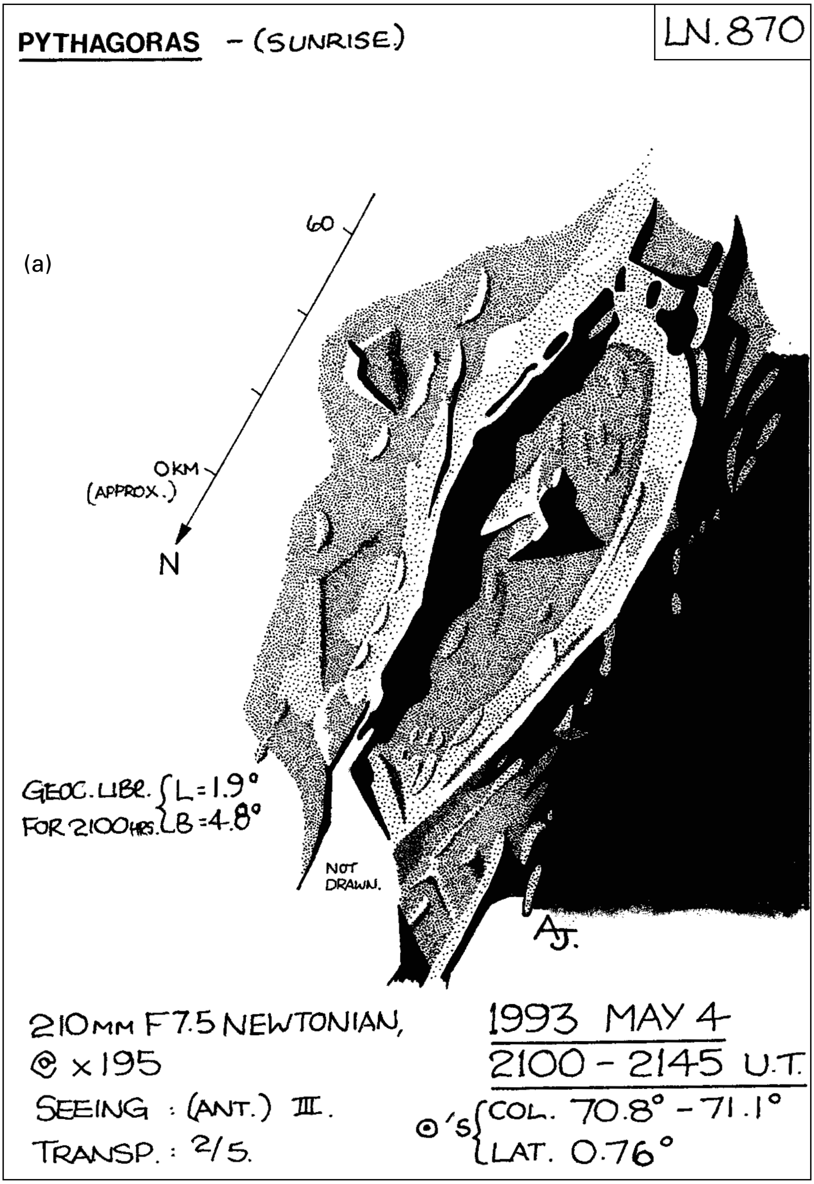


Figure 8.36 (a) Pythagoras, drawn by Andrew Johnson.

as we are looking towards it and thus providing no shadow relief for us to see.

This 128 km diameter crater would be a magnificent spectacle if it were further round to our side of the Moon. As it is, it is impressive enough during that brief window of opportunity each lunation. Andrew Johnson has made a drawing of this formation under these (sunrise) conditions (see Figure 8.36(a)). If you are wondering about the sunset view, unfortunately

Figure 8.36 (*cont.*)
(b) Pythagoras, photographed using the 1.5 m reflector of the Catalina Observatory. Details in text. (Courtesy Lunar and Planetary Laboratory.)

the Moon is then a waning crescent and will be so close to the Sun in the dawn sky that the seeing is bound to be bad.

Another view of this crater is provided in Figure 8.36(b). This is a photograph taken with the 1.5 m reflector of the Catalina Observatory in Arizona on 1966 October 28^{d} 06^{h} 34^{m} UT. The Sun's selenographic colongitude was 79°.3, the Sun being just a few degrees higher than for Andrew Johnson's drawing.

Although foreshortened, it is quite easy to make out the crater's somewhat hexagonal outline. The spectacular terraced walls soar to 5 km above the arena-like floor of the formation. Examine the crater closely and you will find plenty of evidence of substantial landslips. The central mountain cluster is multi-peaked and reaches up to a height of about 1.5 km.

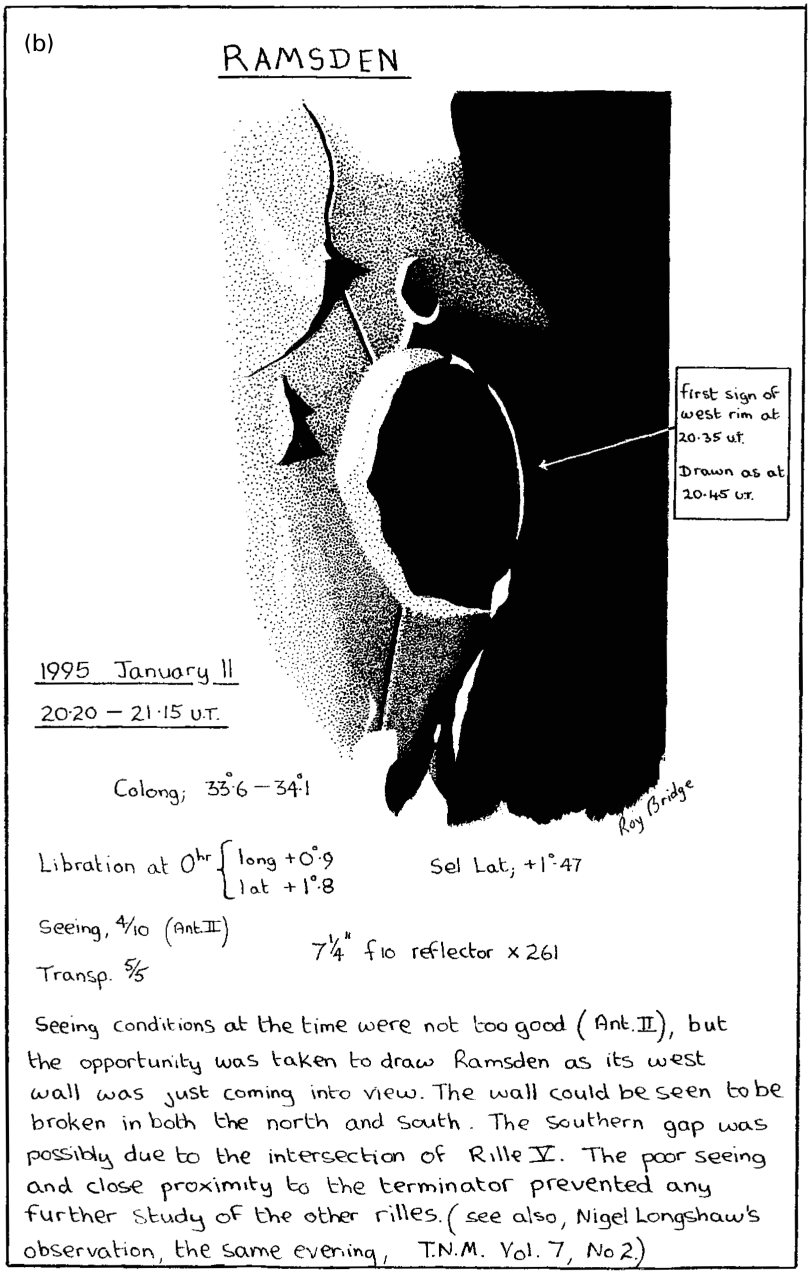
Upper right of Pythagoras in Figure 8.36(b), and extending into the top-right corner of the photograph, is the peculiar formation named Babbage. It seems to be the fusion of two main craters. As well as two large (32 km and 14 km diameter) craters within it, Babbage also contains much interesting detail. I will leave a detailed study of it to you. This is a fascinating area of the Moon, though one that is certainly not the easiest for the telescopist.

8.37 RAMSDEN [33°S, 328°E] (WITH RIMAE RAMSDEN)

The crater Ramsden, 24 km in diameter and about 2 km deep, is fairly unremarkable. It is situated on the Palus Epidemiarum, which is itself connected to both the Mare Nubium and the Mare Humorum (see Section

Figure 8.37 (a) Ramsden and Rimae Ramsden. Catalina Observatory photograph. Details in text. (Courtesy Lunar and Planetary Laboratory.)

Figure 8.37 (*cont.*)
(b) Ramsden and Rimae Ramsden, drawn by Roy Bridge.



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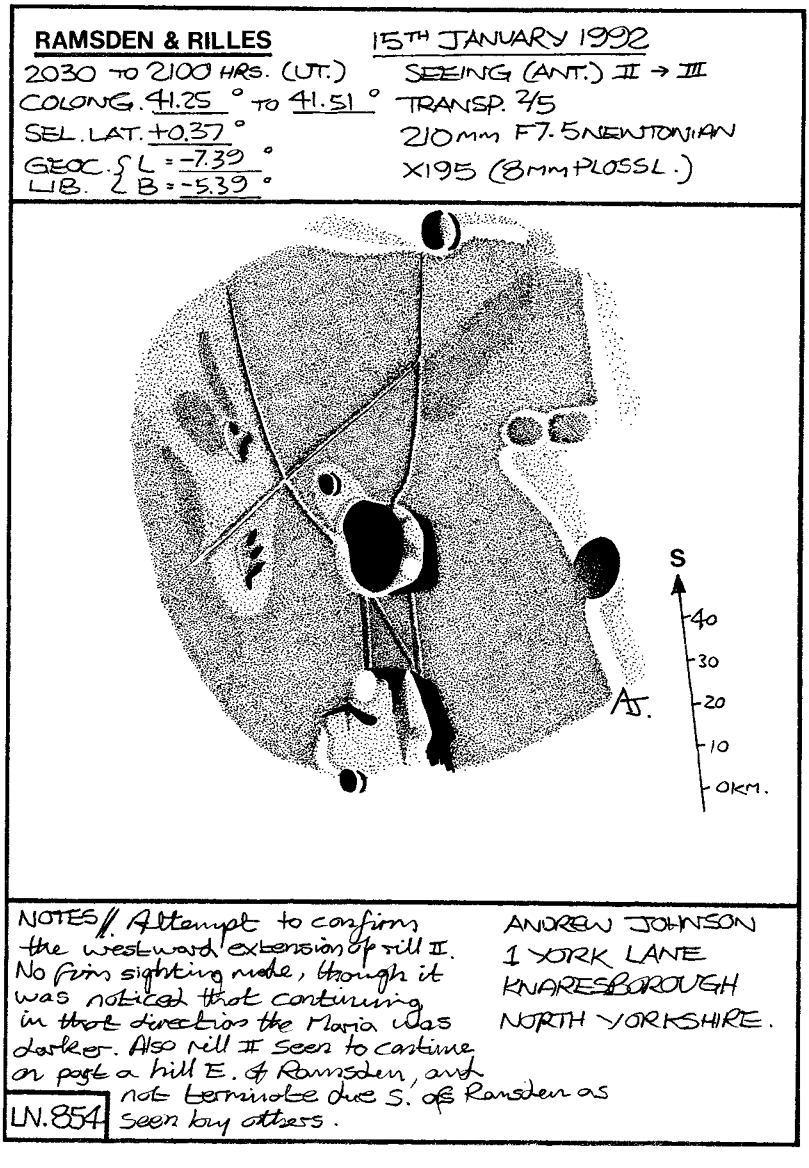


Figure 8.37 (*cont.*)
(c) Ramsden and Rimae Ramsden, drawn by Andrew Johnson.

8.22). The crater appears in the centre of Figure 8.37(a), which is a Catalina Observatory photograph. It was taken with the 1.5 m reflector on 1966 December 23^{d} 04^{h} 54^{m} UT, when the Sun's selenographic colongitude was 39°.9.

The major feature of interest is the system of rilles, the Rimae Ramsden, associated with the crater. This particular system spans about 130 km but

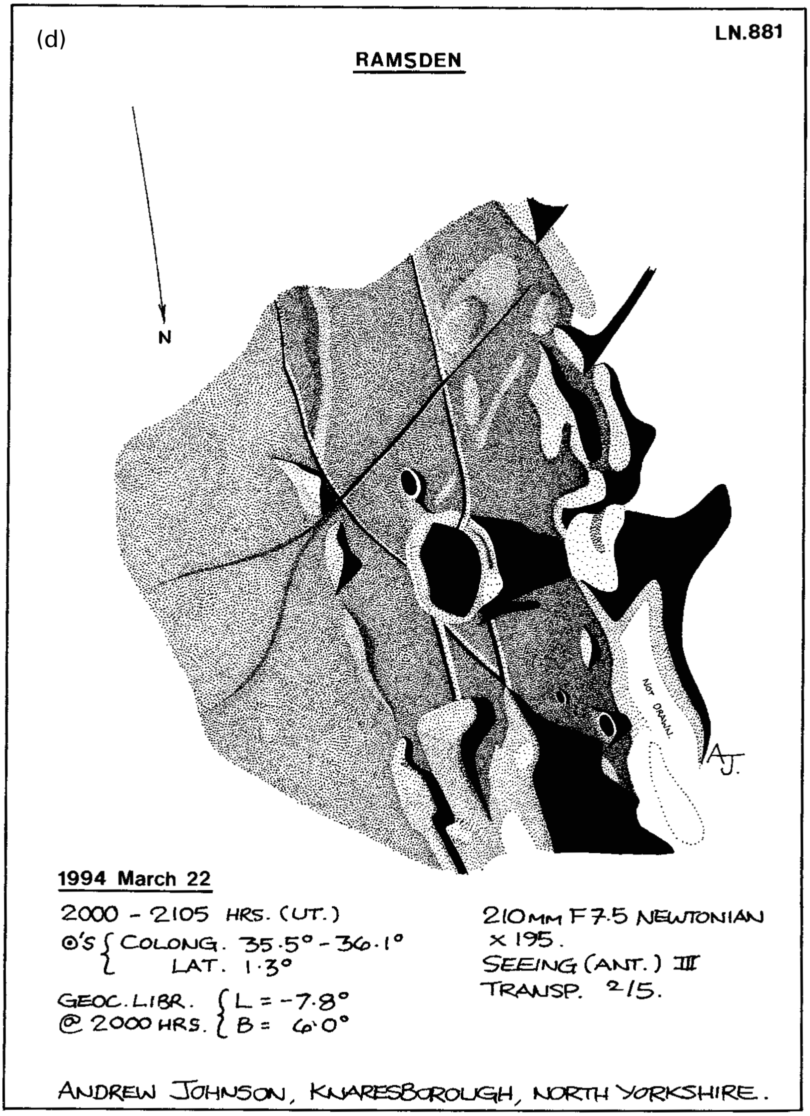


Figure 8.37 (*cont.*) (d) Ramsden and Rimae Ramsden, another drawing by Andrew Johnson.

the area as a whole is rille-ridden. Figure 8.37(b) shows a sunrise drawing of the formation by Roy Bridge, while Figure 8.37(c) and (d) are two further studies made by Andrew Johnson under higher angles of illumination. Figure 8.37(e) is a photograph obtained by the *Orbiter IV* probe. Can you work out the sequence of events that has led to the present vista? I will leave you to study the area and offer the illustrations here as a starting point.

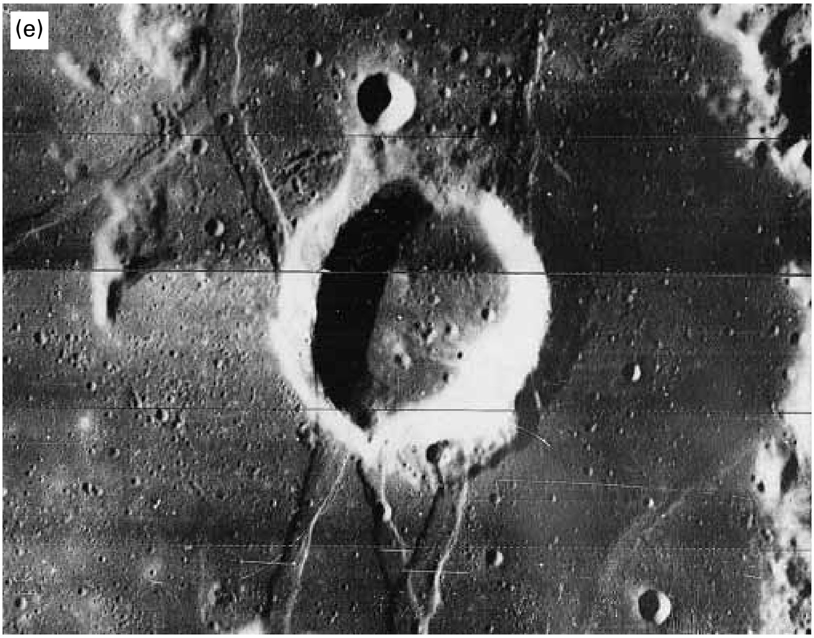


Figure 8.37 (*cont.*)
(e) *Orbiter IV* view of Ramsden. (Courtesy NASA and Professor E. A. Whitaker.)

8.38 REGIOMONTANUS [28°S, 359°E] (WITH PURBACH, THEBIT, WALTER)

Regiomontanus inhabits a very complex area of lunar highlands. Being close to the meridian, the area is perhaps best studied around the times of last and first quarter Moon.

The region is pictured in Figure 8.38(a), which is a photograph taken using the Catalina Observatory 1.5 m reflector. It was taken on 1966 May 29^{d} 04^{h} 41^{m} UT, when the Sun's selenographic colongitude was 22°.6. Regiomontanus is the large and rather oval formation pictured a little above the centre of the photograph. It measures 126 km east–west and 110 km north–south. Notice the eroded walls and the floor peppered with small craters. Does this give you any idea of the age of the crater? The irregular walls rise in places to about 1.7 km above the floor. The attention-grabbing feature of Regiomontanus has to be the off-centre 'central' mountain with its summit crater. Known as Regiomontanus A, this little crater is 5.6 km wide and 1.2 km deep. What do you think about its origin?

Below Regiomontanus in Figure 8.38(a), and overlapping it, is the 118 km diameter 'walled-plain' Purbach. Its very rough walls extend upwards to nearly 3 km above the inner arena. Many interesting details reside inside this formation. What do think about its age?

Above Regiomontanus on Figure 8.38(a) (and not quite completely shown in this view) is the even larger 'walled-plain' Walter. It is also somewhat

Figure 8.38(a) Regiomontanus and environs. Catalina Observatory photograph. The large crater at the top is Walter. The large crater below that is Regiomontanus. Note the off-centre mountain within it, and the mountain's summit crater. Just below Regiomontanus, and encroaching into it, is the large crater Purbach. Near the bottom right of the frame are the overlapping craters Thebit (the largest), Thebit A and Thebit L (the smallest). Further details in text. (Courtesy Lunar and Planetary Laboratory.)

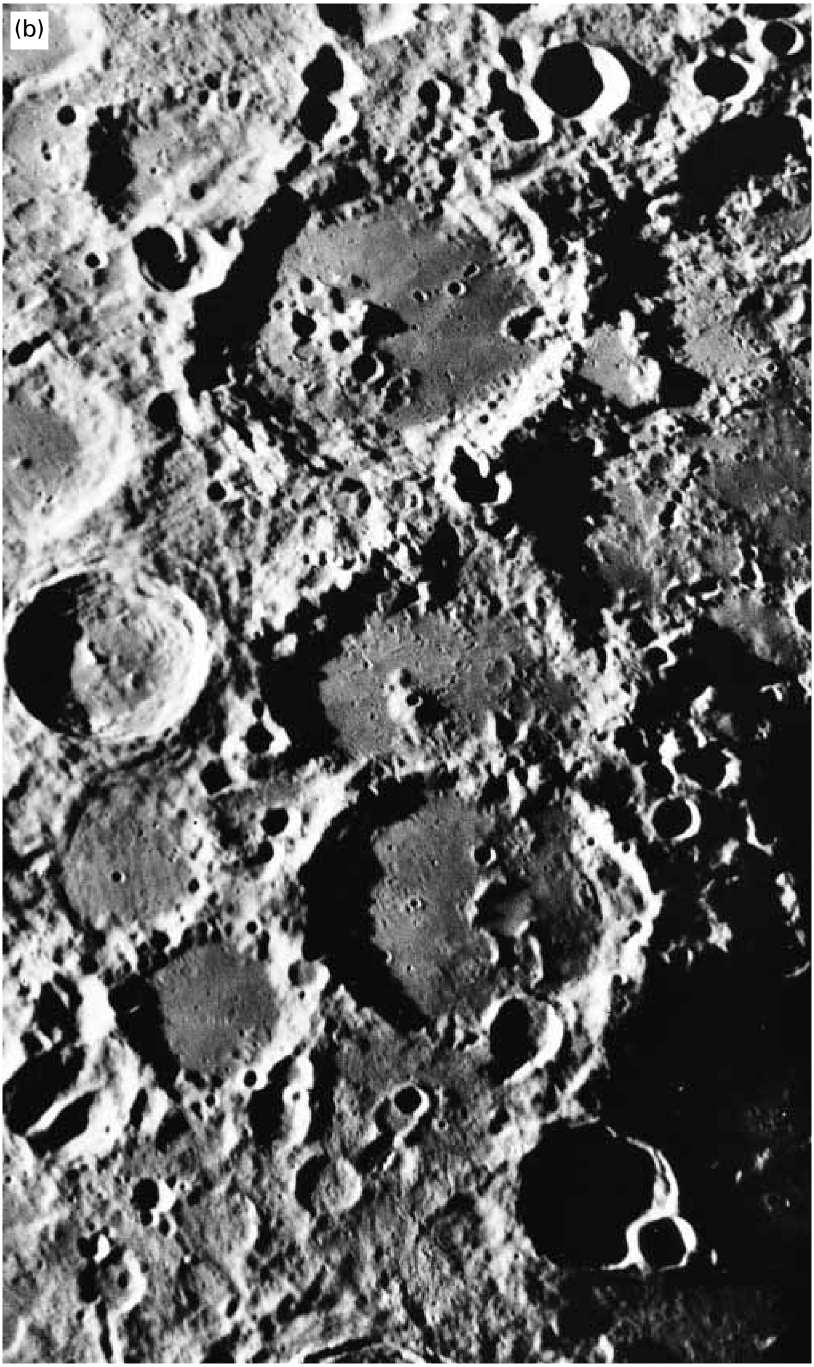
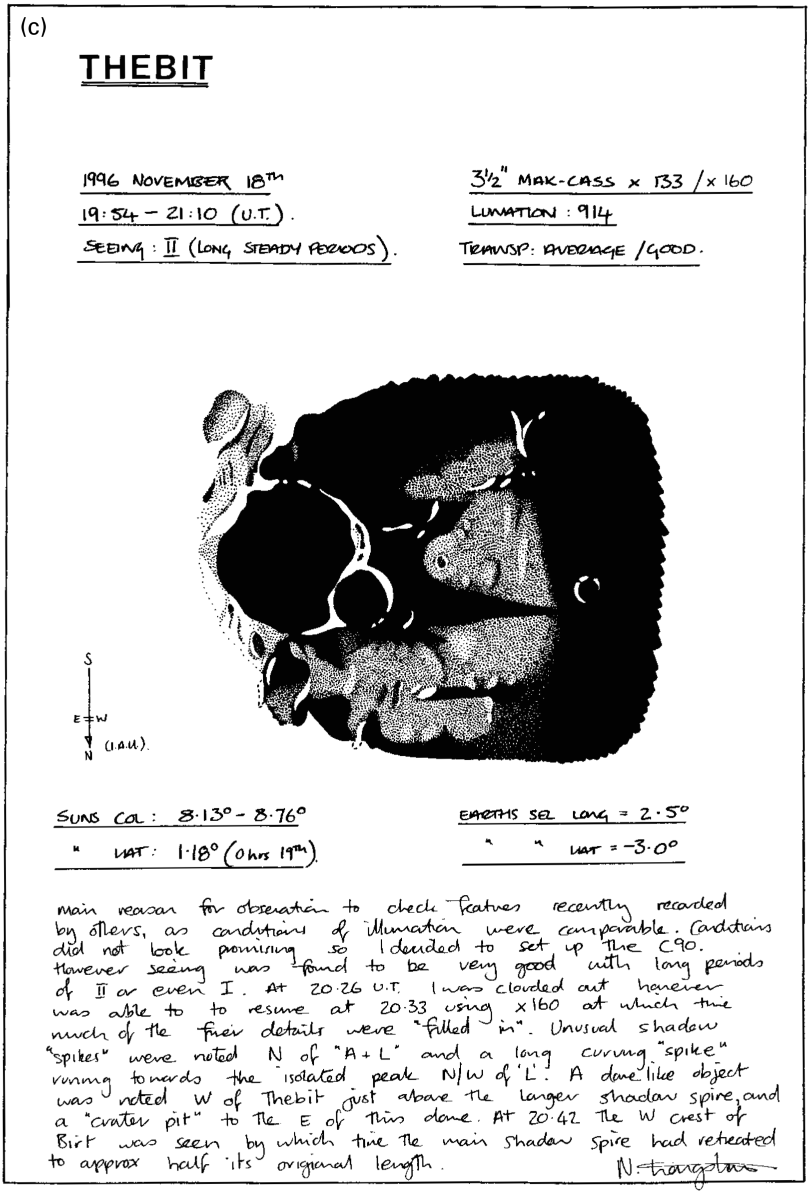


Figure 8.38 (*cont.*)
(b) Regiomontanus and environs shortly after sunrise. Details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

Figure 8.38 (*cont.*)
(c) Thebit, drawn by Nigel Longshaw.



'squashed' in the north–south direction; 132 km, as opposed to its east–west span of 140 km. Its eroded walls rise up to just over 4 km above the rough and hummocky floor. The walls are very broad and are divided by valleys along the southern section. Of particular note is the cluster of craters on its north-east (lower left in the photograph) quadrant. Any ideas on the evolution of this and the other craters in the area?

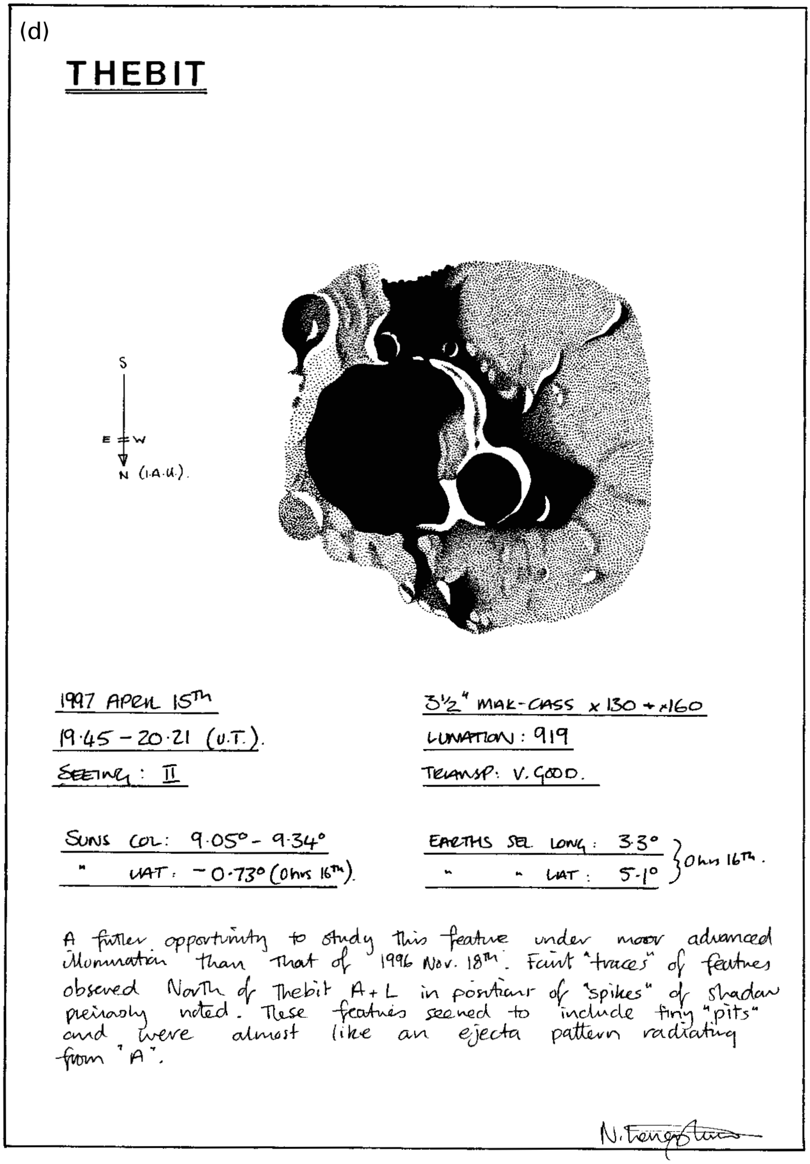


Figure 8.38 (*cont.*)
(d) A further study of Thebit, by Nigel Longshaw.

Figure 8.38(b) is another Catalina Observatory, 1.5 m telescope, photograph. It shows Walter in its completeness. It also shows the area very shortly after local sunrise, the selenographic colongitude here being 7°.1. The photograph was taken on 1967 January 19^{d} 02^{h} 45^{m} UT.

In the lower-right corner of Figure 8.38(a) (and (b)) is pictured a rather beautiful little arrangement of overlapping craters. The largest of these, at 55 km diameter, is Thebit. It is 3.3 km deep and has a rather rough floor. This crater is intruded upon by the 20 km diameter Thebit A. It has a smoother, almost bowl-like, profile and a small flat floor, at a level 2.7 km below that of the crater rim. Thebit A is, itself, invaded by a yet smaller crater. This one is now officially known as Thebit L (you may find other designations elsewhere) and is 12 km across. It is very shallow and has a tiny central crater within it.

Proponents of the endogenic theories of crater production made much of this formation in order to support their views. As well as the sequence of craters of diminishing size supporting their idea of a diminishing scale of volcanism occurring along a fault to produce the formation, they cited the undeniable evidence of the perfection of the crater outlines up to the point of the junction between them. They argued that any explosive event would have produced a shaking down of the walls of the earlier craters. However, when we look at lunar craters at much higher resolutions than is usually obtainable by conventional observations through our atmosphere we **do** see a degree of disturbance; enough not to need an endogenic creation mechanism for the intruding crater. The fact that intruding craters are almost always smaller than the craters they break into is explained by the fact that the smaller number of large impactors was more rapidly used up, leaving the greater number of smaller rocky (and icy?) fragments to subsequently pepper the Moon. So, the mystery disappears. In fact, there was never really a mystery at all.

Nonetheless, Thebit has always attracted the attention of observers. Figure 8.38(c) and (d) are two excellent studies of the formation by Nigel Longshaw. The whole area is rich in detail and full of interest. I commend its study to you.

The southern part of the crater rim shown at the bottom of Figure 8.38(a) belongs to Arzachel. I included it so that you might see how this region connects with that detailed in Section 8.4. Immediately west of Thebit is the formation known as "The Straight Wall", more properly the Rupes Recta. This is discussed in Section 8.43.

8.39 RUSSELL [27°N, 284°E] (WITH BRIGGS, BRIGGS A, BRIGGS B, EDDINGTON, KRAFFT, SELEUCUS, STRUVE)

The crater Russell is situated near the western edge of the Oceanus Procellarum and is very close to the north-eastern limb of the Moon. Roy Bridge has made an excellent drawing of sunrise over this formation and this is presented in Figure 8.39(a). This formation is the remains of an ancient 'walled-plain' type crater, about 99 km in diameter. A wider view of the area is shown in Figure 8.39(b), in which it can be seen that Russell is connected, via its missing south wall, to another great ring structure. This one we now call Struve. In older maps it is called Otto Struve and Russell is sometimes denoted as Otto Struve A. On other old maps, Russell

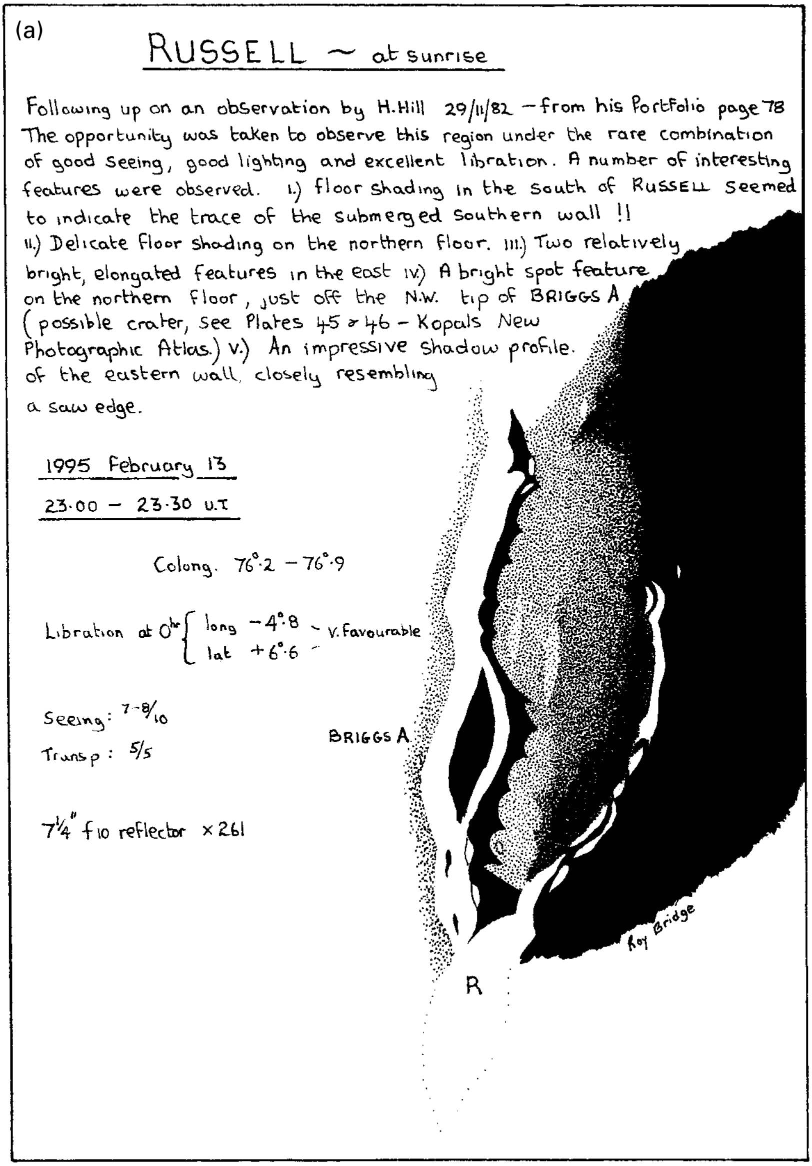


Figure 8.39 (a) Russell, drawn by Roy Bridge.

is taken to be part of Otto Struve. As well as A now being called Russell, the adjoining crater now commemorates all three astronomers Struve (Friedrich G. Wilhelm von Struve, his son Otto Wilhelm von Struve, and grandson Otto Struve). It is perhaps appropriate that the crater with three peoples' names is so large. It spans 183 km.

Figure 8.39(b) is a photograph taken with the Catalina Observatory 1.5 m reflector on 1966 October 28^{d} 06^{h} 28^{m} UT, when the Sun's selenographic

Figure 8.39 (*cont.*)
(b) Russell (bottom), connected to Struve (large formation on the terminator) and Eddington (adjoining it and sharing its wall with Struve) on the left of Struve. To the left of Eddington is the crater Seleucus. Above Eddington is the crater Krafft. Of the two craters near the bottom left, the upper one is Briggs and the lower (smaller) one is Briggs B. Briggs A is actually on the eastern (left in this photograph) rim of Russell. Other details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

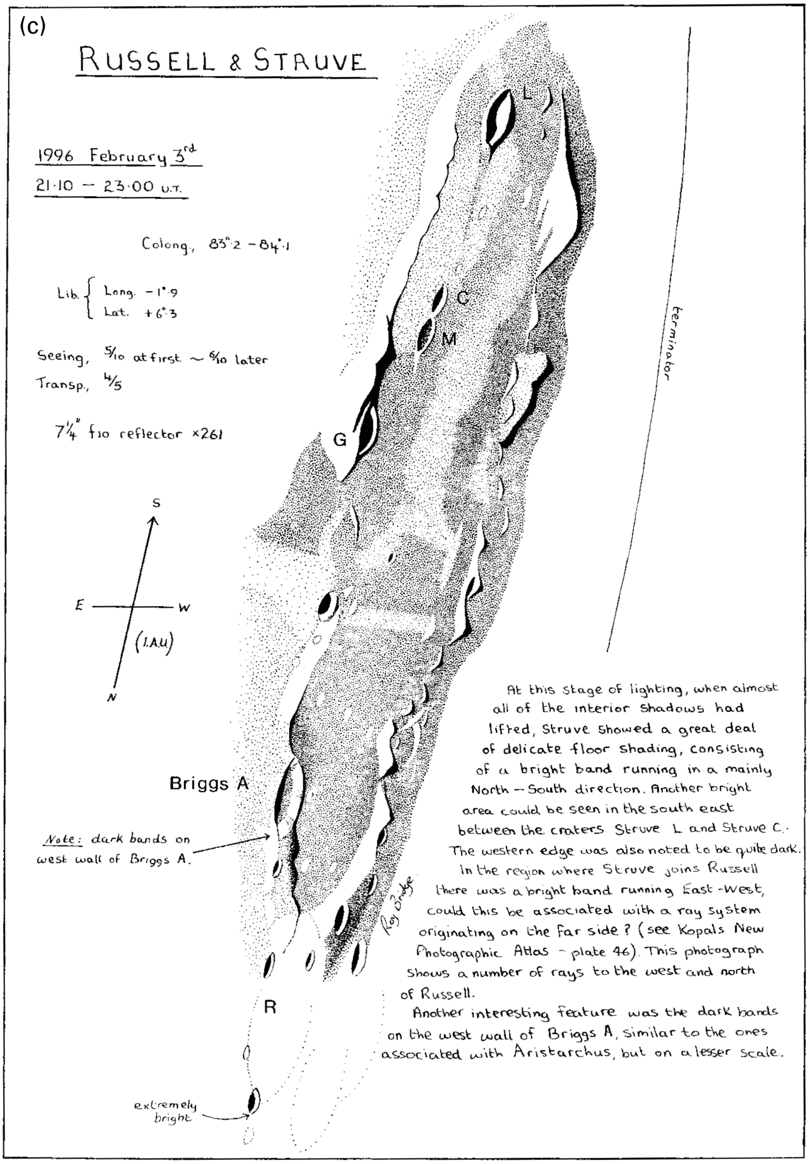


Figure 8.39 (*cont.*) (c) Russell and Struve, drawn by Roy Bridge.

colongitude was 79°.3. Notice how the floors of the craters obviously share the curvature of the Moon's surface (revealed by the shading). This is hardly surprising, since they are all flooded with mare lavas.

Figure 8.39(c) is another of Roy Bridge's splendid drawings. This one shows the wider area, encompassing Russell (at the bottom), and Struve. Notice that Roy has included the letter designations of many of the smaller craters. He has also picked out some radial dark bands running up the

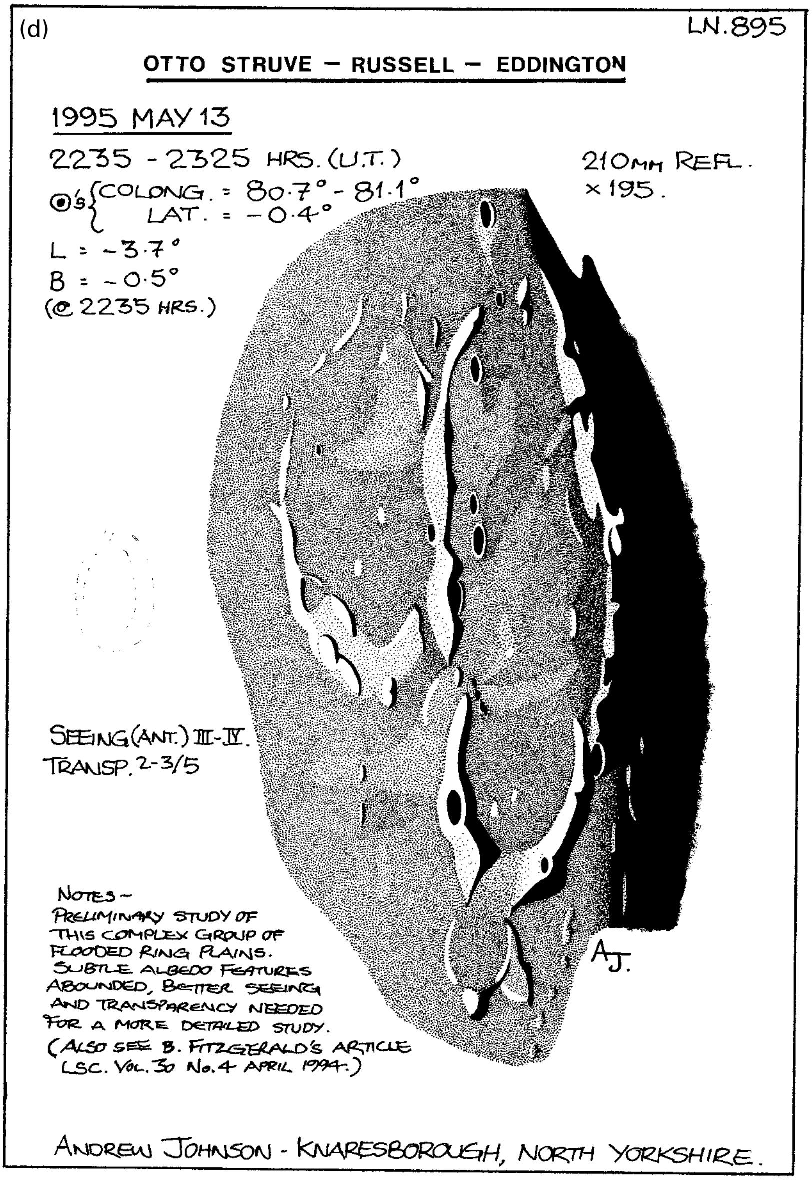


Figure 8.39 (*cont.*)
(d) Russell, Struve (old name "Otto Struve") and Eddington, drawn by Andrew Johnson.

interior of the crater Briggs A, situated on the eastern rim of Russell. You might look for these yourself. Briggs A has a diameter of about 23 km.

Locate Russell, then Briggs A near the bottom of Figure 8.39(b) and you will see two craters to the left (east) of Briggs A. The upper crater is Briggs. It is 39 km in diameter and has a most interesting interior. I will leave its examination to you. The lower one is Briggs B. It is 25 km in diameter.

Attached to the eastern flank of Struve, and sharing part of its rim, here significantly enhanced, is another flooded and ruined old ring. On modern maps this one is called Eddington. Confusingly, on some old maps this crater is known as Otto Struve A. It is 134 km in diameter. Figure 8.39(d) shows a splendidly detailed, and yet wide-angle, view of Russell, Struve and Eddington by Andrew Johnson.

A short distance east of Eddington is the 43 km diameter prominent crater Seleucus. It is well shown in Figure 8.39(b). Notice the unusual profile of this crater. It is very deep for its size, the depth being approximately 3 km.

The prominent crater near the top of Figure 8.39(b) is the 51 km diameter Krafft. Notice the pretty cluster of small craters around it, like bees around a honey pot.

The notes I have given here are very brief. In common with the later sections of this chapter, my intention is just to highlight some interesting areas of the Moon for you to investigate for yourself. I am sure that you will agree that in this region there is plenty to investigate.

8.40 SCHICKARD [44°S, 305°E] (WITH LEHMANN)

Schickard is a vast, partially flooded crater of the 'walled-plain' variety. It is 227 km in diameter and is situated near the Moon's south-eastern limb. A portrait of this great edifice is presented in Figure 8.40(a). It was taken with

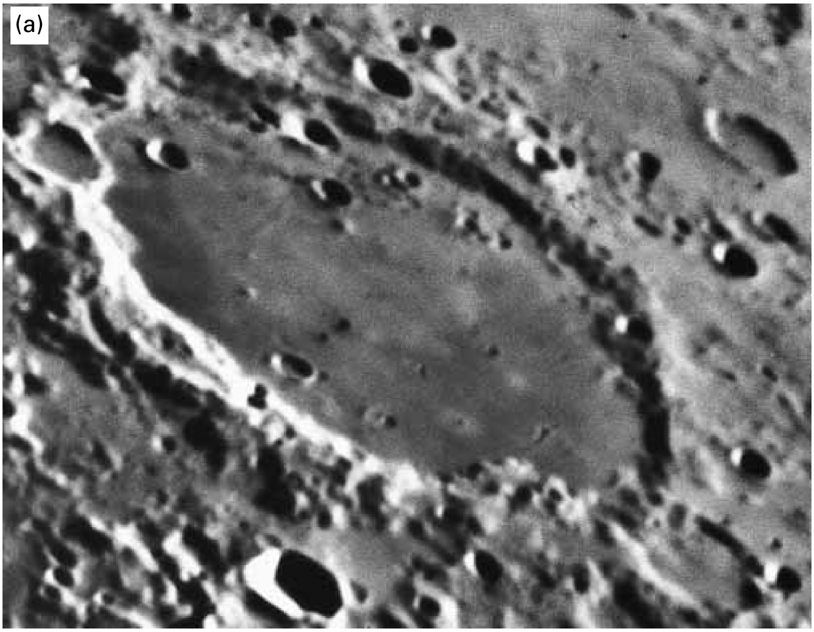


Figure 8.40 (a) Schickard. See text for details. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

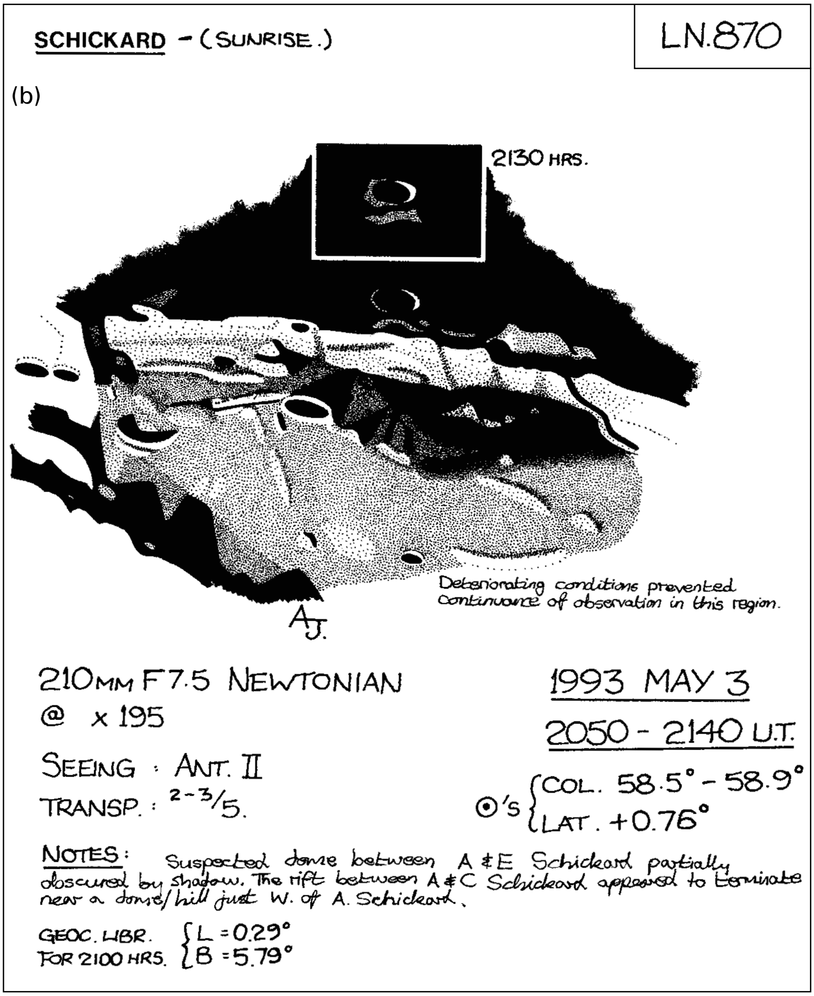


Figure 8.40 (*cont.*)
(b) Sunrise over Schickard, drawn by Andrew Johnson. Note the drawing is orientated with west very approximately uppermost.

the Catalina Observatory 1.5 m reflector on 1966 September 10^{d} 12^{h} 02^{m} UT, when the Sun's selenographic colongitude was 216°.8.

BAA Lunar Section members have long been interested in Schickard and the variety of objects that litter its floor. Probably the selenographer who has, more than most, made this formation his own is Keith Abineri. He began his telescopic studies in April 1946 and continues to work at this feature even to the time of writing these words. Though he no longer uses a telescope, he applies himself to the examination of *Orbiter* and *Clementine* space-probe imagery. He has published many papers in the BAA *Journal* and BAA Lunar Section publications, such as *The New Moon*. You might like to search these out for yourself. As well as being interesting in their own

(c)

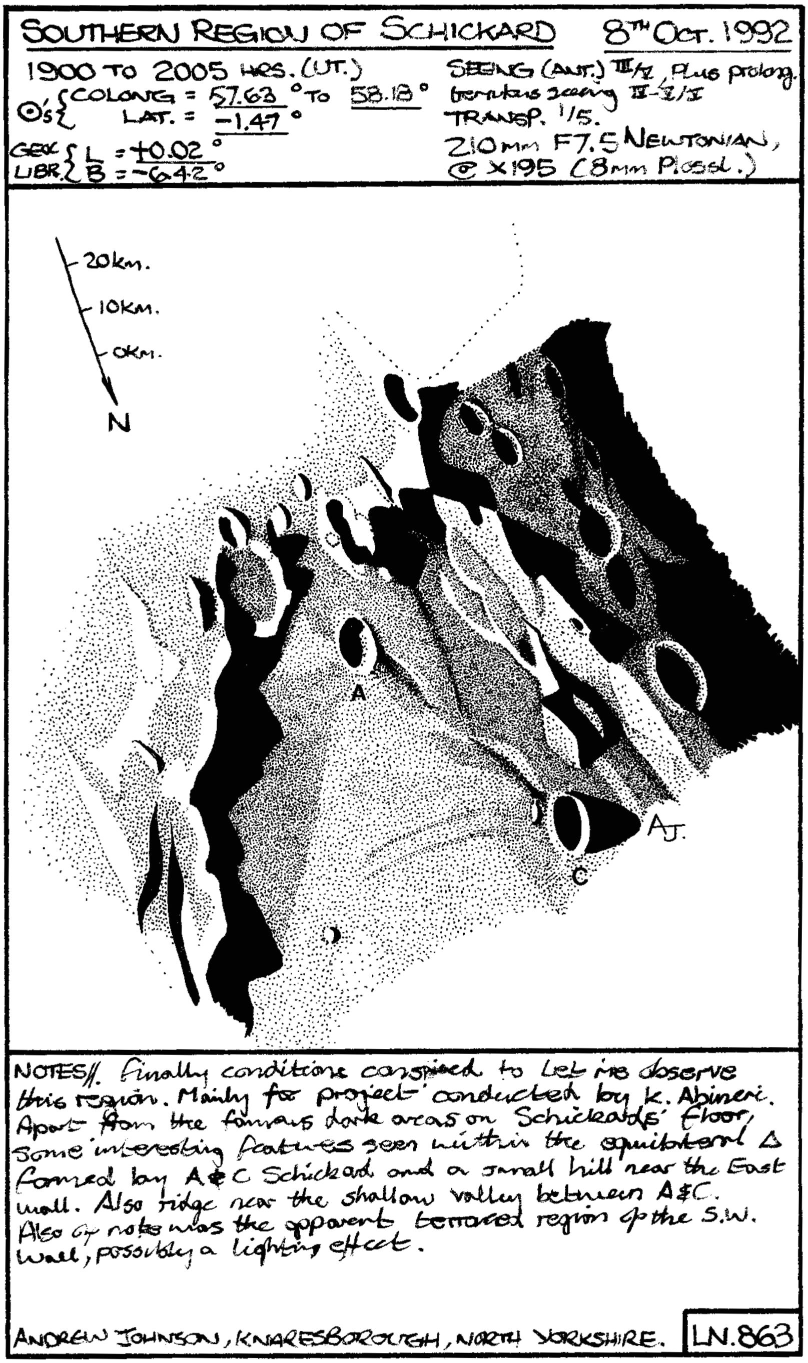
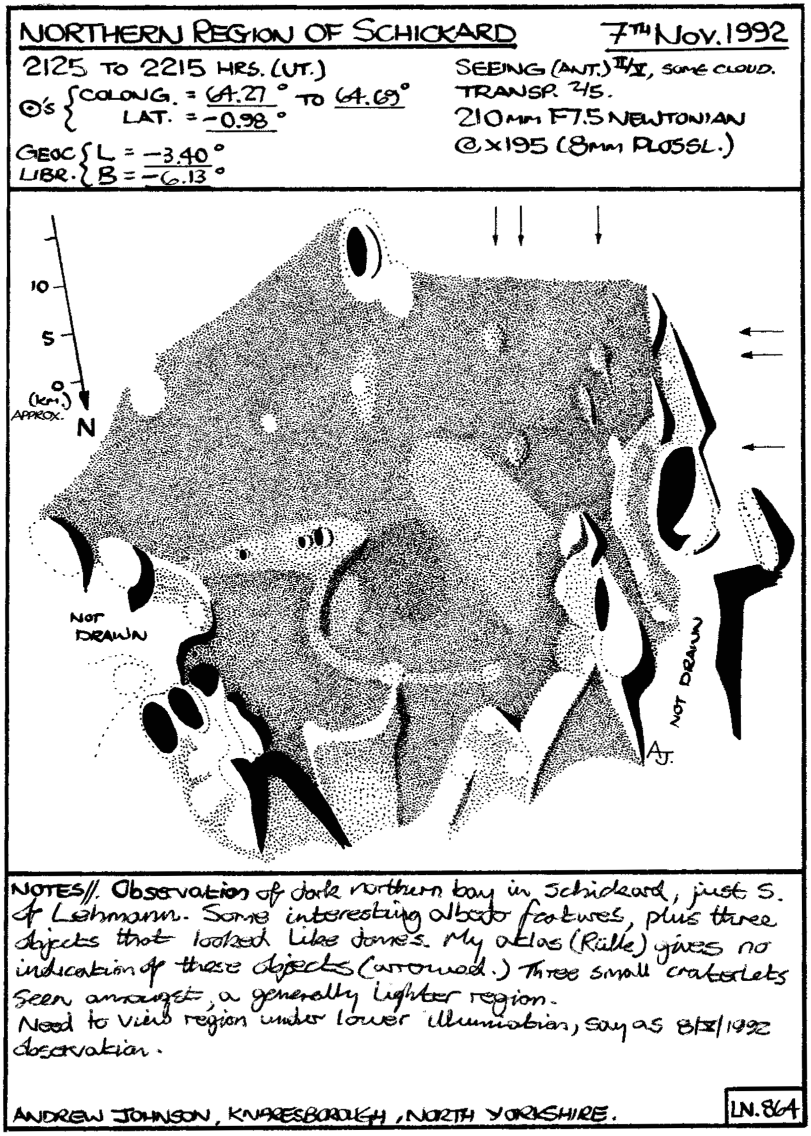


Figure 8.40 (*cont.*)
(c) The southern half of Schickard, drawn by Andrew Johnson.

Figure 8.40 (*cont.*)
(d) The northern half of Schickard, drawn by Andrew Johnson.

(d)



right, you might find some of these instructive with regard to the methodology he adopts.

Figure 8.40(b), (c) and (d) are recent telescopic studies of sections of this formation undertaken by Andrew Johnson.

A roughly triangular swath of lighter-hue material crosses the floor of Schickard from the south-west (where it is widest) to the north-east, the rest of the crater floor being very dark. This appearance is best seen under a high Sun, though indications of it are visible in Figure 8.40(a).

The rim of Schickard is interrupted by various craters and the largest abutting crater, at 53 km diameter, is the highly eroded Lehmann. It is shown in the bottom-right corner of Figure 8.40(a).

8.41 SCHILLER [52°S, 320°E]

Not far from the giant crater Schickard (see previous section), is a real lunar oddity. At first glance Schiller appears like a considerably elongated crater. It is 179 km long and spans 71 km at its widest point. Figure 8.41(a) to (d) illustrate the crater under a series of lightings from early morning (a) to sunset (d). They are photographs taken with the Catalina Observatory 1.5 m reflector and the details of date, time and selenographic colongitudes are given in the accompanying captions. Figure 8.41(e) presents a much more detailed view, this having been obtained by the *Clementine* space probe.

The usual explanation given in print for this formation is that it is the fusion of two craters. However, I disagree. I think that Schiller was formed from at least three, possibly four, fused craters or, perhaps, by at least three, possibly more, large projectiles arriving virtually simultaneously. My reasoning stems from the outline of the formation. To me, the southern rim has a smaller radius than that of the adjoining main section. The narrower northernmost section also constricts sharply where it ends

Figure 8.41 (a) Schiller, photographed using the 1.5 m reflector of the Catalina Observatory in Arizona, on 1966 April 2^{d} 08^{h} 03^{m} UT, when the Sun's selenographic colongitude was 48°.7. (Courtesy Lunar and Planetary Laboratory.)

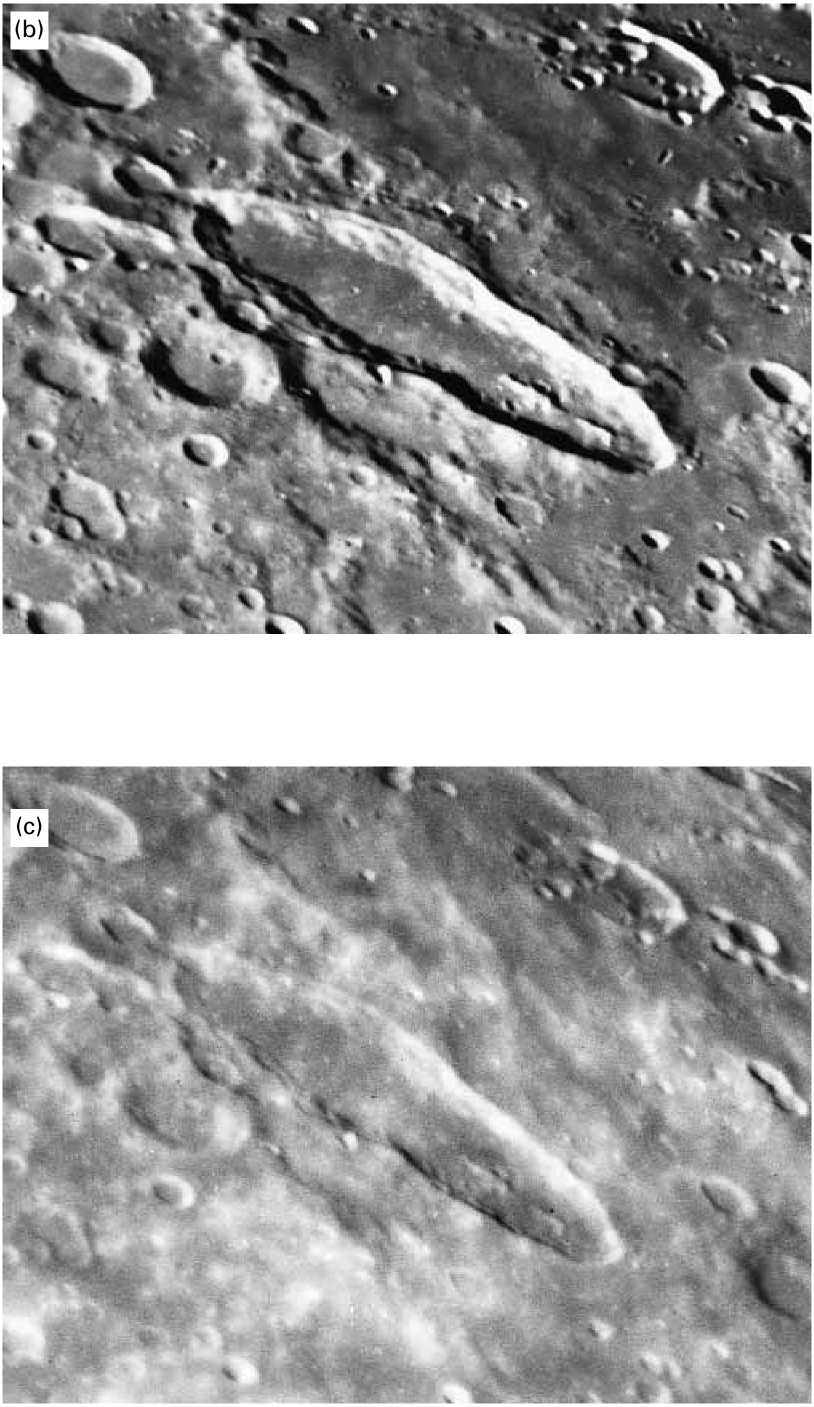


Figure 8.41 (*cont.*)
(b) Schiller, photographed using the 1.5 m reflector of the Catalina Observatory in Arizona, on 1967 February 22^{d} 03^{h} 43^{m} UT, when the Sun's selenographic colongitude was 61°.0. (Courtesy Lunar and Planetary Laboratory.)
(c) Schiller, photographed using the 1.5 m reflector of the Catalina Observatory in Arizona, on 1966 January 6^{d} 05^{h} 45^{m} UT, when the Sun's selenographic colongitude was 80°.9. (Courtesy Lunar and Planetary Laboratory.)

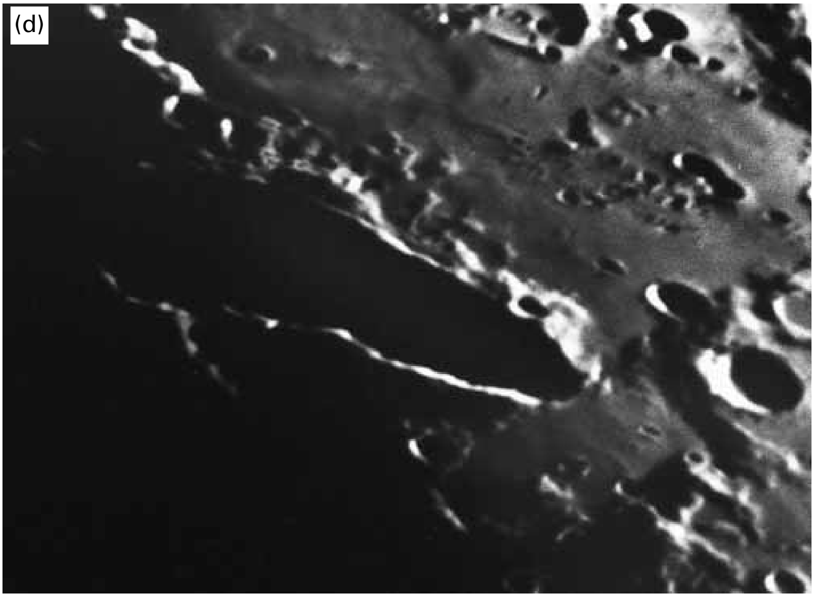


Figure 8.41 (*cont.*)
(d) Schiller, photographed using the 1.5 m reflector of the Catalina Observatory in Arizona, on 1966 September 10^{d} 12^{h} 02^{m} UT, when the Sun's selenographic colongitude was 216°.8. (Courtesy Lunar and Planetary Laboratory.)

in an arc of smaller radius. Moreover, the northern section sports two 'central peaks' both of which are highly elongated into ridges running along the long axis of the southern part of Schiller. The northern half of Schiller doesn't quite follow the same axis. It slightly 'kinks' a little to the east.

Putting the, albeit superficial, evidence together, I most favour the idea that a tight cluster of projectiles, whether they be cometary or asteroidal fragments, impacted the Moon at a low angle. The direction would obviously be along the long axis of the formation – but from which direction? The fact that just the southern end of Schiller has a 'central peak' type of formation might be significant. Was any part of the current formation already in existence on the Moon before the impacts that created the rest of it, or was it all formed in one go?

Of course, I must make it very clear that the foregoing is nothing official. It is merely my speculations on the subject. One thing is certain, though: there is much more to Schiller than the simple 'fusion of two craters' idea usually peddled. What do you think about it?

Figure 8.41 (*cont.*)
(e) *Clementine* image of
Schiller. (Courtesy NASA.)

8.42 SIRSALIS, RIMAE [14°S, 320°W] (WITH SIRSALIS, SIRSALIS A)

Situated near the Moon's western limb, the Rimae Sirsalis is just about the longest of the lunar rilles. Its length is 330 km. It is even more noteworthy in that it is one of the straightest over such a long length. Most of it is just one rille, the Rima Sirsalis, but it does have a few branches and extensions. Hence the more exact name of Rimae Sirsalis.

Figure 8.42 shows the main part of it in a photograph taken using the 1.5 m reflector of the Catalina Observatory, in Arizona. It was taken on 1966 February 4^{d} 07^{h} 02^{m} UT, when the Sun's selenographic colongitude was 74°.2. The rille can be seen running down the centre of the photograph. It is a graben; a slump feature. What caused it? The outer fringes of the Orientalis Basin are not too far away. However, the rille runs neither radial to it, nor tangential. So, was the Orientalis impact the cause?

Many amateurs have observed this feature as a sport, trying to trace the limits of its extension north and south. Four serious studies of the rille are presented here in Figure 8.42(b)–(e). From the first two, they cover sections going progressively northwards along it.

The significant pair of overlapping craters shown close to the centre of Figure 8.42(a) are Sirsalis and Sirsalis A. The complete one is Sirsalis. It is 44 km in diameter and is about 3 km deep. The central mountain is small, really just a hill, but is nonetheless prominent. Sirsalis A is actually slightly larger, at 49 km diameter, than Sirsalis though it is significantly overlapped by Sirsalis.

Figure 8.42 (a) Sirsalis and Sirsalis A (the overlapping craters below the centre) and Rimae Sirsalis (running down the middle). Details in text. (Catalina Observatory photograph – courtesy Lunar and Planetary Laboratory.)

Figure 8.42 (*cont.*)
(b) Sirsalis and Rimae Sirsalis, drawn by Andrew Johnson.

(b)

LN.894

SIRSALIS & RILLE

1995 APRIL 12

2000 – 2110 HRS. (U.T.)

☉'s { COLONG. 61·1° – 61·7°
LAT. 0·4° }

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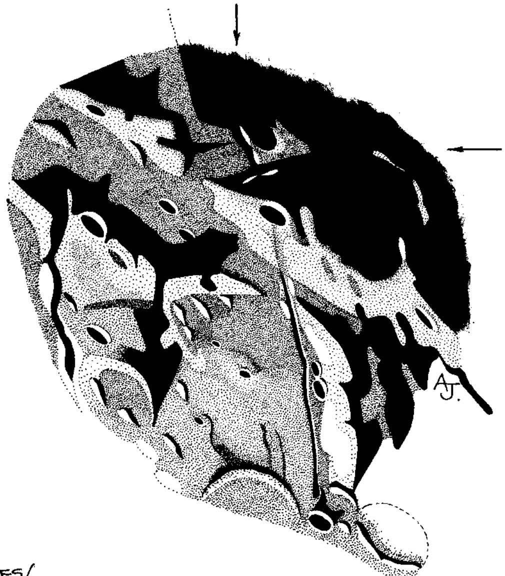


NOTES/
Further observation in search of confirmation that the Sirsalis rille does reach Sirsalis J, climbing the surrounding slope of the crater. This observation was made under a lower angle of illumination, and as the rille was indeed seen, and that it lacked any real shadows, perhaps these conditions indicate that the rille may be quite shallow over this section of its path? Arrows indicate possible extension of rille beyond the terminator.
(Shadows shown as at 2025 HRS.)

ANDREW JOHNSON, KNARESBOROUGH, NORTH YORKSHIRE.

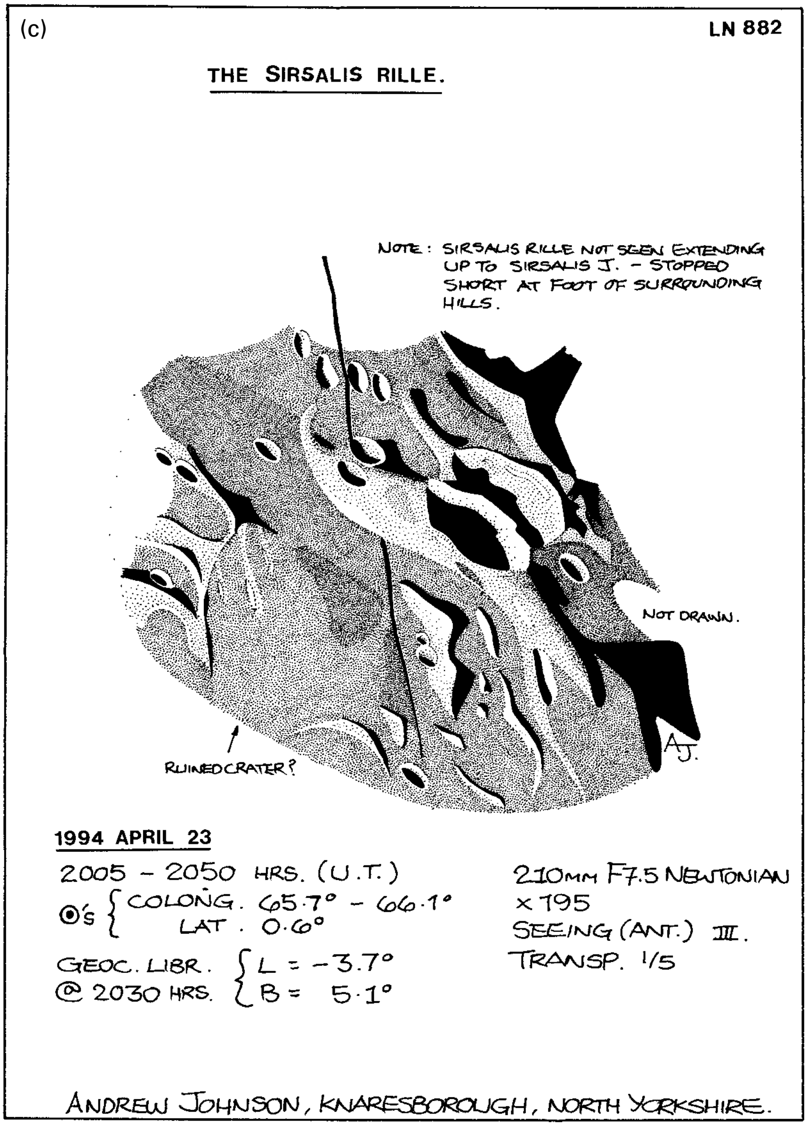


Figure 8.42 (*cont.*) (c) Sirsalis and Rimae Sirsalis, another drawing by Andrew Johnson.

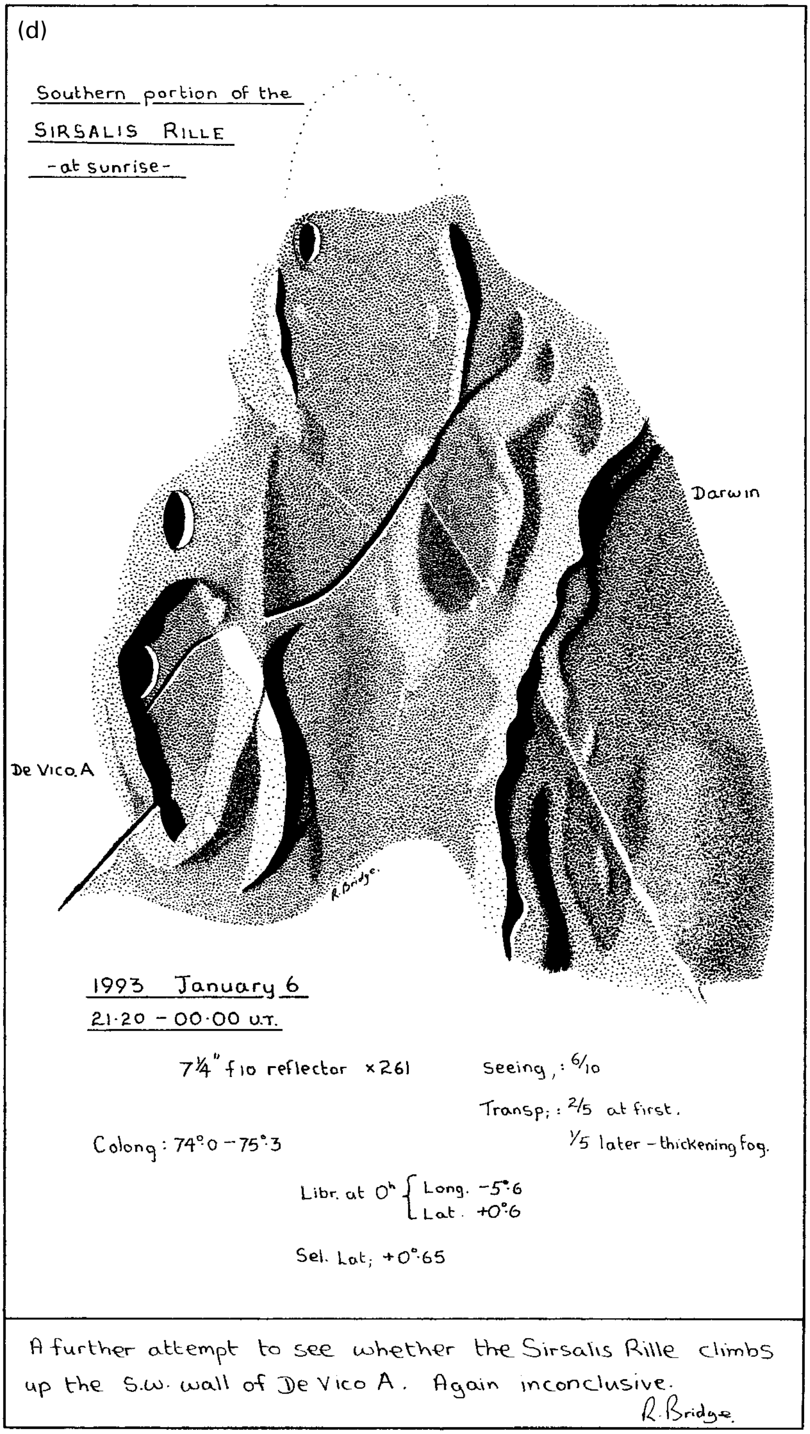


Figure 8.42 (*cont.*)
(d) Rimae Sirsalis and De Vico A, drawn by Roy Bridge.

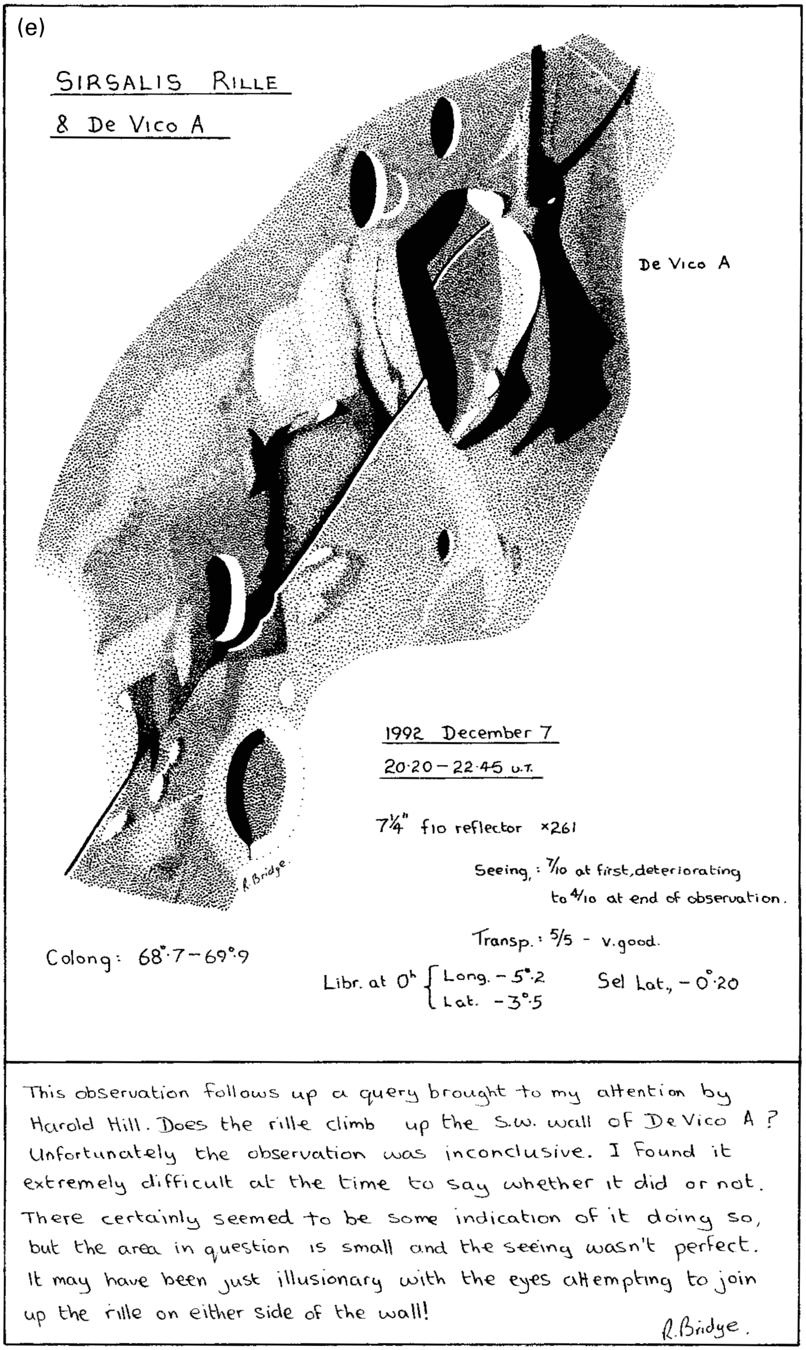


Figure 8.42 (*cont.*)
(e) De Vico A and the northern section of the Rimae Sirsalis, drawn by Roy Bridge.

8.43 "STRAIGHT WALL" {RUPES RECTA} [22°S, 352°E] (WITH BIRT, BIRT A)

Properly known as Rupes Recta, this formation is so widely and popularly known by its old name of the "Straight Wall" that I have entered it here under that name.

One of Tony Pacey's excellent photographs shows it well (Figure 8.43(a)). Tony used his 10-inch (254 mm) Newtonian reflector and a 4 mm Orthoscopic eyepiece to project the image onto FP4 film. The ½ second

Figure 8.43 (a) The "Straight Wall" formation, more properly called Rupes Recta, photographed by Tony Pacey. Appearing here as a thin black line, the overlapping craters Thebit, Thebit A and Thebit L are just to its left and the small but distinctive Birt, with Birt A on its rim, is just to its right. Other details given in the main text.

Figure 8.43 (*cont.*)
(b) Rupes Recta, photographed using the 1.5 m reflector of the Catalina Observatory in Arizona. Details in text. (Courtesy Lunar and Planetary Laboratory.)

exposure was given at 1988 April 24^{d} 22^{h} 00^{m} UT. At the time the Sun's selenographic colongitude was 356°.8.

Rupes Recta is situated near the eastern border of the Mare Nubium, just west of the distinctive overlapping craters Thebit, Thebit A and Thebit L (see Section 8.38). Tony Pacey's photograph shows the general environs, including the Thebit trio and Regiomontanus (upper-left corner) and Arzachel, Alphonsus and part of Ptolemaeus (in the lower left). These areas are detailed in Sections 8.38 and 8.4, respectively. The crater Pitatus is shown in the upper-right corner of Figure 8.43(a) and this feature is described in Section 8.32. Just west (right in Figure 8.43(a)) of Rupes Recta is a small but distinctive crater, Birt, with a small crater on its rim, Birt A. Birt is a bowl-shaped formation 17 km across and 3.5 km deep. Birt A has a diameter of 6.8 km and a depth of 1 km.

The "Straight Wall" is not particularly straight and it most certainly is not a wall. It comes into daylight just after first quarter Moon and appears as a thin black line when illuminated from the east (local morning). As with most lunar relief features, it washes out near full Moon but then appears as a thin light line towards the late afternoon, then being illuminated from the west. This shows that there is a difference in height of the ground to either side of it.

Despite appearances, the feature is not a shear cliff-face of extraordinary height. Rather it is a fairly gentle slope linking the higher ground to the east with the lower plain to the west. The average slope is of the order of 7° and its height is not much more than 240 m. However the formation is remarkable in view of its length, which is about 110 km.

What caused it? Is it a case of the ground to the east being uplifted, or the ground to the west slumping downwards? Opinions are still divided but the most popular view is that the ground to the east was buckled upwards under compressional forces across this part of the Mare Nubium.

Take a careful look at Figure 8.43(a) and you should be able to discern the outline of an almost entirely obliterated crater. Look at the border of the terrae to the east of the Rupes Recta. Thebit actually lies across the old rim. The lavas of the Mare Nubium have melted away most of its western rim but traces of it can still be made out on the mare. You will see that Rupes Recta spans much of the diameter of this old 'ghost' crater. Could that be significant?

I will leave you to ponder on this intriguing formation but, to get you started, you might like to consider the other buried ring at the southern end of it and the rille that runs approximately parallel to it, a little to the west and passing just beyond Birt. A close-up view is provided in Figure 8.43(b), which is a Catalina Observatory photograph, taken using the 1.5 m reflector on 1966 May 29^{d} 04^{h} 41^{m} UT, when the Sun's selenographic colongitude was 22°.6.

8.44 THEOPHILUS [11°S, 26°E] (WITH CATHARINA, CYRILLUS, MÄDLER, MONS PENCK).

One of the most striking arrangements of craters on the Moon must be that of Catharina, Cyrillus and Theophilus. They first come into sunlight about 5–6 days after new Moon and then present the spectacle shown in Figure 8.44(a). Figure 8.44(b) shows the area under a higher Sun. Even then the grouping still looks impressive. The craters are shown lit from the opposite direction in Figure 8.44(c), which is a view you will see about 19–20 days after new Moon. The craters fill with shadow and are finally extinguished at a lunar age of about 19½ days (see Figure 8.44(d)).

In part, the dramatic appearance of the craters is heightened by the scarp Rupes Altai framing the group to the west. The scarp is a raised ring of mountains uplifted at the time of the impact that created the nearby, and now lava-flooded Nectaris Basin. Cyrillus, Catharina and Theophilus are thus sandwiched between the Mare Nectaris, to their east, and the Rupes Altai, to their west. The rest of the Mare Nectaris region is discussed in Section 8.30.

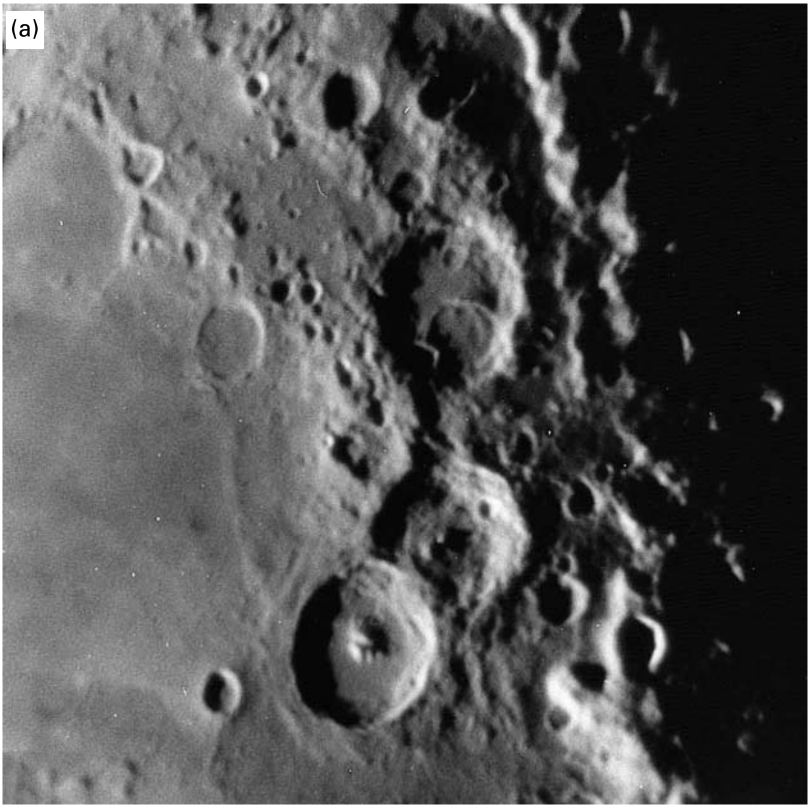


Figure 8.44 (a) Theophilus (bottom large crater), Cyrillus (above and adjoining Theophilus) and Catharina (above Cyrillus), photographed by Tony Pacey using his 10-inch (254 mm) Newtonian reflector on 1991 March 21^{d}. The approximate time of the exposure was 20^{h} UT and the approximate value of the Sun's selenographic colongitude was 330°. The ½ second exposure was made on T-Max 100 film, processed in HC110 developer. The small crater on the left of Theophilus is Mädler, which is actually sited on the mare Nectaris.

Figure 8.44 (*cont.*)
(b) Theophilus and environs photographed using the 1.5 m reflector of the Catalina Observatory on 1966 September 3^{d} 09^{h} 19^{m} UT, when the Sun's selenographic colongitude was 130°.0. (Courtesy Lunar and Planetary Laboratory.)

The southernmost of the trio of craters is Catharina. It is 97 km in diameter. Its rough walls are very irregular in outline and heavily crater-spattered. They reach up to 3.1 km above the crater. Notice the interior details. There is a story here, but I will leave its investigation to you.

Catharina is clearly the most eroded, and thus the oldest, of the trio but the middle crater, Cyrillus, is not much younger as far as lunar chronology goes. Notice the apparent channel connecting Cyrillus to Catharina. In reality the connection is the result of further impacts, though a degree of ground-slumping is also evident.

Cyrillus is 93 km in diameter and is of similar depth to Catharina, though its gentler interior slopes do give the impression of it being deeper than it really is. Notice the prominent double-peaked mountain near the centre of Cyrillus. It is instructive to compare the floors of the craters

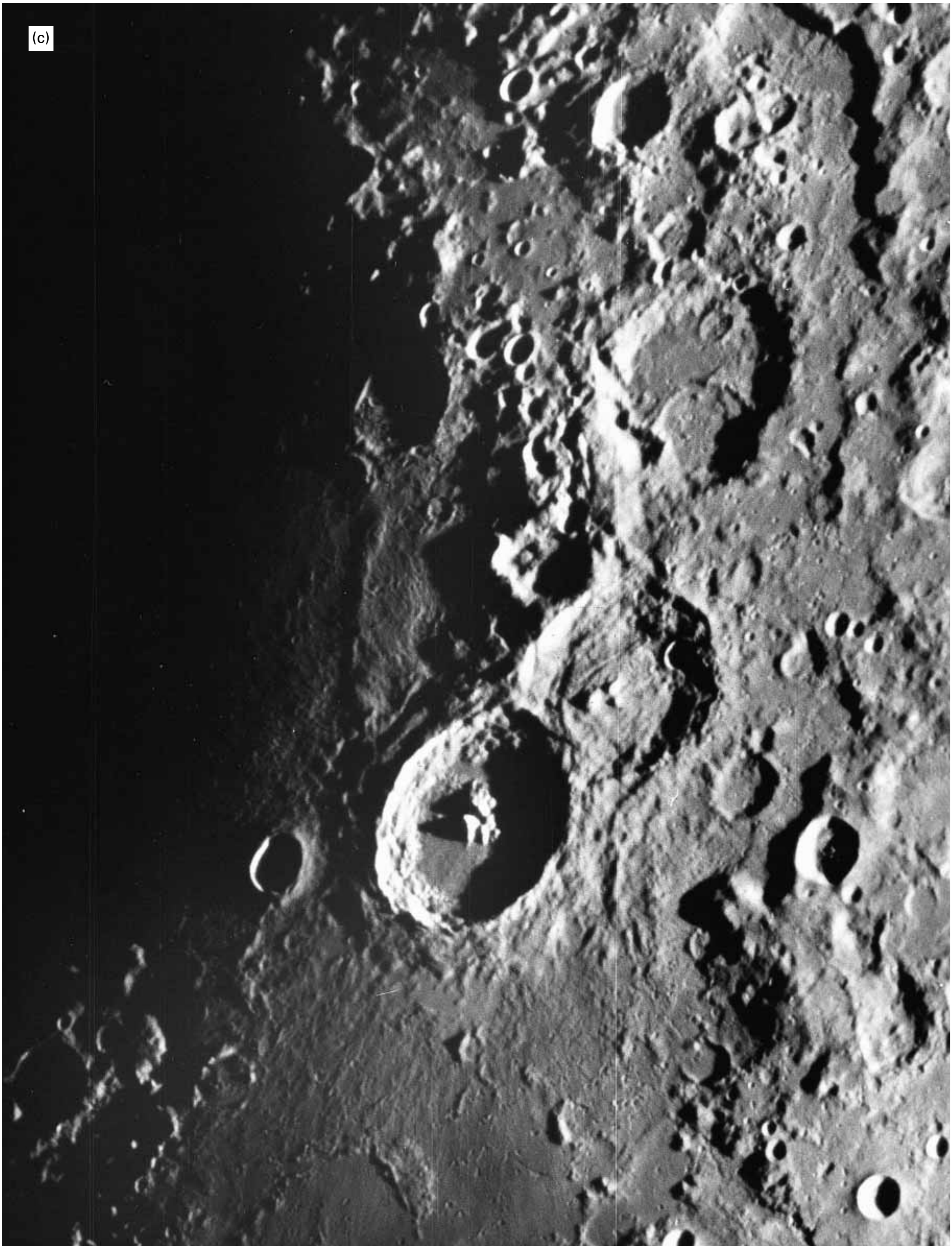

(c)

Figure 8.44 (*cont.*)
(c) Evening approaches for Catherina, Cyrillus and Theophilus in this photograph taken by Dr T. W. Rackham with the 1.07 m reflector of the Pic du Midi Observatory in France. Notice how the terminator follows the outline of the mare Nectaris. The only other detail available is that the photograph was taken before the end of July 1964.

Cyrillus and Catharina. What are their similarities and what are their differences – and how do you explain them?

Obviously the youngest of the three craters is the 100 km diameter Theophilus. It is a spectacular object in its own right, even divorced from the presence of Catharina and Cyrillus (which it invades). The outer flanks of this crater are very complex and the crater rim rises up to about 1.2 km above the level of its outer surrounds. The interior is rather deep, extending to 3.2 km below the level of the outer surrounds. As the accompanying illustrations show, the interior slopes of Theophilus are very complex. Clearly the initial terracing has been much degraded by localised landslips. Notice the smooth central arena that surrounds the magnificent central mountain cluster. The highest peaks of this complex soar up to about 2 km above the level of the crater floor. I wonder when it will be that a lunar mountaineer will climb the main mountain and from the summit view the incredible spectacle of the surrounding unearthly landscape?

Various observers have noted odd appearances in Theophilus and many consider it to be a 'TLP hot spot'. I have never seen anything untoward in it, myself.

At the position where the Rupes Altai passes closest to Theophilus is a prominent mountain peak reaching further eastwards than the rest of the range at this point. This feature is named Mons Penck and it is the subject of the drawing by Andrew Johnson shown in Figure 8.44(d). Figure 8.44(e) presents one of Terry Platt's stunning CCD images of Theophilus.

The Mare Nectaris lavas encroach right up to the eastern flanks of Theophilus and the significant crater to the east of Theophilus, called Mädler, actually sits in the junction of the Mare Nectaris with the Mare Tranquillitatis. It has a somewhat distorted outline, its diameter averaging about 28 km. It is very deep for its size, measuring about 2.7 km vertically from floor to rim.

Just a little north of this area of grand craters and spectacular mountains is a little grouping of very small and apparently insignificant craters that are, nonetheless, fascinating in their own right and may even hold a secret or two. These are the subject of the next section.

(d)

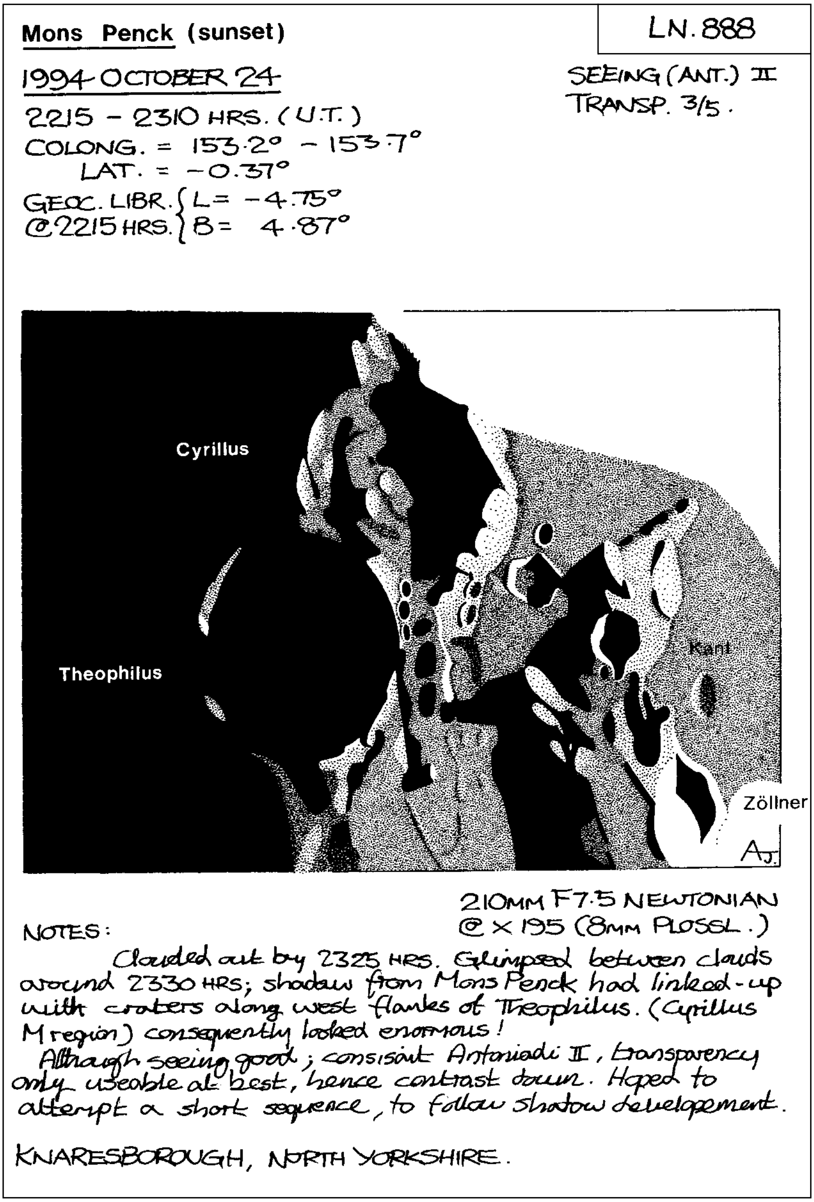


Figure 8.44 (*cont.*)
(d) Theophilus, Cyrillus and Mons Penck, drawn by Andrew Johnson.

Figure 8.44 (*cont.*)
(e) Theophilus. CCD image by Terry Platt, using his 12½-inch (318 mm) tri-schiefspiegler reflector and *Starlight Xpress* CCD camera. Other details not available. The author has applied slight image sharpening and brightness re-scaling.

8.45 TORRICELLI [5°S, 28°E] (WITH CENCORINUS, MOLTKE, RIMAE HYPATIA, TORRICELLI A, B, C, F, H, J AND K)

Less than two hundred kilometres north of Theophilus, on the Mare Tranquillitatis, is an interesting little group of features. These are shown in Figure 8.45. This figure and Figure 8.44(b) in the previous section are reproductions of parts of the same Catalina Observatory photograph and the details are given in the previous section. (See the accompanying caption to Figure 8.45 for the identification of the features listed.)

Despite its small size (about 20 km diameter), Torricelli does tend to catch the eye because of its 'keyhole' shape. In fact it seems to be the fusion of two craters, one smaller than the other.

The crater Cencorinus is only 3.8 km wide and yet it is very attention-grabbing when seen under a high Sun. Its interior is very highly reflective and it is surrounded by a patch of bright ejecta. It is normally written that Aristarchus is the brightest crater on the Moon. Undoubtedly that is the case when one takes into account its much larger size. **Area for area**, though, I think Cencorinus is brighter when it is seen under the highest angles of illumination. Cencorinus is probably one of the freshest craters on the Moon that is big enough to resolve with a backyard telescope.

Another prominent, though much less brilliant, little crater is Moltke. It is a bowl-shaped edifice with a diameter of 6.5 km and a depth of about 1.3 km. Space-probe images show it to have a razor-sharp rim and a bright, smooth, interior. It also possesses a fairly bright ejecta nimbus. The eastern end of the Rimae Hypatia passes between Moltke and the hinterland just

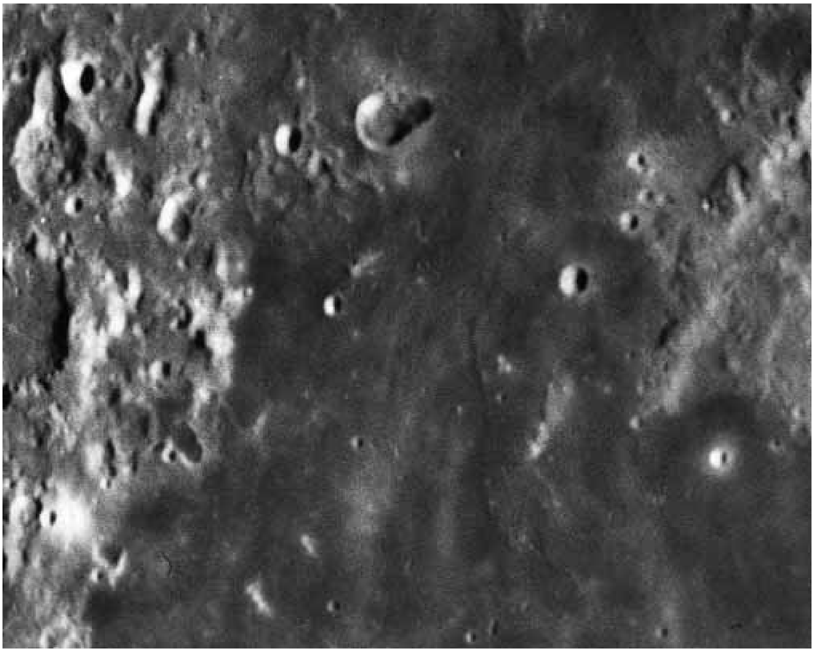


Figure 8.45 The 'keyhole' crater Torricelli (top centre), Cencorinus (bright crater near bottom-left corner), and Moltke (bright crater, two-thirds of the way down close to the right-hand side), photographed by the Catalina Observatory 1.5 m reflector. Same details as for Figure 8.44(b). The crater half-way along a line between Torricelli and Moltke is Torricelli C. Notice the little arc of craters just above Torricelli C. From top to bottom the three main ones are Torricelli K, J, and H. Of the two craters just to the left of Torricelli, the larger one is Torricelli A and the smaller one Torricelli F. Below these craters is the crater Torricelli B, notable as the origin of many recent reports of Transient Lunar Phenomena. (Courtesy Lunar and Planetary Laboratory.)

to the south of it. You might be able to see faint indications of it on Figure 8.45, though the lighting is not suitable to show it at its best.

The identified craters Torricelli A, B, C, F, H, J, and K have diameters of 11, 7, 11, 7, 7, 5 and 6 km, respectively. Of these, Torricelli B is particularly interesting. Space-probe images show it to be rather conical in profile and the interior is rather asymmetrically surfaced with deposits of varying composition. In particular the *Clementine* images show a brilliant streak of material (which I think is rich in feldspar – not enough room here for me to explain why – though I do not at the present time know if this is the official view) 'splashed' up the north-east interior from the centre to the rim. Much of the south-west of the interior flank seems to be also, though less richly, covered in the same material. This explains the brilliant 'blob' in the corresponding position that I have observed in this crater on many occasions through my own telescopes.

Torricelli B seems to be one of the more definite TLP 'hot spots'. It, and the other craters around it, show variations in brightness and prominence during the progress of a lunation. All perfectly normal and understandable. The crateriform aspect of Torricelli B is most obvious when the Sun shines at a low angle over it and much of its interior is filled with shadow. Under a higher Sun it becomes a greyish disk, brightest close to the time of full Moon. Every so often, though, Torricelli B looks either much brighter or much duller than one expects that it should at the given point in the lunation. I also find that its colour occasionally changes from its normal white and takes on a very strong blue caste. When the colour is strong the crater can even take on a purplish halo! I have also watched the crater erratically varying in brightness with the variations happening on time-scales of the order of minutes. Meanwhile the surrounding features, such as the craters Moltke and Cencorinus stay sensibly constant in appearance. Naturally any variations of the order of a second or two, and less, could well be caused by atmospheric turbulence – but variations of brightness on time-scales of minutes?

The BAA Lunar Section members have kept an eye on this crater since the first anomalies were noticed in January 1983. In particular one member, Mrs Marie Cook, has diligently observed Torricelli B visually and with the use of coloured filters from then right up to the time of writing. She has made many hundreds of observations of Torricelli B, using Moltke and Cencorinus as comparisons. Her results do seem to confirm my impression of occasional erratic changes of colour and brightness and it is a pleasure to pay tribute to her work here.

Are these changes illusory, or is there a real physical process happening on the Moon? Certainly spurious colour and bad seeing conditions can, and do, effect the appearances of features. I am sure that this is the correct explanation for the vast majority of reports of supposed TLP. For instance, the brilliant Cencorinus is often bedevilled by spurious colour (prismatically created by the Earth's atmosphere).

Sometimes Cencorinus shows an anomalous brightness change, as occasionally does Moltke, though neither show significant colourations other than that caused by spurious colour. An intriguing area of the Moon, ripe for observation and research.

8.46 TYCHO [43°S, 349°E]

As Figure 8.46(a) shows, the crater Tycho is an impressive formation when seen under a low angle of solar illumination. Figure 8.46(b) is a drawing of this crater made by Andrew Johnson and Figure 8.46(c) is one of Terry Platt's astounding CCD images. The crater is 85 km across and is very deep, as lunar craters go. The vertical height of the crater rim above its deepest point is 4.8 km. The interior terraces leading down from the rim to the central arena are spectacular by any standards, as Figure 8.46(c) probably shows best even though it was made under the conditions of a higher Sun-angle. As one might expect, space-probe images show the crater in greater detail. Figure 8.46(d) is a stunning view obtained from *Orbiter V*. The central mountain massif soars upwards to a point 1.6 km above the crater floor.

As I said, the crater is spectacular enough when seen under a low angle of illumination. If anything, it becomes even more so under a high Sun.

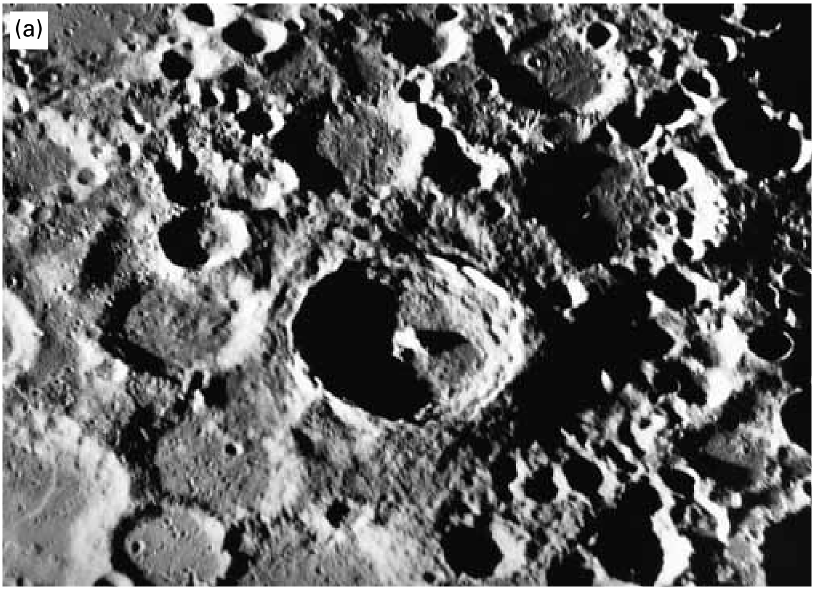


Figure 8.46 (a) Tycho photographed on 1967 January $20^{d}\ 01^{h}\ 52^{m}$ UT, using the 1.5 m reflector of the Catalina Observatory in Arizona. At the time of the photograph the Sun's selenographic colongitude was 18°.5. (Courtesy Lunar and Planetary Laboratory.)

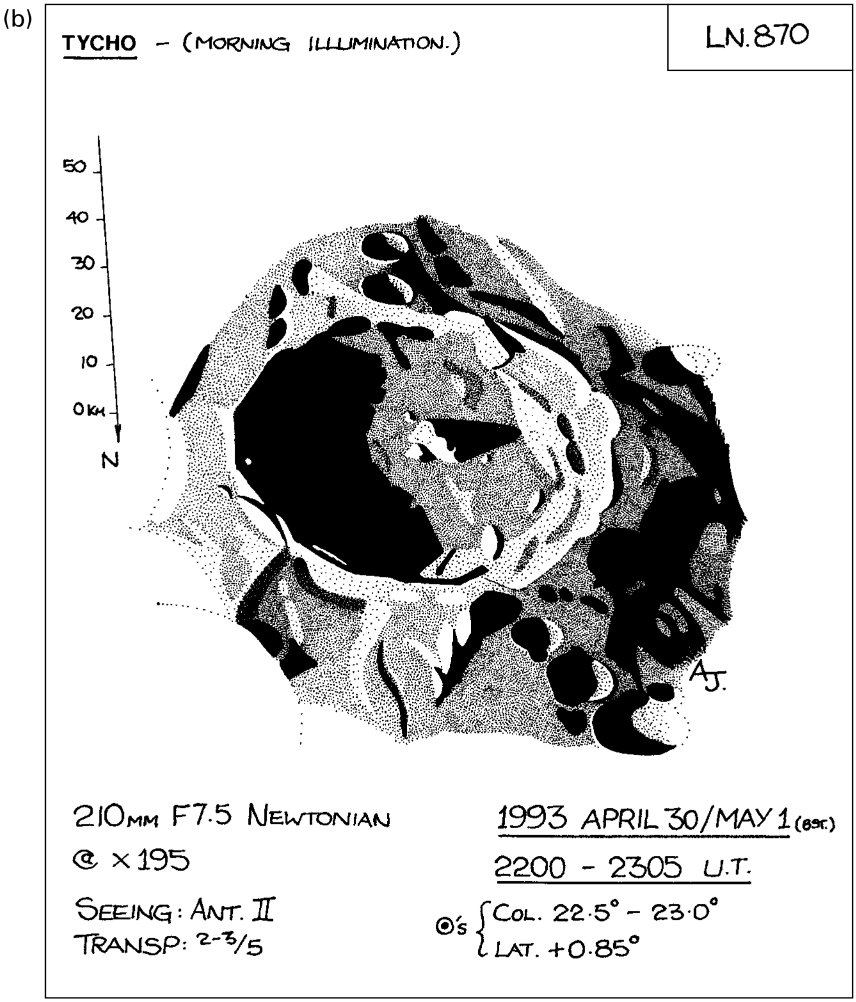
True, the interior relief disappears but the crater then becomes a white disk with a brilliantly white ring marking the crater rim and an equally brilliant 'blob' marking the central mountain. The crater itself is then surrounded by a darkish halo. Beyond this commences a magnificent ray system, which radiates across much of the Moon's visible face (see Figure 8.46(e)).

The ray systems associated with craters had long puzzled selenographers and a wide range of theories were 'cooked up' to explain them. We now know that they were generated by the impact explosion that created each parent crater. The rays are composed of a very fine sprinkling of pulverised ejecta (mainly glassy beads) spattered ballistically across the Moon. In the space of a few hundred million years the rays fade away because of the effect of solar-wind bombardment, micrometeorite impacts and, particularly, the 'gardening' (churning) of the topsoil that results from micrometeorites and the diurnal thermal stresses.

Figure 8.46(f) was, despite its appearance, taken from Earth. In fact, a Catalina telescope photographic image was projected onto a white sphere and this was photographed, to produce a 'rectified' view of Tycho and its rays. Note the zone of avoidance in the ray system, indicating the direction of the incoming projectile that created Tycho.

The obvious rarity of large craters with ray systems lends support to the idea that no large meteorites have struck the Moon for a very long time. In fact, with the possible exception of the crater Giordano Bruno, Tycho is

Figure 8.46 (*cont.*)
(b) Tycho, drawn by Andrew Johnson.



reckoned to be the youngest large crater on the Moon. One of the rays from Tycho passes across the *Apollo 17* landing site. It was from the samples brought back that the nature of the rays was finally settled. Also the impact that created Tycho was determined as having happened about 100 million years ago.

There have been a number of reports of Transient Lunar Phenomena associated with this crater but I have never seen anything I cannot explain as being due to the conditions and/or lighting effects. One relevant observation of mine might be that of 1995 March 10^{d} 22^{h} UT (mid-time – I observed for several hours). Using my 18¼-inch (0.46 m) reflector, at ×144, I could see that parts of the shadow inside the crater were not quite as deep-black as the rest, see Figure 8.46(g). The effect was delicate but, nonetheless,

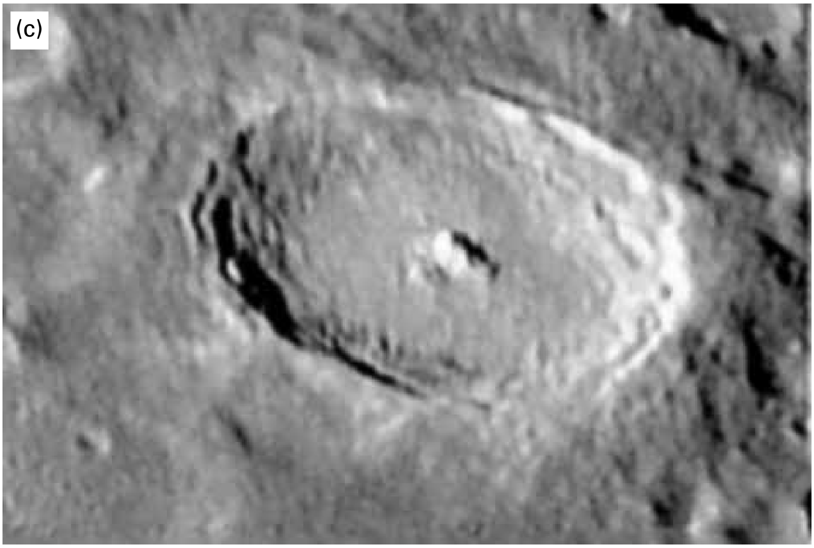


Figure 8.46 (*cont.*)
(c) Tycho. CCD image by Terry Platt, using his 12½-inch (318 mm) tri-schiefspiegler reflector and *Starlight Xpress* CCD camera. No other details available. The author has applied slight image sharpening and brightness rescaling.

too strong to be anything but real. I telephoned other BAA members and got them to examine the black shadow in Tycho (but without revealing the details) and was not surprised to get back confirmation.

How black are the shadows in craters? They certainly **look** very black most of the time. However, if you were sitting in one of these shadow regions you would certainly have no trouble in seeing details around you. For one thing, there would be a weak glow thrown down by the stars in the black sky. Much more than that, there would be a very bright Earth shining down on you (if we can see your locale from the Earth, it follows that you can see the Earth from where you are on the Moon). Also, and this is the factor of relevance to my Tycho observation, you will be able to see beyond the shadow-covered ground to the moonscape which is brilliantly illuminated by sunlight. I think the pools of slightly less deep-black shadow in my Tycho observation were mostly created from light reflected off the central mountains which were sticking up into the sunlight, this being enhanced by the light reflected from the encircling crater walls. Of course, the central peak also interrupted some of the light reflected back from the far walls, hence the darker divide between the two 'grey' regions. In how many craters can you see details within the 'black' shadows?

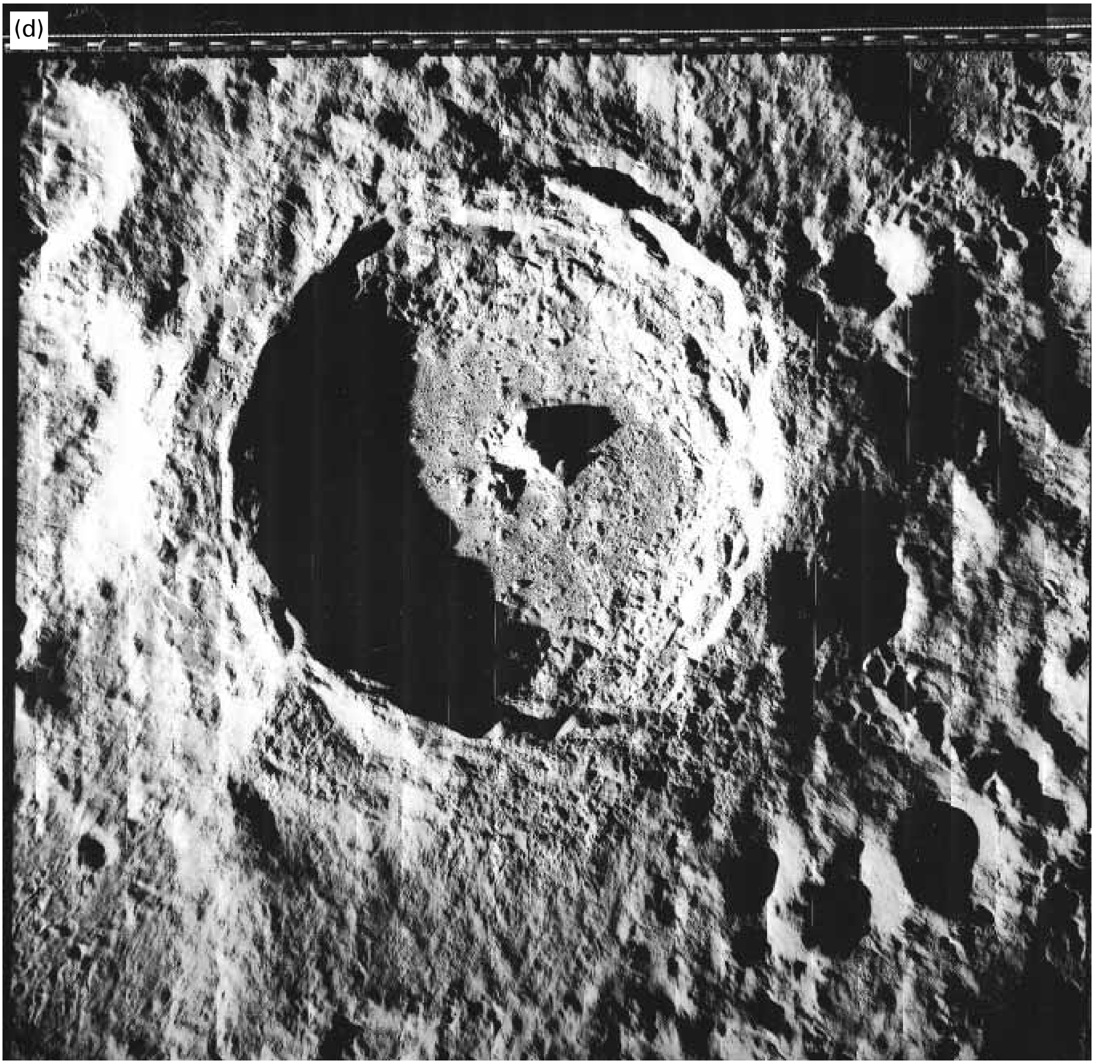


Figure 8.46 (*cont.*)
(d) *Orbiter V* image of Tycho. (Courtesy NASA and Professor E. A. Whitaker.)

Figure 8.46 (*cont.*)
(e) Tycho and its ray system dominate this photograph of the Moon, taken by Tony Pacey. He used his 12-inch (305 mm) reflector to image the Moon onto Pan F film at the telescope's f/5.4 Newtonian focus (no additional optics used). The 1/500 second exposure was made on 1992 November 11^{d} 21^{h} 45^{m} UT, when the Sun's selenographic colongitude was 100°.9.

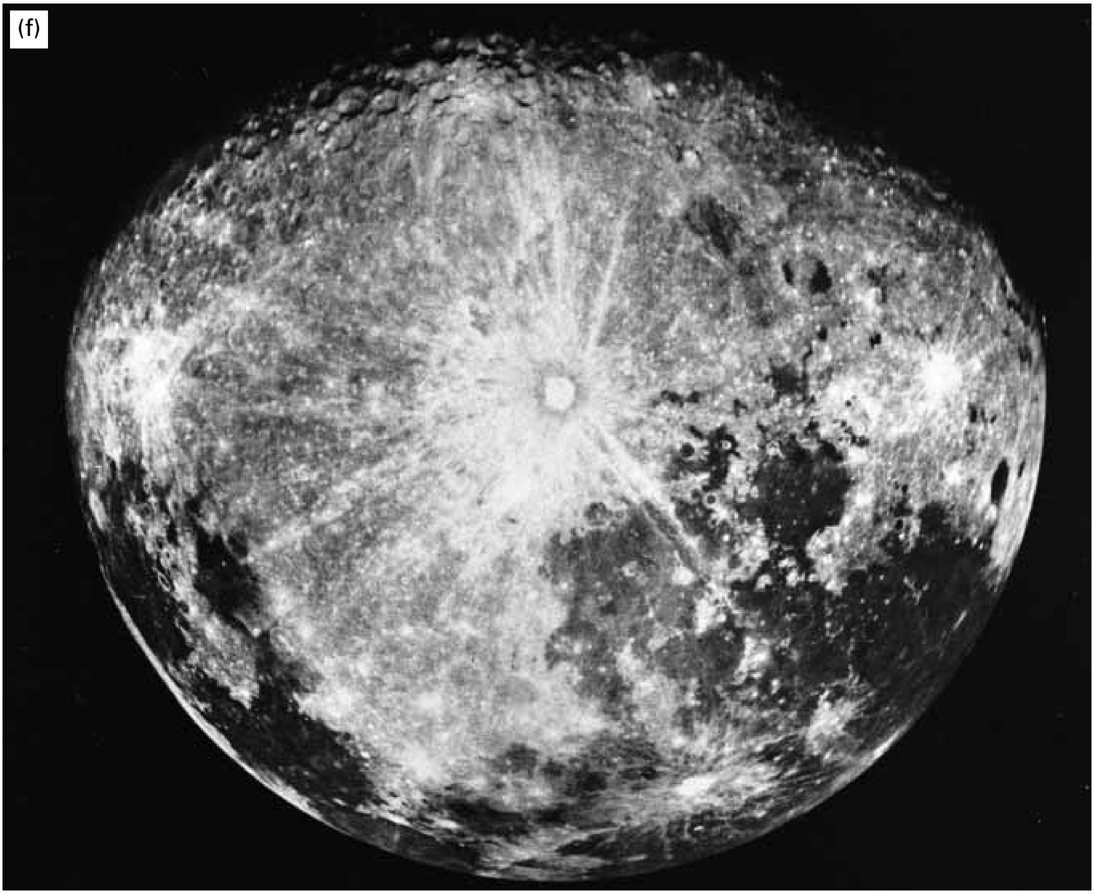


Figure 8.46 (*cont.*)
(f) Rectified image of Tycho and its ray system. (Courtesy Lunar and Planetary Laboratory.)

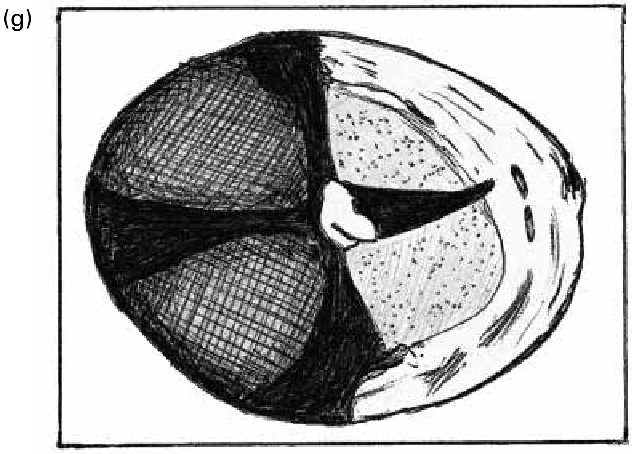


Figure 8.46 (*cont.*)
(g) Tycho. Sketch by the author (details in text) showing the areas of 'less deep-black' shadow. The effect is here grossly exaggerated for the sake of clarity. In reality the patches were very ill-defined and hard to see, scarcely lighter than the deep-black shadow. At the time of the observation the value of the Sun's selenographic colongitude was 7°.8.

8.47 WARGENTIN [50°S, 300°E] (WITH NASMYTH, PHOCYLIDES)

This is the largest (84 km diameter) of a very rare breed of lunar craters indeed – ones filled to the brim with basaltic lava. A CCD image of it by Terry Platt is shown in Figure 8.47(a) and Figure 8.47(b) shows a drawing made by Andrew Johnson that highlights the tree-like pattern of wrinkle ridges on its surface. Wargentin is joined along its lunar southern edge by the vast (114 km diameter) flooded crater Phocylides, while adjoining both is the overlapped (by both) remnants of the once 77 km diameter Nasmyth. The whole grouping is best seen a little before full Moon. Figure 8.47(c) and (d) show Wargentin together with Nasmyth and Phocylides under this sort of lighting (details given in the accompanying captions). I commend you to seek out Wargentin and have a look at it yourself. It is strange to see this lunar 'cup that runneth over'.

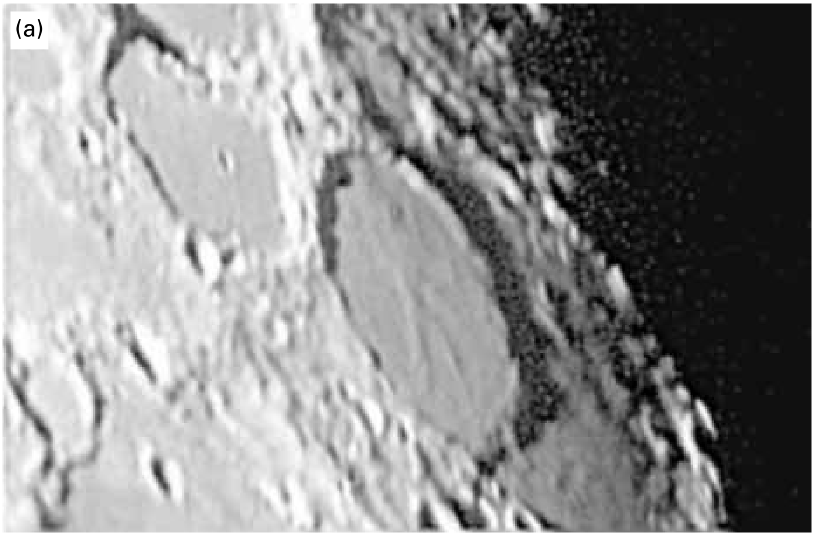
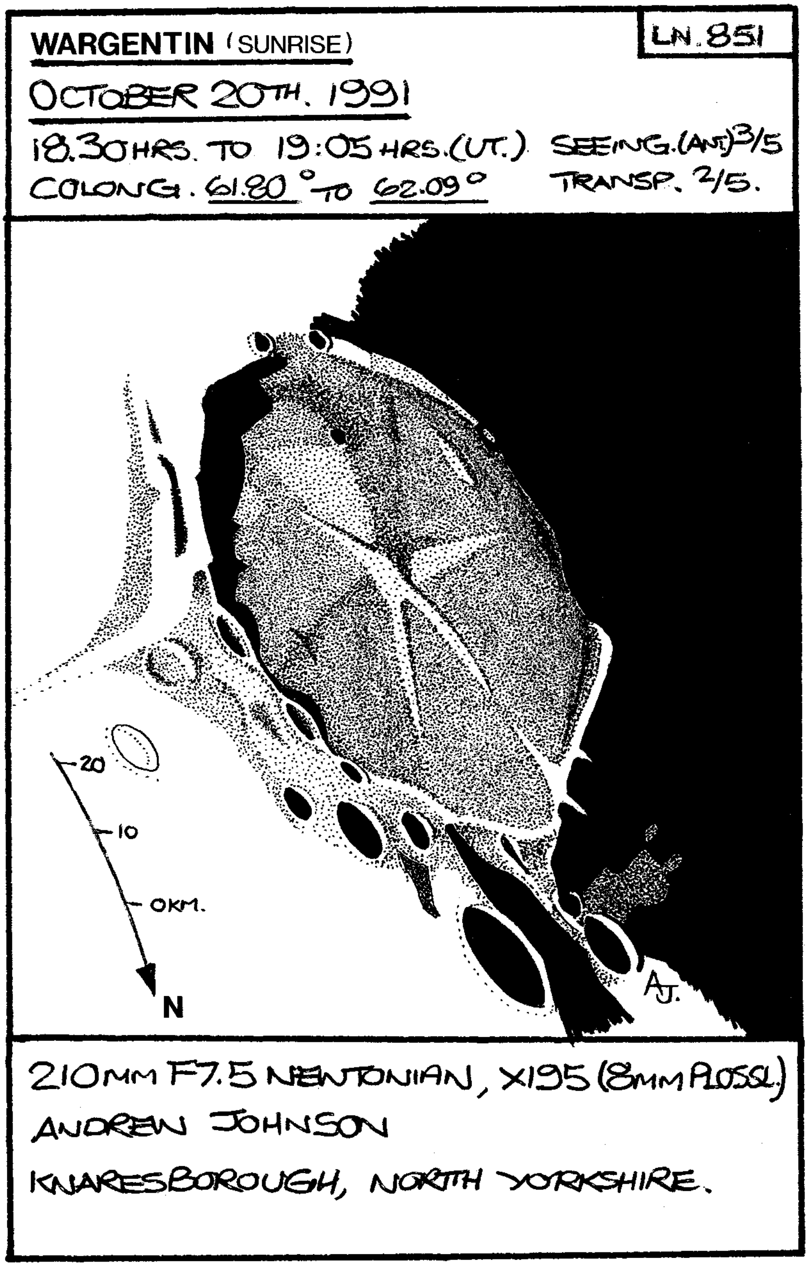


Figure 8.47 (a) Wargentin, imaged by Terry Platt using his 12½-inch (318 mm) tri-schiefspiegler reflector and *Starlight Xpress* CCD camera. The author has applied slight image sharpening and brightness re-scaling. No other details available.

Figure 8.47 (*cont.*)
(b) Wargentin, drawn by Andrew Johnson.

(b)



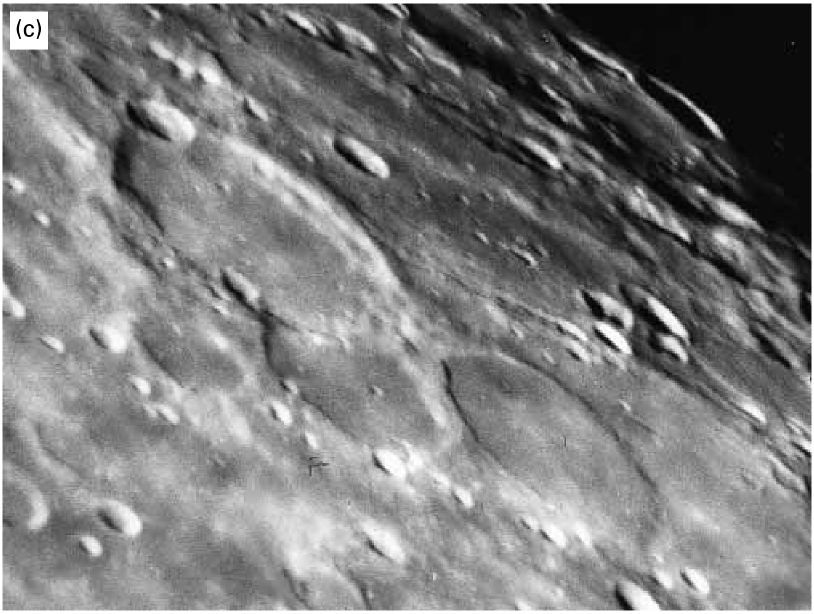


Figure 8.47 (*cont.*)
(c) Wargentin (lower right), Phocylides (largest crater – upper left), and Nasmyth (large crater attached to, and overlapped by, both Wargentin and Phocylides), photographed using the 1.5 m reflector of the Catalina Observatory. The photograph was taken on 1966 January 6^{d} 05^{h} 45^{m} UT, when the Sun's selenographic colongitude was 80°.9. (Courtesy Lunar and Planetary Laboratory.)
(d) Wargentin, Phocylides and Nasmyth, photographed using the 1.5 m reflector of the Catalina Observatory on 1967 February 22^{d} 03^{h} 43^{m} UT, when the Sun's selenographic colongitude was 61°.0. (Courtesy Lunar and Planetary Laboratory.)

8.48 WICHMANN [8°S, 322°E]

In the previous 47 sections we have explored many formations replete with spectacle and grandeur. I have deliberately finished this chapter with a region of the Moon that seems obscure and even uninteresting to the casual glance. Situated on the south-eastern sector of the Oceanus Procellarum, the little (10.6 km diameter) crater Wichmann certainly does not grab your attention as you peer through the telescope eyepiece.

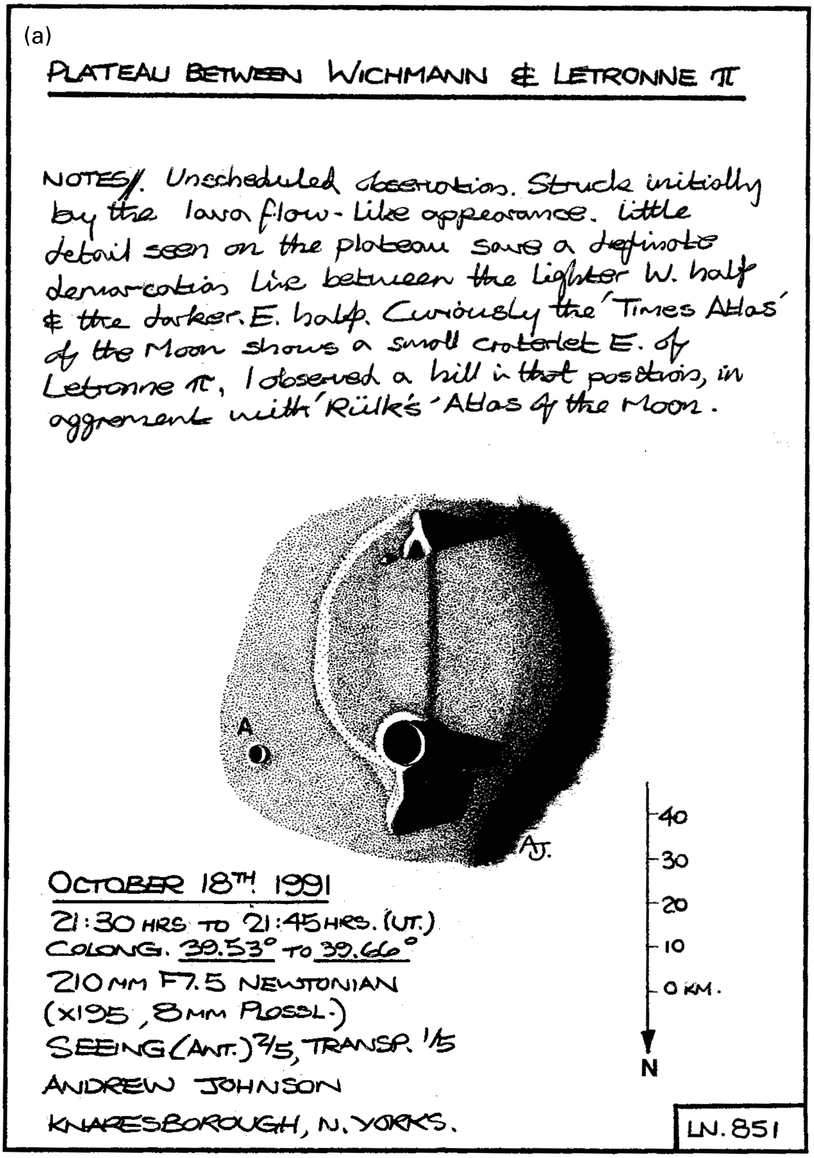


Figure 8.48 (a) Wichmann region, drawn by Andrew Johnson.

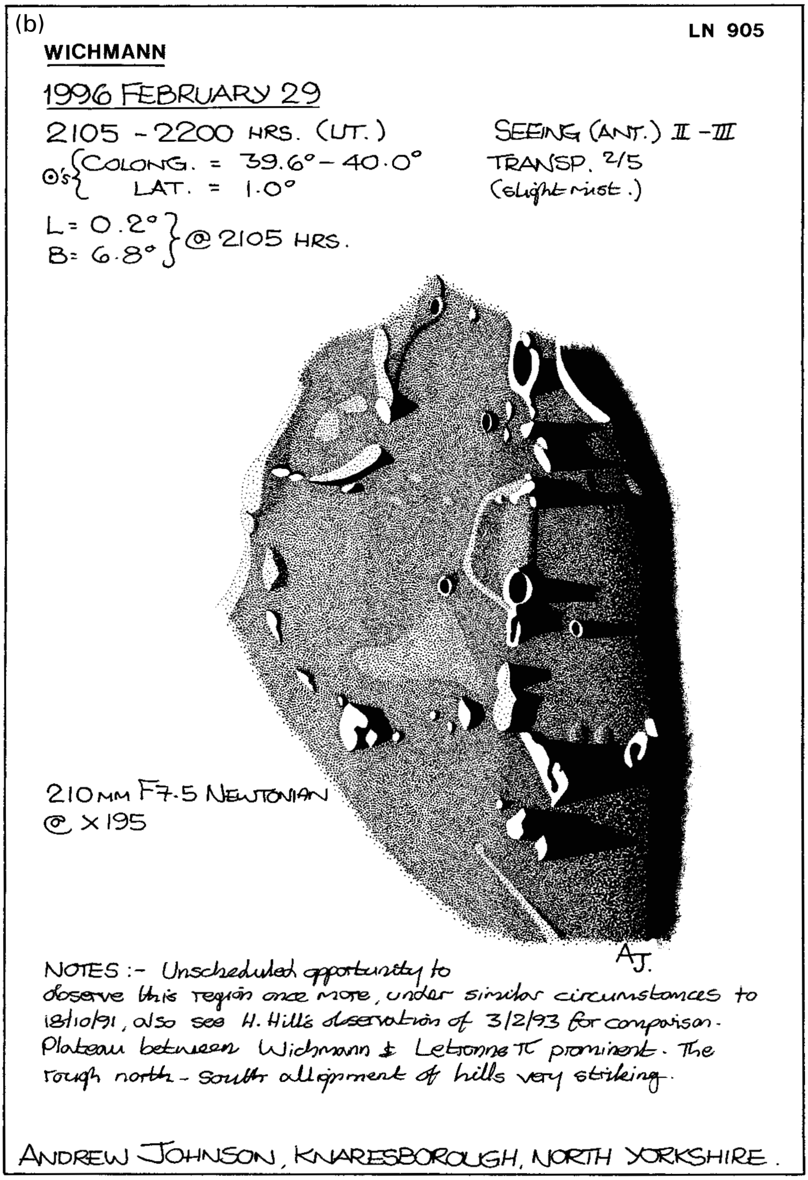


Figure 8.48 (*cont.*)
(b) Another study of the Wichmann region of the Moon, by Andrew Johnson.

However, what do you see when you look – when you **really** look? You see all sorts of interesting detail – wrinkle ridges, chains of mountains, the raised plateau on which the crater stands. Andrew Johnson has looked – **really** looked. Figure 8.48(a) and (b) show two of his drawings. What are the origins of these features? How do they relate to the Moon as a whole?

The point I am driving at is that the ‘old favourite’ Moon features may have a great attraction but there is a great deal to be learned from the more obscure areas. The whole of the surface of the Moon tells a story – the story of how it all came to be as it is. I hope that you will feel inclined to investigate the lunar surface for yourself – if so, you will find much of value in some of its less ‘well-trodden’ regions.

CHAPTER 9

TLP or not TLP?

One of the few areas of study for the amateur lunar specialist that remains of genuine scientific use is the highly controversial one of Transient Lunar Phenomena (TLP – Americans use the term 'Lunar Transient Phenomena, LTP). The reason for the controversy is that a number of people have made quite ridiculous claims of frequent weird happenings on the Moon's surface. The credibility of the subject has suffered greatly from the fanaticism of these people and others of the 'lunatic' fringe. Now, many people dismiss the whole subject out of hand. Some go as far as to deride all who would study the phenomena.

Most of the serious, long-term, students of the Moon – both amateur and professional – are wisely cautious about supposed transient lunar phenomena but accept that there is some evidence to support the view that there is, at the very least, something worthy of investigation. I count myself amongst their number. In this chapter I present some of the evidence and explain how you might take part in this study yourself.

9.1 THE MYSTERY UNFOLDS

Observers, most significantly regular watchers of the Moon, report occasional odd appearances, including short-lived glows (sometimes coloured) and mist-like obscurations, involving small areas of the Moon's surface. This is not a new phenomenon. Indeed, reports go back centuries but by the twentieth century, when it was established that the Moon has essentially no atmosphere, most astronomers were of the opinion that all the observed oddities could be explained as mere tricks of the eye.

However, a professional astronomer – Dr Dinsmore Alter – obtained some hard evidence of something more than a simple illusion happening on the Moon in 1955. He used the 60-inch (1.52 m) reflector at Mount Wilson to photograph areas of the Moon in near-infrared and near-ultraviolet–

violet–blue light. He did this by using appropriate filter and photographic emulsion combinations. While all remained clear in the infrared photographs, he found that several of the UV–blue images showed a loss of detail on part of the floor of the lunar crater Alphonsus. Some researchers wondered if Dr Alter had recorded the presence of a temporary mist emanating from that part of the crater. Infrared light would penetrate a tenuous mist, while the ultraviolet would not do so easily. A few amateur and professional astronomers became interested. One of them was Nikolai Kozyrev, in Russia.

Kozyrev used the 50-inch (1.27 m) Cassegrain reflector of the Crimean Astrophysical Observatory to take regular spectrograms of the Moon's surface. He monitored the Moon through the guiding eyepiece of the spectrograph while he did so. His efforts were rewarded on 3 November 1958 when he obtained spectrographic evidence of a real physical transient event at the Moon's surface.

On that night he was conducting his normal programme when, at just after 01^h UT, he noticed that the central peak of the crater Alphonsus was enveloped in a reddish haze. (See Section 8.4 for more about this crater, including photographs of it.) He set the entrance slit of the spectrograph across the image of the central peak of the crater and began taking spectra while he continued to monitor the view through the guiding eyepiece (the slit jaws being reflective, allowed guiding and the precise selection of the part of the image sampled by the spectrograph).

During the next couple of hours Kozyrev saw the peak of Alphonsus become very bright and white. Between $03^h\ 00^m$ and $03^h\ 40^m$ UT the appearance of the crater returned to normal and Kozyrev ceased taking spectra. When the spectrographic plates were processed several of them showed an anomaly that afflicted the part of the spectrum – the stripe running through the centre of it – formed by the light from the central peak. Meanwhile the parts of the spectrum formed from the other parts of the crater sampled by the slit showed nothing but the normal features of sunlight reflected from the Moon's surface. The spectra taken when the central peak appeared bright showed strong emission bands. Actually these were identified as being the 'Swan Bands' produced when molecular carbon vapour, C_2, is excited into emission. Other spectral features were present (indicating other chemical components in the gas), blending with the spectrum of carbon. The last spectra taken showed that all had returned to normal, in accordance with the visual impression.

Kozyrev's observation aroused world-wide interest. You will find an account of it in the February 1959 issue of *Sky & Telescope* magazine. It is titled 'Observation of a volcanic process on the Moon', reflecting his interpretation of what he had observed. Few others accepted this explanation, even at the time.

Kozyrev gives a more detailed account of his procedures, reductions and conclusions in a paper 'Spectroscopic proofs for existence of volcanic processes on the Moon' in *The Moon – Symposium No. 14 of the International Astronomical Union*, edited by Kopal and Mikhailov for the Academic Press, 1962. Not an easy reference to obtain; perhaps an academic library/inter-library loan service can obtain a copy for you. It is worth reading, even though Kozyrev still gives his interpretation of volcanism in it. Most scientists thought at that time (and still do today) that what Kozyrev had recorded was the relatively quiescent effusion of a gas from the lunar surface.

In the same book, Kozyrev's paper is followed by another: 'Microphotometric analysis of the emission flare in the region of the central peak of the crater Alphonsus on 3 November 1958', by A. Kalinyak and A. Kamionko of the Pulkovo Observatory in Russia. The authors conduct a detailed analysis of Kozyrev's spectrum and conclude that the event was indeed a gas release and the gas was excited to fluoresce under the action of solar radiation. They conclude that the temperature of the gas was less than 480 °C (maybe much less) and was of rather similar composition to the gas found in the heads of comets. They confirm the presence of the Swan bands of carbon and deduce that the pressure of the gas was certainly less than one-hundred-millionth of a millimetre of mercury (this is about one-hundred-thousand-millionth of the sea-level pressure of the Earth's atmosphere), and perhaps rather smaller than that.

There is a fascinating exposé of the American efforts to verify and understand Kozyrev's spectrum given in the October 1996 issue of *Sky & Telescope*. The article is entitled 'The lunar volcanism controversy'. The once sceptical American astronomers, particularly the famous Gerard P. Kuiper, changed their views when they eventually had the chance to study the original spectrographic plates for themselves.

Some amateur and professional astronomers kept a watch on Alphonsus for any signs of after-effects subsequent to the 1958 episode. There were a few reports of red patches seen on the floor of the crater, though no photographic evidence was ever secured (as far as I know!) and nothing remained of them after some months had passed.

Kozyrev continued his programme of lunar observations and he 'turned up' a couple more spectrographic anomalies – one in Alphonsus on 23 October 1959 and one in the crater Aristarchus (see Section 8.7 for more about this crater) on 1 April 1969 – though the results were not quite as definite as for the 1958 event. In the first, all that was identifiable was a brightening at the red end of the spectrum. The spectrum of the Aristarchus event sported the same general reddening but with bands of molecular nitrogen and of the molecular species CN just about identifiable.

Astronomers Greenacre and Barr at the Lowell Observatory, USA, using the 24-inch (0.61 m) refractor reported seeing intensely red and pink coloured patches in the vicinity of the crater Aristarchus on 30 October 1963. They first saw the coloured glows at about 1^h 30^m UT. The glows changed in intensity while the astronomers watched, disappearing after about 25 minutes.

Further sightings of red glows were reported by an astronomer using the 69-inch (1.75 m) reflector at the Perkins Observatory in the USA.

Many amateur groups, particular the Lunar Sections of the British Astronomical Association and the Association of Lunar and Planetary Observers (ALPO), began looking for TLP. Observers soon began reporting anomalies. Undoubtedly many of these are explainable as being due to things other than real events at the surface of the Moon (actually I think the vast majority are not genuine TLP – more about this in Section 9.5) but there are a number of instances which are not so easy to dismiss.

Barbara Middlehurst and her colleagues in the USA and Patrick Moore in the UK were independently compiling catalogues of the reported instances of TLP but they eventually published a combined catalogue in 1967. Patrick Moore updated it in 1971, the number of entries then standing at 713.

A pattern emerged from the hundreds of TLP reports. TLP were not distributed randomly. There seemed to be a preference for 'events' to occur around the borders of the lunar maria and within certain craters. The highland areas were avoided. The crater Aristarchus came out as the 'hottest' TLP spot on the Moon with about a third of all reported events involving this crater.

Aristarchus has even been the subject of a space-borne observation of an anomaly. The three astronauts aboard *Apollo 11* reported a glow localised in the wall of the crater on 19 July 1969. At 18^h 45^m UT the crew could first see an illuminated area to the north of the spacecraft. As they drew nearer they confirmed their first impression that it was inside Aristarchus. Part of the transcription of their communication to Mission control (it is difficult to make out, so the transcription is incomplete) is:

> It's getting to be about zero phase. One wall of the crater (Aristarchus) seems to be more illuminated than the others. It is definitely brighter than anything else I can see. It's an inner wall of the crater . . . there doesn't appear to be any colour involved in it . . . it (is) the inner part of the west-north-west, the part that would appear more nearly normal . . . looking at it from the Earth. . . .

Earth-based astronomers also confirmed the presence of the brightening, as well as reporting other anomalies in Aristarchus on other dates around the same time. Actually it was because of the earlier ground-based observations that the astronauts were asked to keep a look out for anything unusual.

During the *Apollo 16* mission Ken Mattingly, in the orbiting Command Module, witnessed several flashes from the lunar surface (though I do not have any further details about this) and *Apollo 17* astronaut Harrison Schmidt witnessed a flash emanating from the region of the lunar crater Grimaldi. This is another TLP 'hot spot'. See Section 8.20 in Chapter 8 for more about this crater.

Another TLP hot spot (at least it was in the 1960s and 1970s, even if rather less so since then) is the crater Gassendi. See Section 8.22 for photographs and details about it. Transient bright points of light were seen by Walter Haas (10 July 1941) and H. P. Wilkins (17 May 1957) but the most significant 'event' involving Gassendi occurred on 30 April 1966. First detected by P. K. Sartory, for about four hours a reddish wedge-shaped streak was seen to span the central peak to the south-west rim of the crater. Several independent observers witnessed this phenomenon. One of these was Patrick Moore and he describes it as "the most unmistakable red event I have ever seen on the Moon".

Back in those days there was an assumption that all TLP should appear as red glows. One BAA Lunar Section member, Peter Sartory, designed a device, called a 'Moonblink' which consisted of a unit containing red and blue filters that was plugged into the telescope before the eyepiece. Turning a knob brought either filter into the optical path. By manually alternating between the red and blue filters while watching through the eyepiece, any red patch on the Moon would appear light when seen through the red filter but would show up as darker when seen through the blue filter. Many positive 'blinks' were obtained by observers using this arrangement.

Meanwhile, in the USA, a network of professional astronomers was set up under the auspices of NASA using more sophisticated versions of this device (utilising an electronic detector rather than a human eye – see the July 1967 issue of *Icarus* for an account of this work).

One of the team, Winifred S. Cameron, has been involved in research into TLP for decades (and she still is, though now retired) and is widely regarded as the world's foremost authority. She is a prolific author of papers and articles on the subject. One reference you might especially like to seek out is an article, entitled 'Lunar Transient Phenomena', in the March 1991 issue of *Sky & Telescope*.

One of the cases she cites in the article involves the crater Pitatus (see Section 8.32 for illustrations and for details about this crater) and she shows two photographs taken by Gary Slayton of Fort Lauderdale, Florida, of a bright 'blob' in the crater which **moves** between the time the two photographs were taken (the times are not given, though the date was 5

September 1981). This is not the only instance of moving lights on the Moon being reported by Earth-based observers.

Returning to the subject of the 'blink' devices, there are problems with them. In particular, *spurious colour*, described later, is an effect which has its cause in the Earth's atmosphere and many 'blinks' were undoubtedly due to this, rather than anything real on the Moon. Eventually observers realised that the majority of TLP were actually not even red, only a minority of visual anomalies showing any significant colour at all. Blink devices have now rather gone out of fashion.

Since I have only room enough to cite a few examples of TLP, I think this would be a good point to interrupt this potted history to summarise the main types of the visual anomalies observed.

9.2 CATEGORIES OF TLP

The following are the types of visual anomaly most often reported. In each case the area of the Moon affected is usually only a few kilometres square.

Short-term albedo changes

These are unusual increases or decreases in the apparent brightness of the Moon's surface. The change might last for a few hours, though mostly for rather less than a hour. Sometimes the change occurs and then is fairly steady – say the brightness of a small patch of the Moon increases, then remains at roughly the same elevated level for a while only then to steadily decrease back to the normal value once more. At other times the brightness pulsates. When this happens the brightness usually varies rather erratically. These brightness fluctuations can happen on time-scales as short as a second or two.

Obscurations of surface details

A small patch of the Moon might appear blurred or indistinct while the surrounds remain sharp and clear-cut. The effect often lasts for about an hour. Significantly, the blurring sometimes is seen to start out very localised and distinct but then spreads out, becoming less obvious as it does so – almost like a cloud of vapour thinning out.

Coloured effects

Sometimes coloured effects are seen as an accompaniment to brightness changes, or to surface obscurations. Sometimes coloured effects are seen on their own. Most observed anomalies do not show significant colours. However, there have been rare instances when the colours have been very vivid. In my own experience, regions showing short-term brightness changes tend to show a bluish tint if any colour is visible at all.

Flashes of light

These are the rarest of all reported TLP. However, there are too many reliable reports to dismiss them. They appear as bright (sometimes very bright) flashes of light or brief twinkles of light against the Moon's surface. At least two photographs show apparent flashes, though I must say that any one of a host of photographic faults could well be the true explanation for them – let alone other (less probable) explanations such as a glint of reflected sunlight from a satellite that happened to pass through the field of view at the time the photograph was taken! Occasionally flashes are seen along with other types of TLP in progress.

9.3 THE MYSTERY CONTINUES

The growing interest of amateur and professional astronomers in Transient Lunar Phenomena through the 1950s and 1960s continued into the 1970s. Unfortunately, as I said in the introduction, the subject also attracted more than its fair share of cranks. These people tended to go to their telescopes and see all manner of coloured effects, plumes of smoke erupting from craters, etc. Many rushed into print with half-baked, and ill-informed, ideas about the mechanisms producing these physical phenomena.

I only wish I could say that this sad state of affairs was entirely in the past, but I cannot. There are still some today for whom the Moon is a fairground of amazing phenomena. Not only do these people bring the derision of many astronomers on the whole subject, their 'reports' pollute the data, making any serious study difficult. It is for that reason that I give low weighting to the results of statistical studies based on the complete TLP databases. Various links, such as with the solar activity cycle, with the position of the Moon in its orbit (and so the passage of the Moon through the Earth's magnetotail), with moonquake activity, etc., all have been variously 'proved' and 'disproved' by researchers.

Fortunately we do have **some** good evidence and data. As you would expect, it is the work of the professional astronomers which is taken most seriously. For instance, astronomers of the Tokyo Astronomical Observatory have conducted many long-term studies of the Moon's surface brightness and the way the Moon's surface *polarises* the incident sunlight it reflects (some vibration angles of the light-waves are reflected more than others).

In 1970 they observed an event involving Aristarchus which they described in *The Moon – issue 2 (1971)*. Their paper is entitled 'An anomalous brightening of the lunar surface observed on March 26, 1970', and is authored by Naosuke Sekiguchi. While on their normal programme of photometric (brightness) and polarimetric observations with a 36-inch

(0.91 m) reflector, Sekiguchi and co-workers found, on that date, the region around Aristarchus became 0.3 magnitude brighter than normal. At the same time its colour index decreased by 0.1. In other words, as well as becoming over 30 per cent brighter, the region became significantly bluer. The change in optical polarisation that was recorded only in the Aristarchus region also adds weight to the assertion that a genuine TLP was recorded. In his paper, Sekiguchi refers to some of the many other papers which detail other professional observations of this phenomenon. He also suggests that the TLP he recorded may be related to a major solar flare that occurred 29 hours before his observation.

I will finish this 'potted history', sketchy as it is, with the briefest possible account of my own involvement in TLP research and a summary of the 'state of play' at present.

In 1979, after returning to live in my parents' home (in Seaford, East Sussex, UK) at the end of my undergraduate years, I joined the Lunar Section of the British Astronomical Association and straight away resumed making lunar observations with my 6¼-inch and 18¼-inch reflecting telescopes. There existed a 'telephone alert network' whereby an observer reported any suspect appearances to a central co-ordinator. The co-ordinator then contacted all the available active observers who had joined the network. In the years that followed I observed the Moon whenever I could, through changes of home and occupation. I arrived in Bexhill-on-sea, in East Sussex, in 1983. My observational work continues to this day, though a long-term illness has reduced the amount I can manage to do in recent years.

I responded to many 'alerts' in those years. In some cases I could not confirm any visual anomaly. In some I could, though most often concluding that the effect was caused by a mechanism other than anything happening on the Moon (see Section 9.5 for more about this). In a few instances, there seemed to be something genuinely anomalous at the surface of the Moon. I instigated a few 'alerts' myself, though in some of these cases I suspected (but could not be sure of) causes other than a genuine TLP. I should, perhaps, make it clear that the person providing the alert would never give more than the general location of the supposed 'event'. Any corroboration, or otherwise, was sought **after** the event by checking the written reports and any accompanying sketches.

My eventual location in Bexhill proved expedient when the opportunity arose to be a guest observer at the Royal Greenwich Observatory, just a twenty-minute drive away. Thanks to introductions by Patrick Moore, and because I am qualified as an astronomer, I was afforded the very great privilege of using the RGO's equipment. From January 1985 to March 1990 I had the run of the 'Equatorial Group' of telescopes and additional facilities in the main buildings. My main purpose there was to repeat Kozyrev's efforts in the hope of obtaining a good-quality spectrum of a TLP in action.

Figure 9.1 The 30-inch (0.76 m) coudé reflector at the Herstmonceux site of the former Royal Greenwich Observatory. The light from the telescope emerges from the door in the back of the telescope tube to be intercepted by the mirror at the top of the tall tripodal gantry. The light is then passed down into the head of the spectrograph. The various parts of the spectrograph are arranged on three floors of the building!

The main instrument I used was the 30-inch (0.76 m) coudé reflector with its elaborate high-dispersion spectrograph (Figure 9.1). Another useful instrument there was the 36-inch (0.91) Cassegrain reflector in the adjacent dome. I used to set up both telescopes for lunar observing sessions. The Cassegrain reflector was better for monitoring purposes (Figure 9.2) and it took but moments to move through the adjoining corridors from one to the other.

Figure 9.2 The author can be seen below the 36-inch (0.91 m) Cassegrain reflector at the Herstmonceux site of the former Royal Greenwich Observatory.

Of course, I took many standard spectra for comparison purposes with the hope of recording the spectrum of a TLP in action. The equipment would now be considered old-fashioned, in that the spectra were recorded on 7-inch × 1-inch (178 mm × 25 mm) photographic plates – which I had to cut from standard 10-inch × 2-inch stock of *Kodak* IIaO plates, subsequently processing them after the exposures were made in the telescope's spectrograph. Today's newly graduated astronomers would consider this a quaint art practised in a bygone age!

Figure 9.3(a) shows a print I made from one of the plates. Some details are given in the accompanying caption but suffice it to say here that you can see it is of very high spectral resolution. I scanned the plates using the RGO's temperamental plate density scanning instrument (PDS) which produced 3 metre long tracings (plots of intensity versus wavelength) from each plate. A very small part of one of these is shown in Figure 9.3(b). The tracings allowed for detailed measurements of any spectrum I suspected of showing an anomaly. For a fuller description of the equipment and procedures see the July–September 1987 issue of *Astronomy Now* magazine.

Now the big question – did I spectrographically record a TLP? I am afraid I did not.

On 27 September 1985 I was busy in the dome of the 30-inch (0.76 m) telescope when a 'TLP alert' came through by telephone. The seeing was extremely bad and I had already taken a standard spectrum of Aristarchus. In response to the alert I set the telescope so that Torricelli B, the subject of the alert – suspected variations of brightness – was on the slit. Actually this was difficult to do since it was nearly invisible in the violently unsteady seeing. I made the required exposure (9 minutes in that case). When I processed the plate, and subsequently scanned it, I found that it contained nothing but the usual spectrum. I must say that there was little hope of success on that night, even if Torricelli B was undergoing a genuine TLP, as only for a very small amount of the exposure was the light from this small crater actually dropping through the entrance slit of the spectrograph. Most of the time the turbulent distortions made Torricelli B miss the slit and so the spectrum was mainly built up from the light of the surrounding moonscape.

The next night a thick fog hung over Bexhill and I decided to stay at home. However, the telephone rang – there was another 'TLP alert', again concerning Torricelli B. After a hazardous drive to the observatory I set up the equipment and gave the plate a much longer exposure than normal (to try and offset the effects of the fog). Even so, the processed and scanned plate proved useless; no anomalies were detectable, save the 'noise' generated by the thinness of the image.

Frustratingly, one of the few periods the RGO telescopes were not available to me because of other usage coincided with some significant TLP activity. All I could do was to use my own telescopes. One of these instances concerned Torricelli B. On 31 May 1985 I was using my 0.46 m reflector when, at $20^h\ 23^m$ UT, I noticed that Torricelli B was bright and mauve coloured and sported a mauve 'halo'. I ran inside and telephoned the co-ordinator. At $20^h\ 29^m$ UT I was back at the eyepiece but the colour had gone!

(a)

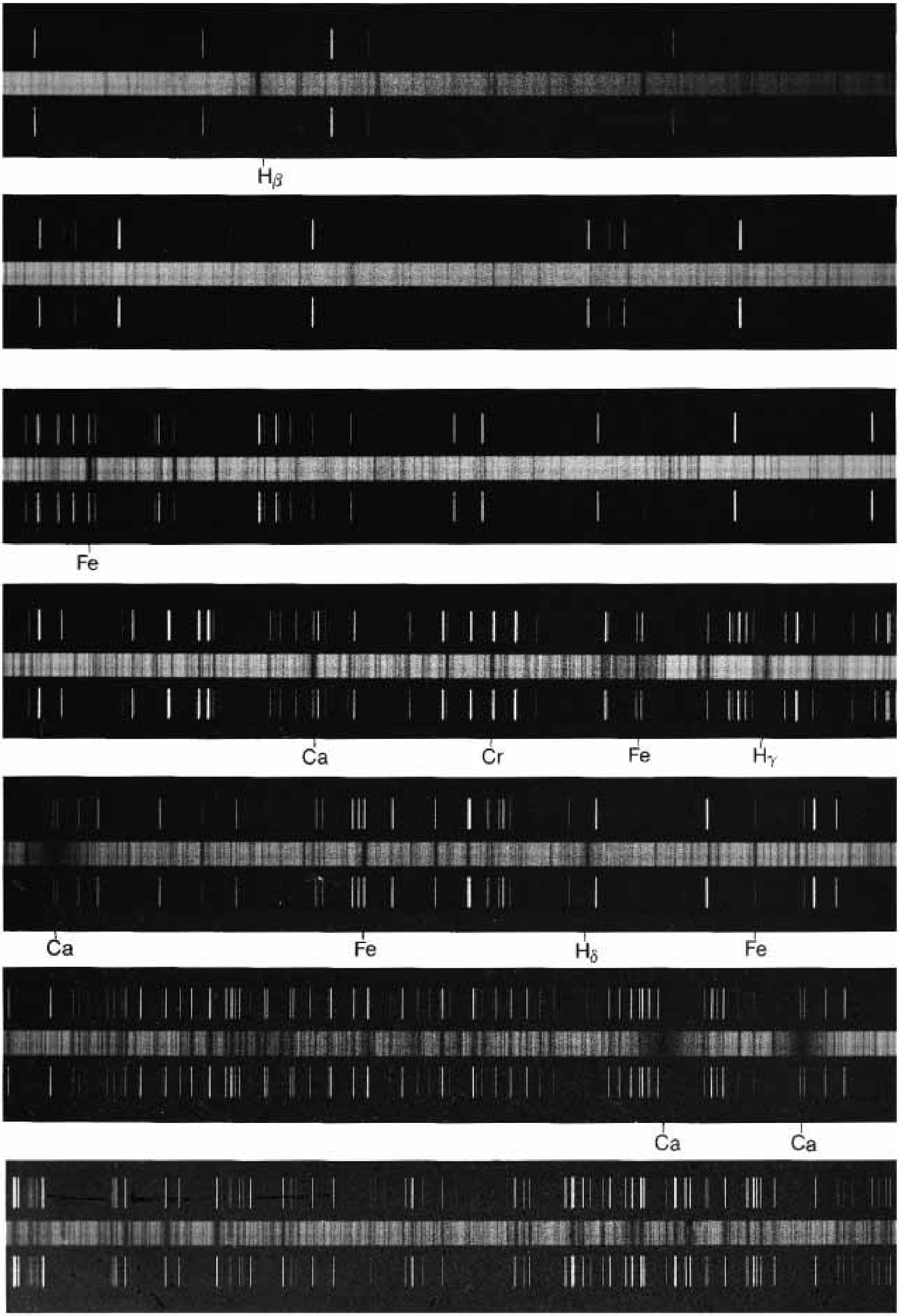


Figure 9.3 (a) High-resolution spectrum of sunlight reflected from the surface of the Moon, taken by the author, using the 30-inch (0.76 m) coudé reflector and high-dispersion spectrograph of the Royal Greenwich Observatory. The wavelength range covered is approximately 355 nm (left-hand side of the bottom strip) to 504 nm (right-hand side of the top strip), the wavelength increasing from left to right along each strip. There is a small amount of overlap between each strip. Above and below the main spectrum is a copper–argon emission spectrum exposed on the plate at the same time as the Moon spectrum for calibration purposes.
(b) A small part of a tracing from the spectrum. The two broad dips in the spectrum of moonlight (upper trace) correspond with the broad calcium (Ca) absorption features indicated at the right-hand end of the second strip from the bottom in (a).

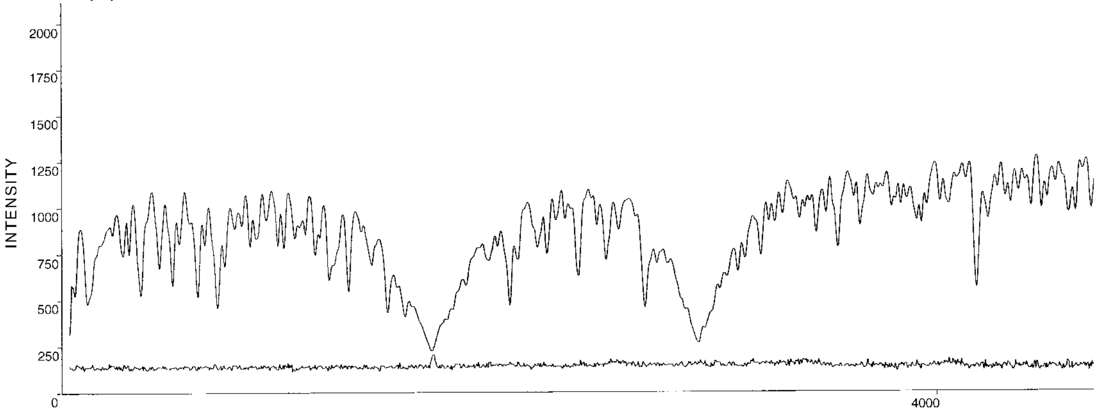
The crater seemed to be pure white in hue and varying erratically in brightness, with a mean period judged to be about 2 seconds. The ambient seeing conditions caused a general lapsing of focus with a mean period estimated at about 5 to 10 seconds, while the turbulent rippling of the image had a period of about half a second. At 20^{h} 34^{m} UT I noted that the crater had taken on an intermittent pinkish tinge. From then until close of observations at 22^{h} 18^{m} UT I noticed definite variations in the apparent brightness of the crater that seemed not to be the result of the atmospheric conditions. The two other observers in the BAA Lunar Section available under clear skies that night independently recorded similar brightness and colour variations, along with 'star-like flashes' occurring inside the crater. They agree to the nearest minute about the times of the flashes. I saw no flashes.

The most significant TLP I have ever witnessed occurred the day before this one. Patrick Moore, in company with Paul Doherty, noticed an anomalous brightening of the west wall of Aristarchus, plus some blurring on the north-west wall. Myself and another five members of the BAA Lunar Section were alerted and observed this crater (remember – no details of the anomaly were ever passed on during an alert; merely the general location of the suspected anomaly).

I had bad seeing conditions but by 20^{h} 53^{m} UT I noticed that in brief flashes of good imaging a pink tinge was present along the northern sector of the crater interior. At 22^{h} 08^{m} UT I noticed that there was an odd appearance to the shadow on the north-west wall (see Figure 9.4) – a notch formed in it! By 22^{h} 54^{m} UT an intense ruby-red colouration developed on the inside of this 'notch'. The seeing deteriorated to the point that I had to pack up by 23^{h} 08^{m} UT. All who took part agreed on most of the points about the anomaly, and the timings – and two others agreed with me about the 'notch' in the interior shadow – and all the reports were entirely independently made!

My anguish about not having the use of the RGO telescopes on those two nights was intense. There were other frustrating occasions when

(b)



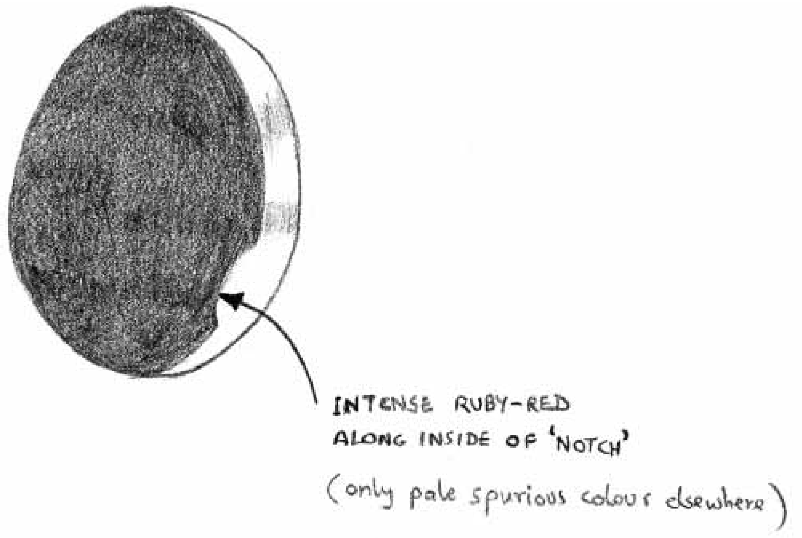


Figure 9.4 A visual anomaly recorded by the author in Aristarchus (see text for details).

'TLP alerts' were telephoned to me but the skies were not clear over Herstmonceux. So, I had failed to secure a spectrum of a TLP in action. Nonetheless, I enjoyed myself immensely using the professional telescopes for those five years and I did conduct other successful observational projects with them. It was a great experience and it only came to an end when the RGO moved to Cambridge. More recently, the RGO has closed down altogether – a piece of Britain's scientific heritage cast into the garbage can by our politicians.

For me, it was back to the backyard telescopes. I did build a spectrograph onto my largest telescope (Figure 9.5 – and see my book *Advanced Amateur Astronomy* for a fuller description) but the illness I have already mentioned was beginning to tighten its grip and I found myself able to do less and less observing. Nonetheless, amid changes to the BAA Lunar Section I even took over as co-ordinator of the TLP observing group, which by then was flagging for various reasons. I managed to re-activate the group but, after a few years, had to give up this work also.

The present situation is that there are a few scattered groups active around the world in the field of TLP observation and study, though I cannot say that there is as much enthusiasm as there once was. There are exceptions. ALPO, for instance, conduct energetic observing programmes. The BAA Lunar Section continues with the TLP work, though with fewer active members than it had in its heyday.

I wish there was space to give more examples of TLP observations, particularly those recorded by professional astronomers. However, I hope I have said enough to whet your appetite. Of course, the burning question arising from all this is – what causes Transient Lunar Phenomena?

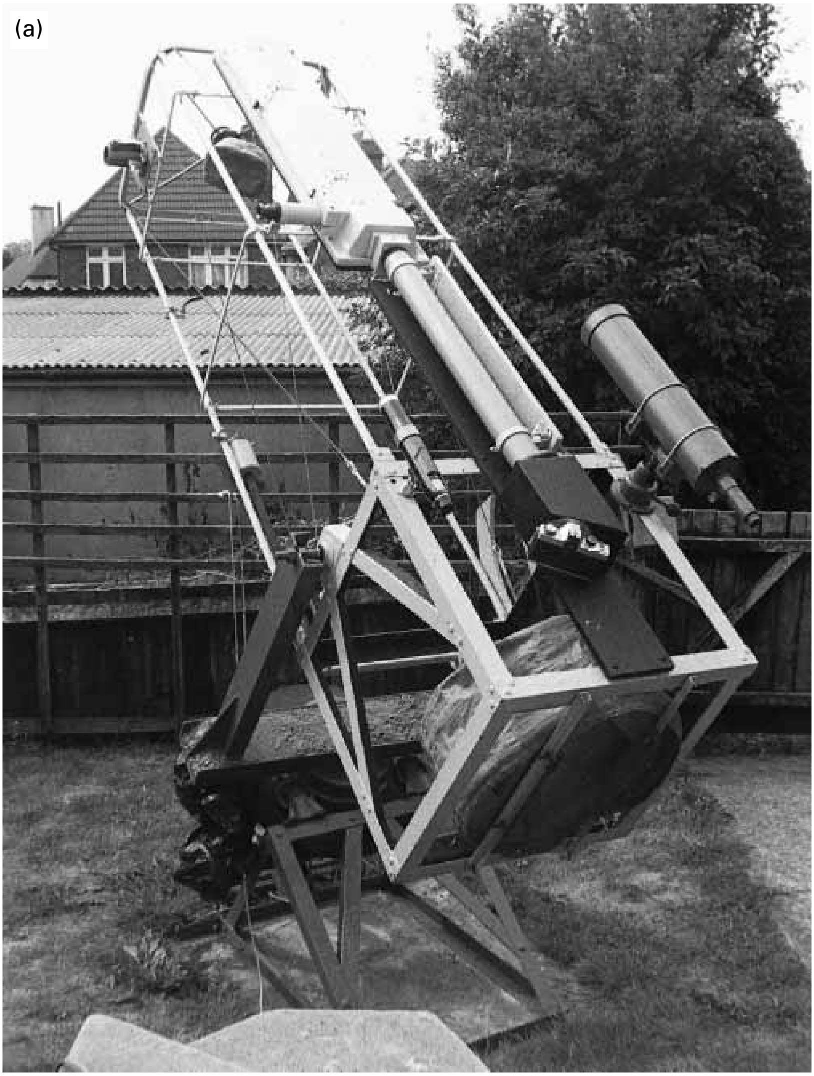
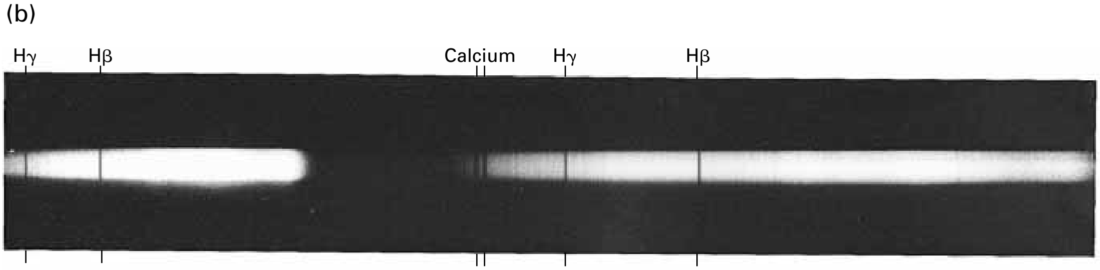


Figure 9.5 (a) The spectrograph the author built onto his 18¼-inch (0.46 m) reflector can be seen arranged along the back of the 8-feet long tube of the telescope.
(b) Spectrum of sunlight reflected from the Moon, obtained by the author, using his spectrograph.



9.4 WHAT MIGHT BE THE CAUSE(S) OF TLP?

If we only ever had one genuine TLP, the example which Kozyrev observed and recorded the spectrum of in 1958, I would have concluded that Kozyrev had witnessed the after-effects of a small piece of cometary material striking the Moon at, or very close to, the central peak of Alphonsus. I would have reckoned that the explosively uplifted surface materials produced the initial reddish cloud. When this cleared it might have left the gases from the vaporised impactor to fluoresce under the solar radiation (the sunlight plus the solar wind bombardment).

However, we do not just have the one TLP. Hundreds have been recorded. The greatest difficulty with the comet impact theory is explaining why it is that certain locations on the Moon's surface seem especially prone to TLP. Surely cometary impacts, if they were the correct explanation, should produce a random distribution of TLP-type events?

Could it be that the Moon has, at least in certain locations, large quantities of sub-surface comet-type ices and these are released through fissures? This seems wildly improbable. True, there has been some surface ice apparently detected by the *Lunar Prospector* probe near the polar regions (the jury is still out on this interpretation of the received reflectance data) but comet-type ices below the surface over much of the globe is quite another thing. Most planetary scientists/geologists would react to such a notion with great hilarity.

Much more reasonable is the case for radioactive gases and the remnants of gases left over from the Moon's more volcanically active ancient past emanating through fissures from deep below the surface. Interestingly, the seismometers left on the Moon have provided data which indicates that TLP sites tend to lie above moonquake epicentres (though see my earlier note of caution about supposed statistical correlations).

I also think that the solar wind and radiation from the Sun might play a part in producing TLP. Simple calculations show that the average solar-wind flux conveys insufficient energy to produce any visible manifestations at the surface of the Moon. However, the solar wind is very gusty and the most intense blasts do convey sufficient energy. I have already referred to Sekiguchi's observation of 26 March 1970, and the fact that he draws attention to a major solar flare that occurred 29 hours earlier as the possible source of the fluorescence he recorded.

Certainly this fluorescence might just be in the surface rocks. In fact, we have long known that there is more to moonlight than simply reflected sunlight. A really significant study of this was undertaken by the 'Manchester Group' in the 1960s. Z. Kopal's article in the May 1965 issue of *Scientific American* is well worth the trouble of obtaining. He, along with T. W. Rackham, photographically recorded a number of luminous events at Pic du Midi. Some of the photographs are presented in the article. The lunar craters Copernicus, Kepler, Plato, and Aristarchus were particularly affected. At times, temporary enhancements in brilliance up to about 80 per cent of that due to the incident sunlight were detected. Later work suggests that the Moon normally shines about 10 per cent brighter than is due to reflected sunlight alone. Kopal presents a detailed analysis in his article and concludes that corpuscular radiation from the Sun is responsible.

It is worth noting that not everybody accepts that the Kozyrev 1958 spectrum is the result of a gas release. For instance E. J. Öpik, in *Advances in Astronomy and Astrophysics, Volume 8 (1971)* (edited by Z. Kopal), points out that the region of bright emission did not encroach into the part of the central peak of Alphonsus in shadow. The demarcation visible on the spectrum is sharp, which is not what one would expect from a cloud of gas. Öpik concludes that fluorescence from the solid lunar surface occurred, rather than any gas emission.

I have great faith in the lunar-rock fluorescence theory as the explanation for many TLP. However, I still wonder if gas effusion from the lunar surface also forms part of the story. For instance, we know for sure (as a result of the *Apollo* missions) that radon gas escapes from below the lunar surface. The *Apollo* Alpha Particle Spectrometers (AAPS) aboard the *Apollo 15* and *Apollo 16* Command Modules – which orbited the Moon while two of the crew worked on the lunar surface – detected alpha particles with the particular energy spectrum which links them to the radioactive decay of radon gas.

Even better, three American scientists, Paul Gorenstein, Leon Golub and Paul Bjorkholm, have conducted a detailed analysis of the AAPS results and found that the sites of maximum emission coincided with the established 'hot spots' of TLP (this correlation, at least, seems strong enough to be definite!). Their paper 'Radon emanation from the Moon, spatial and temporal variability' is presented in *The Moon, 9 (1974)*. Grimaldi, Alphonsus and the edges of the lunar maria figure particularly highly. They found that the largest recorded radon emissions occurred from the area of Aristarchus – the 'hottest' spot of the lot!

It strikes me as plausible that any effusing radon gas might be excited into fluorescence in the same way as for the surface rocks. Perhaps other gaseous species are brought up along with the radon gas.

The solar-wind particles would cause the gas to fluoresce by colliding with the gas atoms/molecules and causing electrons in the atoms to be temporarily excited to higher energy levels. When they de-excite, the electrons hop down the energy level rungs in the atoms, so producing a characteristic spectrum. This is the way a conventional fluorescent lamp works (such as a sodium street-light). Interestingly, like sodium vapour, radon gas produces a nearly monochromatic spectrum. The main emission in the visible spectrum occurs at a wavelength of 434.96 nm (multiply this figure by 10 if you prefer wavelengths expressed in ångstrom units). This is in the blue–violet part of the spectrum.

Expressing my thoughts rather crudely, if the Sun 'sneezed' an extra strong gust of solar-wind particles and the 'spray' arrived at the Moon just as a particular location 'burped' radon gas, then the interaction between them could easily lead to the sort of blue fluorescent effect that has been observed in features such as Torricelli B.

I also conjecture that if the gas release was particularly 'violent' (though still very feeble by terrestrial standards) then maybe some of the finest (perhaps colloidal-sized) particles could be swept up from the lunar surface to produce a temporary obscuration over a small area of the Moon. Of course, the local topography would determine whether or not a cloud of dust could be raised by a gas escape. One might expect this gas cloud to be either white or to appear reddish in hue, depending on the sizes of the levitated particles. The light scattered by the cloud would also be partially polarised, the extent of the polarisation depending on the particle sizes.

Finally, ionised gas atoms/molecules in motion (and particularly those interacting with fine solid particles in suspension or motion) could lead to charge separation and a resultant build-up of electrical potential difference. The eventual discharge through the gas (a form of sheet lightning) might well account for the rarely observed bright flashes and sparkles.

So much for my theories as to the causes of genuine TLP. I may well be completely wrong. We still need much more data.

Other people have differing ideas, such as piezoelectric discharges from the Moon's surface due to stresses and strains in the surface rocks caused by the diurnal temperature changes, and *triboelectric* discharges, again caused by the piezoelectric effect but with moonquakes providing the stresses and strains. Winifred Cameron provides an extensive review of TLP in her paper 'Lunar Transient Phenomena (LTP): manifestations, site distribution, correlations and possible causes' in *Physics of the Earth and Planetary Interiors*, Volume 14 (1977).

One thing I am sure of is that **genuine** TLP are rare. From my experience I would say that the vast majority of the observed anomalies are nothing to do with any real physical process at or near to the surface of the Moon. For explanations of these we need to look much nearer home.

9.5 POSSIBLE CAUSES OF BOGUS TLP

There are three sources of the spurious reports of TLP. These are: the Earth's atmosphere; the telescope; the observer. There are a number of different mechanisms operating in each of these sources. Any one, or a combination, of these can result in what I call 'bogus TLP'.

The atmosphere

One of the major pitfalls for the observer is the presence of *spurious colour*. The Moon's image is composed of light–dark boundaries. You will often see these fringed with colour. We are all familiar with the effect a triangular glass prism has on a thin beam of white light passing through it. The light is deviated by the prism in a direction towards its base. The light is also sorted into its component wavelengths (colours), the amount of deviation being slightly different for each of the component colours. We call this effect *dispersion*. The violet rays are bent slightly more than the red ones.

The Earth's atmosphere acts rather like a prism orientated with its base uppermost. As well as astronomical objects being slightly elevated – making sunrise happen slightly early and sunset happen slightly late – their light-rays are slightly dispersed as a result. Obviously, for each light–dark boundary in the image a full 'rainbow' is produced. However, the orientation of the boundary and the image structure of its immediate surrounds play a part and usually only a section of the full 'rainbow' is visible. For instance, most lunar craters appear with a bluish fringe along their southern rims, the opposite rim being fringed with red. Plato often shows this effect, though many craters do not show both the half-rainbows with equal prominence. In the case of Plato the red colouration along the northern rim is usually more obvious than the blue colour fringing the southern rim. Some craters, for example Aristarchus, normally display spurious colour of the opposite orientation; blue to the north and red to the south.

This spurious colour effect is usually greatest when viewing the Moon (or other celestial body) when it is low over the horizon. However, it also varies with the ambient atmospheric conditions: temperature, humidity, air pressure and the presence of aerosols and particulates.

The implications for TLP hunting are obvious. Time and time again that 'red glow' enveloping a lunar feature (crater wall, central peak, etc.) will turn out to have been generated by our atmosphere. I would urge you to get to know what coloured effects are usual for a given feature. I have already mentioned Plato and Aristarchus. Another interesting example is the crater Lassell. On many nights, especially near full Moon, Lassell seems enveloped by a bluish haze, while the mountain mass just a short distance to the north-west seems to be covered by an orange glow.

Image turbulence, or more properly *scintillation*, is also a real nuisance. Sometimes the image is soft but fairly steady. At other times it is undulating violently. Most often the two effects occur together. Again, the result is different for different lunar features. Has part of the crater wall really 'gone soft' or is it just that the fine terracing present at that location has run together to give a blurred or 'foggy' appearance? There is no substitute for experience when it comes to deciding whether a real anomaly might be present.

The telescope

No telescope is perfect. Even putting aside any mechanical faults, the optical system will have its limitations, both in design and in manufacturing tolerances. I cover some points in Chapter 3 but lack of space here causes me to refer you to my book *Advanced Amateur Astronomy* for a much fuller and more detailed discussion of telescope optics, their faults and some ways of evaluating and correcting them.

Suffice it to say here that lateral chromatic aberration (colour-fringing) is usually the most misleading error experienced by the TLP observer. Longitudinal chromatic aberration manifests as a general softening of the image when seen near the centre of the field of view. Away from the centre it becomes the lateral form. Observations made with refractors could be suspect because of this but, in the main, it is the telescope's eyepiece which usually produces the worst effect. In that sense, you might experience the greatest trouble if using a reflector of low focal ratio!

Critically examine your eyepieces in use. Do you find that the light–dark boundaries in the image, for instance along the edge of a shadow-filled crater, become fringed with colour as you move the telescope to place the crater near the edge of the field of view? This is classic lateral chromatic aberration. Near the centre of the field of view the image will probably appear colour-fringe free. If you have some high-quality coloured filters try the effect of using them. Does the image seem to sharpen when using the filter? If so, you can be fairly sure that the image is being degraded by the presence of longitudinal chromatic aberration.

The remedy is either to stick to making monochrome observations using coloured filters, or to invest in eyepieces with better correction.

The observer

We all make mistakes. Our eyes are imperfect and the brains behind them are even more so. When you consider how the complex lunar vista changes with lighting it is not hard to understand how the observer can be caught unawares by apparently strange appearances. Most times those 'strange appearances' turn out to be quite normal for particular lighting angles and seeing conditions. Yet again, experience is the key to deciding whether the way a feature appears to you is truly anomalous or not.

9.6 TLP OBSERVING PROGRAMME

As far as telescope requirements go, use what you have got. Once in a while an apparent anomaly will appear which is prominent enough to be seen through a small telescope, so it is difficult to put a definite lower limit to the size of telescope required. Obviously, though, anything larger than 6-inch (152 mm) aperture is desirable, provided it is of good quality. Reflectors are normally to be preferred over refractors, provided they have eyepieces that are well corrected for chromatic errors (see the foregoing notes).

If you are a novice observer, it is essential that you first observe through a few lunations to gain some knowledge of what the Moon really looks like under various lighting angles. Even then, I would recommend concentrating on just one or two specific features and only expand your repertoire when you have gained enough experience to be sure what you are looking at really is normal or not. Perhaps the notes in Chapter 8 of this book may help you get started.

When I go to the telescope to carry out TLP hunting, I adopt a definite strategy. Though this might vary depending on the conditions, I normally split observing sessions into two main activities. First I use a low power ($\times$144 on my 0.46 m telescope) and I 'raster-scan' the whole of the lunar surface, both the sunlit and the darkened hemispheres. This might take about 15 minutes. By 'raster-scanning' I mean east–west sweeps across the lunar surface, for each sweep setting the telescope a little higher in declination. The bands swept out then overlap a little, ensuring full coverage. I carefully scrutinise all the lunar features as they pass through the field of view, looking for any abnormalities.

I then carefully scrutinise any features which I think look suspicious. Perhaps I might momentarily leave the telescope to check charts or photographs of the area in question (under as similar lighting as possible). Obviously, I might keep the area under scrutiny for a while – one can still be flexible within one's 'plan of action'.

Assuming all is normal, as it is the vast majority of times, I then spend some time examining other specific features. My list includes: Aristarchus, Torricelli B, Plato, Proclus, Alphonsus, Messier and Messier A, Tycho. All these are TLP 'hot spots'. Not all will be in sunlight at any one time (except near full Moon) but some features, especially Aristarchus, can often be located in Earthshine.

I then proceed to re-scan the Moon with higher magnifications, spending some time to re-scrutinise my selected features, and so on as the session continues. Most nights I do not increase the magnification beyond $\times$207, anyway, because of the turbulent seeing conditions. If the image you are looking at is at all 'soft', then there is certainly no point in going to greater powers.

Obviously there is a real danger of observational selection by concentrating on specific features. At least making scans of the rest of the lunar surface will tend to dilute this effect.

Keeping a watch for TLP during lunar eclipses is especially useful. Some people speculate that the rapid changes in surface temperature may trigger TLP.

I recommend joining a society with a TLP observing group. Then if suspicions are aroused you can telephone a central co-ordinator with your suspicion – **but only give the general location, otherwise you might prejudice the subsequent analysis**. The co-ordinator can then raise an 'alert' among the other participating members.

You can do valuable work just by visually scanning for TLP. If you can also use other techniques you may be able to make an outstanding contribution. Photography (see Chapter 4), video techniques and CCD imaging (see Chapter 5) are obvious extensions of purely visual work. You could include the use of coloured filters with all the imaging methods. Photometry is possible (especially with video/CCD images saved on a computer). With colour filters in use this becomes *colorimetry* – the relative brightness in specific wavebands. Use a polarising filter and you can do *polarimetry*. If you can build or obtain a spectrograph you could follow in the steps of Kozyrev. For details of these more advanced techniques could I refer you to my book *Advanced Amateur Astronomy*, as I have already exceeded the page allocation set by the publisher for this one!

I have enjoyed observing the Moon for three decades. Despite my current incapacity, I can still do some telescopic observation and I am hoping to do much more again as my fitness improves in the future. Maybe I can go another three decades at the telescope eyepiece? At any rate, I feel sure that I will live long enough to see humans walking on the lunar soil once more.

In this book I have tried to 'shoehorn' as much useful information into the available space as possible. Nonetheless, the treatment is far from complete. This book could be twice as long and still not cover everything. We already know so much about our Moon. Yet there is still much more to learn. I hope, though, I have said enough to persuade you to obtain whatever telescope you can and turn it to the Moon. You will find a world of fascination and mystery among the dramatic mountain ranges and the eerie plains and craters. I hope you will experience for yourself the Moon's "magnificent desolation".

INDEX

Gerald North graduated in physics and astronomy. A former teacher and college lecturer, he is now a freelance astronomer and author. A long term member of the British Astronomical Association, he has served in several posts in their Lunar Section. His books include the acclaimed *Advanced Amateur Astronomy*, which has become a classic guide for astronomers wishing to raise their observing to the next level.

Jacket Image:
Catalina photograph of the Moon's surface. Courtesy of the Lunar and Planetary Laboratory, Arizona, USA.

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