Observing the Moon

Gerald North

The modern astronomer's guide · Second Edition

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Observing the Moon

The Modern Astronomer's Guide, Second Edition

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. In this thoroughly updated Second Edition, the author provides extensive practical advice and sophisticated background knowledge of the Moon and of lunar observation. It incorporates the latest developments in lunar imaging techniques, including digital photography, CCD imaging, and webcam observing, and essential advice on collimating all common types of telescope.

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 was also a Guest Observer of the Royal Greenwich Observatory. He is now a freelance astronomer and author. He is a long-term member of the British Astronomical Association, and has served in several posts in their Lunar Section. His other observing guides include the acclaimed *Advanced Amateur Astronomy* (Second Edition, Cambridge University Press, 1997) and *Observing Variable Stars, Novae and Supernovae* (with Nick James, Cambridge University Press, 2004).

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The modern astronomer's guide

SECOND EDITION

GERALD NORTH BSc

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PREFACE

PREFACE TO THE FIRST EDITION

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 once again be walking 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

PREFACE TO THE SECOND EDITION

The new level of interest in the Moon that I noted in the Preface to the First Edition has been maintained in the years since. Meanwhile much has changed in the arena of practical amateur astronomy. New equipment and techniques have allowed amateurs to make significant advances in the quality of their work and some of the older ways of doing things have fallen by the wayside. The First Edition of this book proved to be popular and it was reprinted a number of times. However things have changed so much since that First Edition was first published it is now time for this new one. Consequently I have re-written much of this book to reflect the amateur astronomer's world of the early twenty-first century. I hope you enjoy reading it – and I hope that you will obtain whatever telescopic equipment you can and turn it to the Moon. Things certainly have moved on in practical astronomy but the Moon remains as beautiful, as thrilling, and as mysterious as ever.

Gerald North
Norfolk

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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, Commander Henry Hatfield, John Gionis, Michael Butcher, Martin Mobberley and Damian Peach. Special thanks are also due to Dr T W Rackham (who sadly has died since the first edition was published) and Manchester University, England, also to Ewen. A. Whitaker and the Lunar and Planetary Laboratory, University of Arizona, USA, and the National Aeronautics and 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 had, for the First Edition, gone to considerable trouble to furnish me with materials and it is very sad for me now to have to record his death along with my thanks. For this edition I have also been given a tremendous amount of help by my many friends of the Breckland Astronomical Society, especially John Gionis, Michael Butcher and Malcolm Dent. In particular Michael Butcher has spent many hours building a photographic-based key map (Figure 7.1), that replaces my hand-drawn version in the First Edition.

Finally I must not forget to thank Dr Simon Mitton and his staff at Cambridge University Press for all their hard work in making the First Edition the success it was. Now I have to thank Vince Higgs along with his staff at the Press again for their sterling work on this Second Edition.

Gerald North
Norfolk

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 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, so I listened hard. I was a young 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.

Those who were around at the time will remember 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 mainly because of reflected sunlight, with a very small contribution from fluorescence caused by the re-radiation at visible wavelengths of invisible short-wave solar radiations and absorbed kinetic energy from solar-wind bombardment.

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

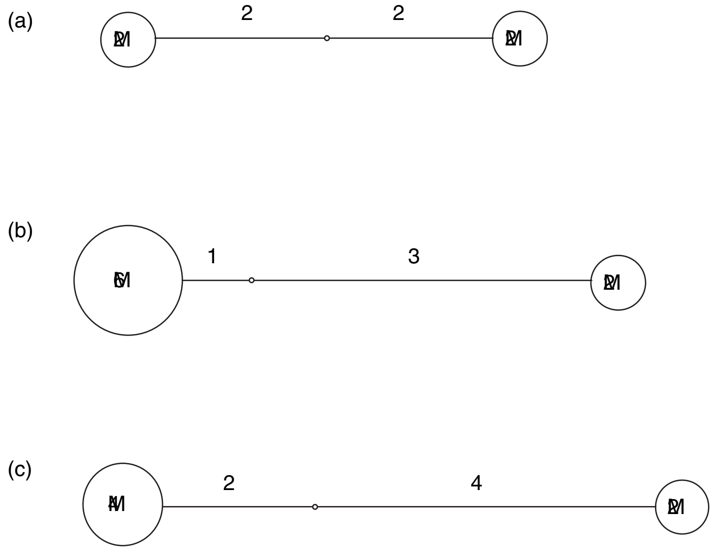


Figure 1.1 The positions of the barycentre for bodies of differing masses. The distances of each of the barycentres from the bodies are in the inverse ratios of their masses in each of these cases.

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 In Depth*, published by Springer–Verlag in 2003) but suffice it to say here that the researches of Copernicus and Galileo in the sixteenth and early seventeenth centuries were pivotal. Of course, one body was not displaced from its situation of orbiting the Earth, as the ancients had mistakenly believed was the case for all the other 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*, sometimes 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 sunlight from the Earth shining on the Earth-facing part of the Moon experiencing night. Leonardo da Vinci is credited as being first to explain this effect correctly. 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 at its most brilliant when largely covered in highly reflective clouds). Finally, the observing conditions local to the observer also have an

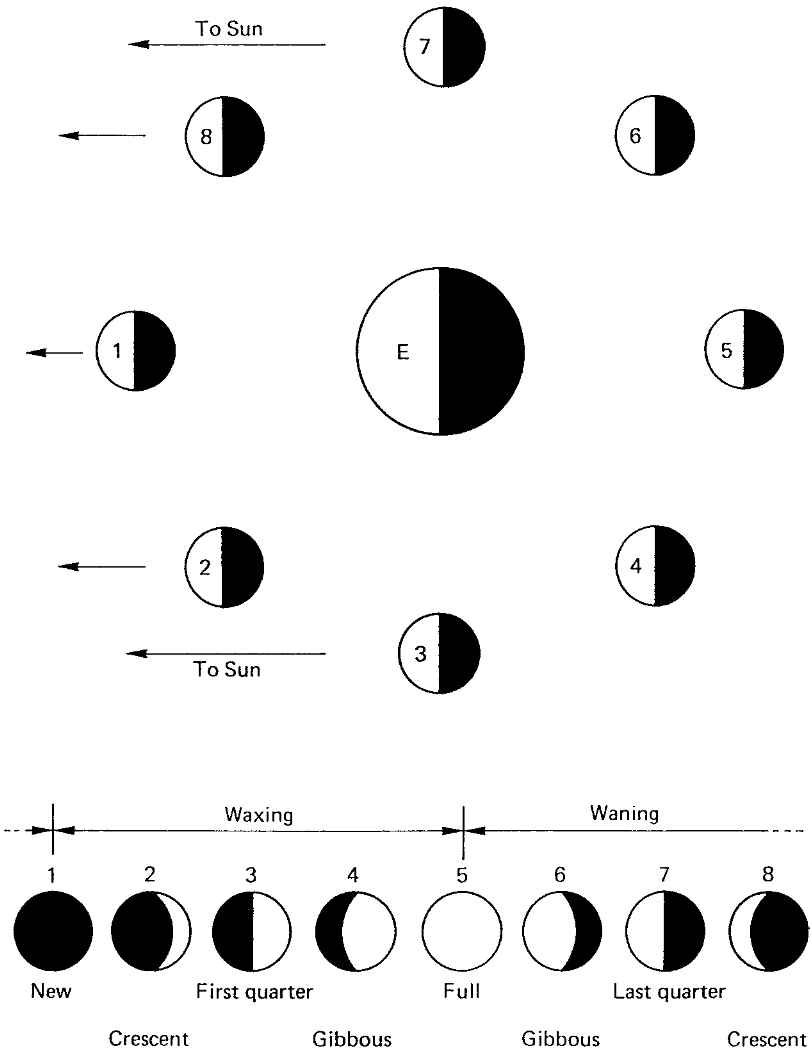


Figure 1.2 The phases of the Moon. The upper section of the diagram illustrates the Moon in various positions in its orbit, while the corresponding phases that we see from the surface of the Earth are shown in the lower section.

important bearing. Poor transparency and haze both inhibit the visibility of earthshine, just as one would expect.

Another inaccuracy in Figure 1.2 is that it does not represent 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 every new Moon (Figure 1.5), even though the diagram might suggest that the Moon should pass exactly between the Sun and

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.

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.

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

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.

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 the sky, which results from our orbit around the Sun (in effect the Sun appears to move once around the sky, through the constellations

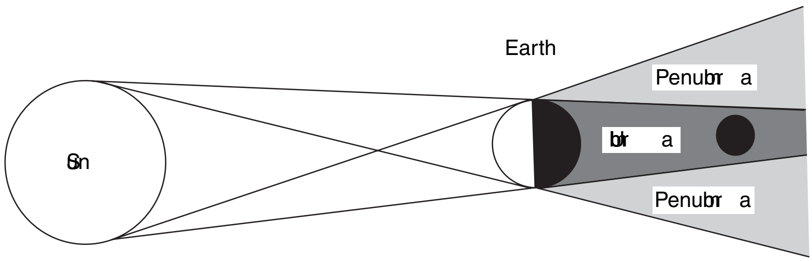


Figure 1.4 Lunar eclipses. With the Moon (black disk) in the position shown, a total lunar eclipse would be the result. This diagram is grossly out of scale for the sake of clarity.

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 appearing to be in the same direction as seen from Earth) are when both are at either the ascending node, or the descending node, at the same instant. Remembering that the

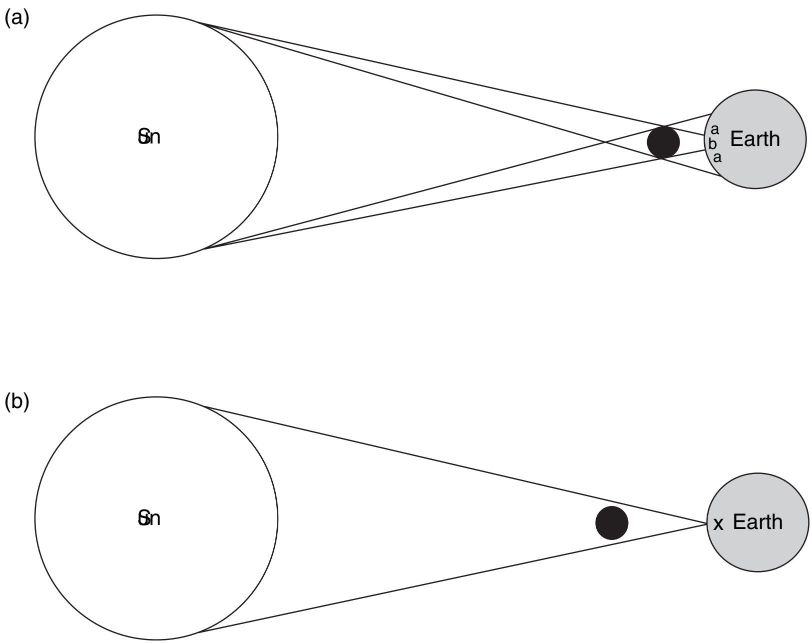


Figure 1.5 Solar eclipses. (a) An observer stationed at **b** would see a total solar eclipse, while someone in the regions shown as **a** would see a partial eclipse. (b) An observer at position **x** would see an annular eclipse. The diagrams are grossly out of scale for the sake of clarity.

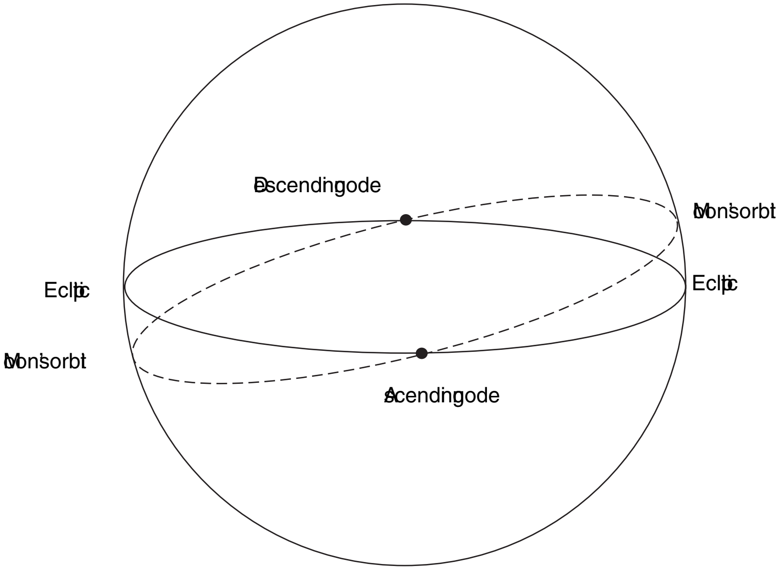


Figure 1.6 The orbit of the Moon projected onto the celestial sphere.

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

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 $23^{h}\,00^{m}$ UT. (c) 3 second exposure at $23^{h}\,20^{m}$ UT.

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 particularly close to its orbital node and may, as a result, 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.

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.

1.3 SOLAR ECLIPSES

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 one 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 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*.

The maximum duration of totality, as seen from any particular location, is about eight 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 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. 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 cherished 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.

1.4 GRAVITY AND 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:

$$F \propto Mm/r^2 \tag{1.1}$$

or

$$F = GMm/r^2 \tag{1.2}$$

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 the *universal constant of gravitation*.

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

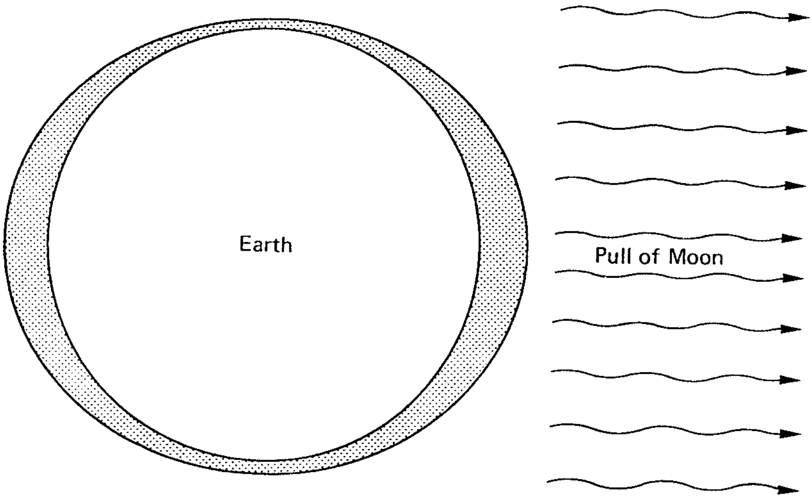


Figure 1.8 The main tide generating process.

attraction of the Moon. In addition, the Earth is also 'pulled away' from the water on the reverse side, so leaving a bulge of water on the opposite side of the Earth, as shown in Figure 1.8. 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 1.9 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 1.10). 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.

1.5 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.

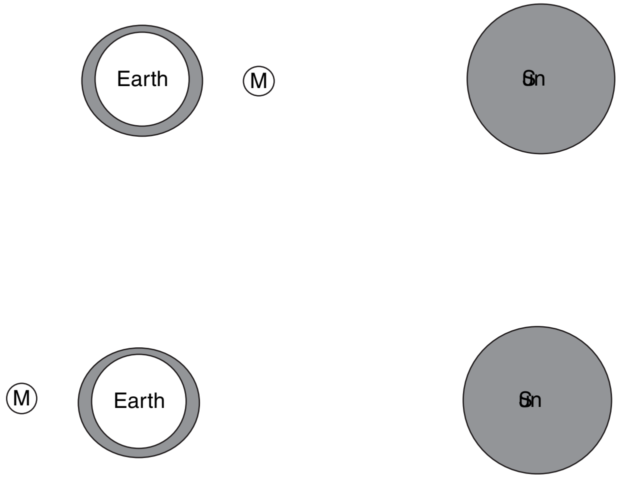


Figure 1.9 Spring tides are formed when the pulls of the Moon and Sun are aligned (even if pulling in opposite directions).

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

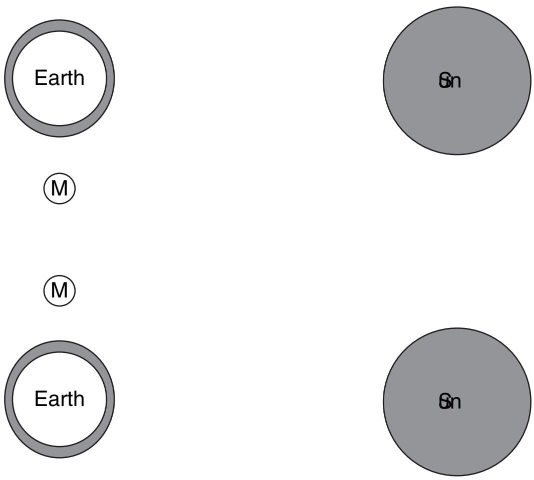


Figure 1.10 Neap tides are formed when the pulls of the Moon and the Sun are at right angles to each other.

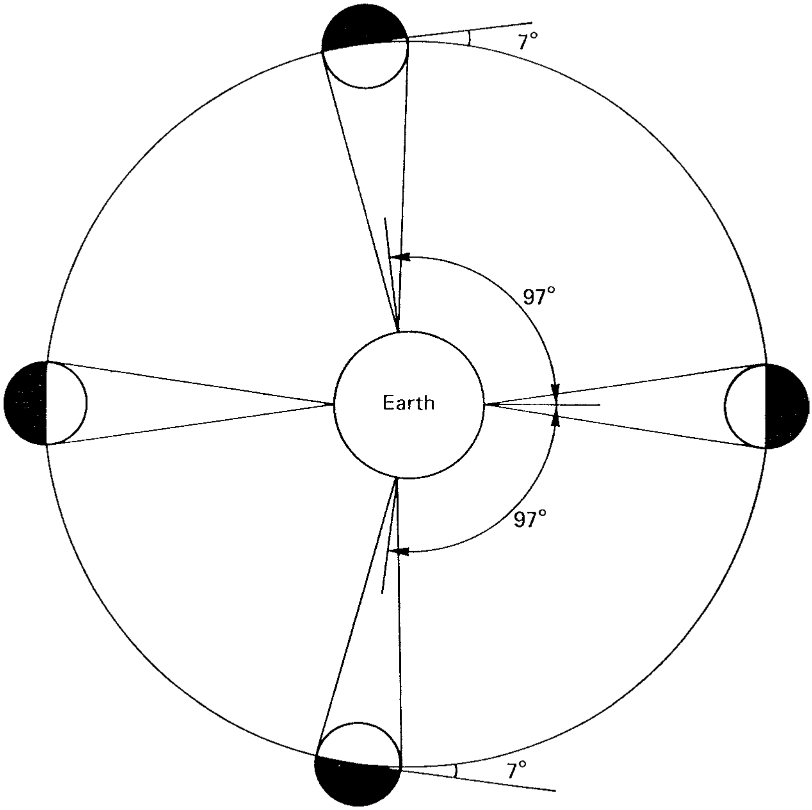


Figure 1.11 Libration in longitude. The Moon turns evenly on its axis but the Moon's speed varies around its elliptical orbit. Consequently the two motions are out of step, although the total time taken for one rotation is the same as the time taken for one complete orbit. The result is that the Moon appears (as seen from the Earth) to swivel back and forth in an east–west direction over the course of one lunation.

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 1.11.

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 1.12). This is libration in latitude.

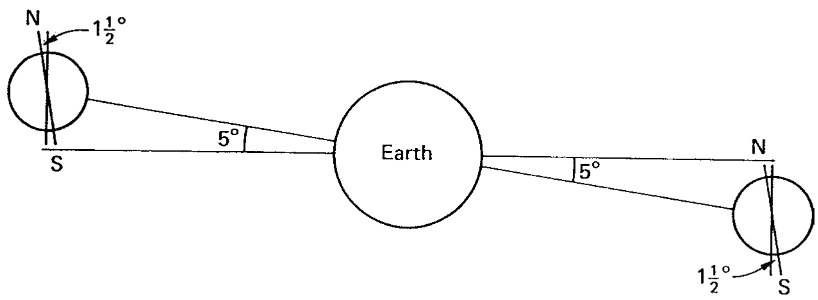


Figure 1.12 Libration in latitude.

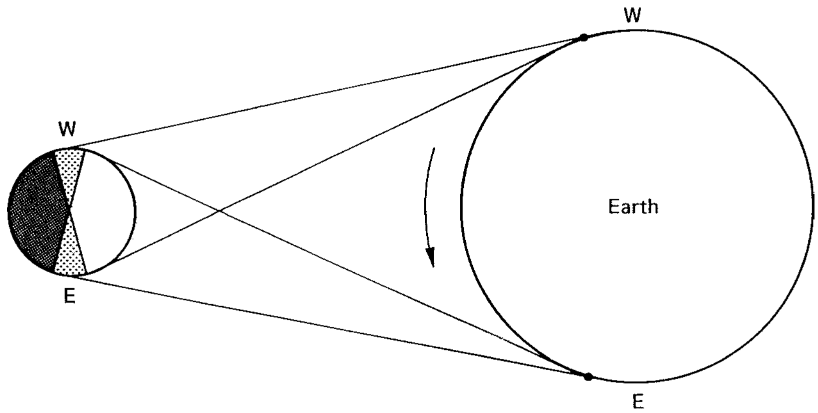


Figure 1.13 Diurnal libration.

Figure 1.13 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 1.14 shows well the effect of libration.

1.6 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.

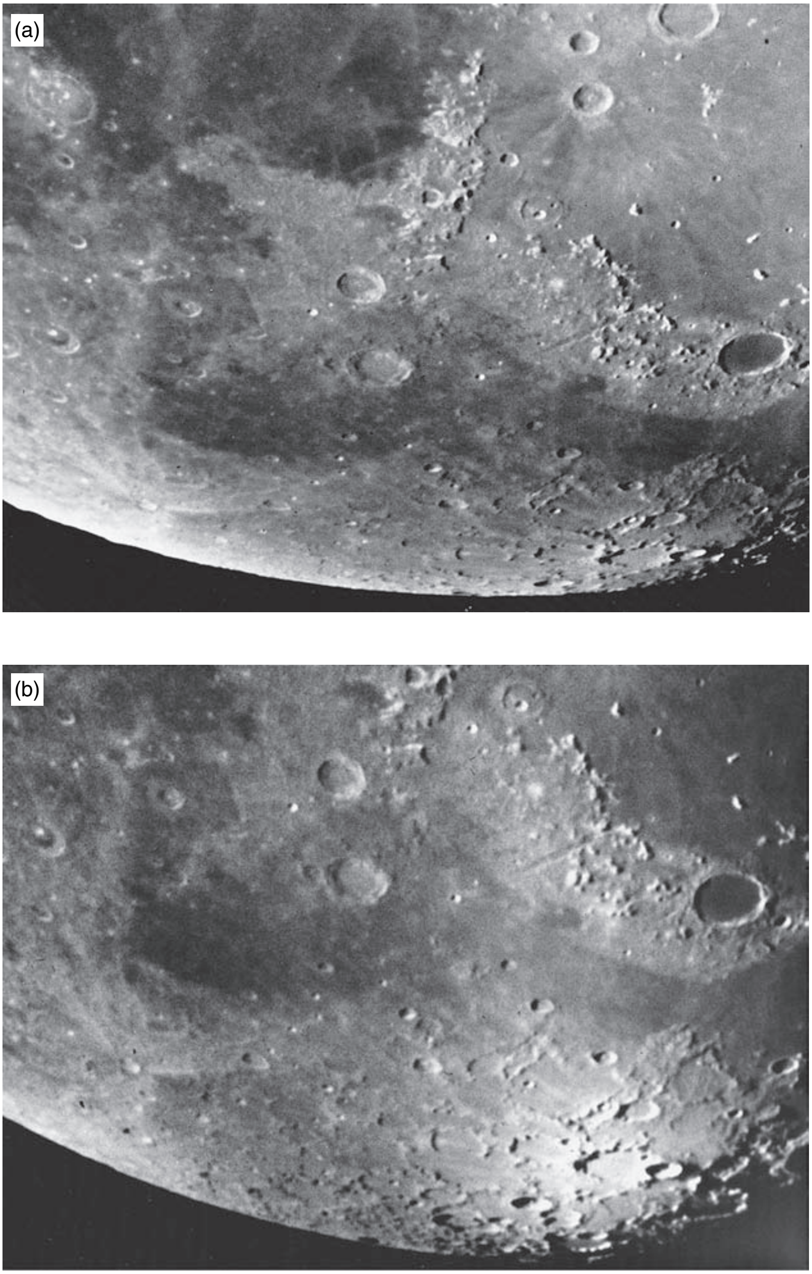


Figure 1.14 The effects of libration are illustrated well by these photographs taken by Commander Henry Hatfield, using his 12-inch (305 mm) Newtonian reflector: (a) was taken on 1966 May 29^{d} 21^{h} 03^{m} UT; (b) was taken on 1966 November 22^{d} 18^{h} 14^{m} UT. In both (a) and (b) the values of 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.

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 $+90^\circ$ 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 1.15 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.

Since the time of publication of the first edition of this book, popular astronomy magazines have increasingly taken to publishing all photographs of the Moon and planets with north uppermost. It is certainly true that observers with modern telescopes (particularly the Schmidt–Cassegrain and Maksutov types now very widely used) often use them with star-diagonals so the old south-up orientation often no longer applies. However in these cases the image is also subjected to a mirror-image reversal (in optics this is properly known as a *lateral perversion*), in which case a mere rotation of the image can never make it match a conventional image or photograph. So, I considered it best in this edition to stick with the south-uppermost orientation that will be commonly encountered in refracting telescopes or reflecting telescopes with an even number of mirrors in the light path.

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.

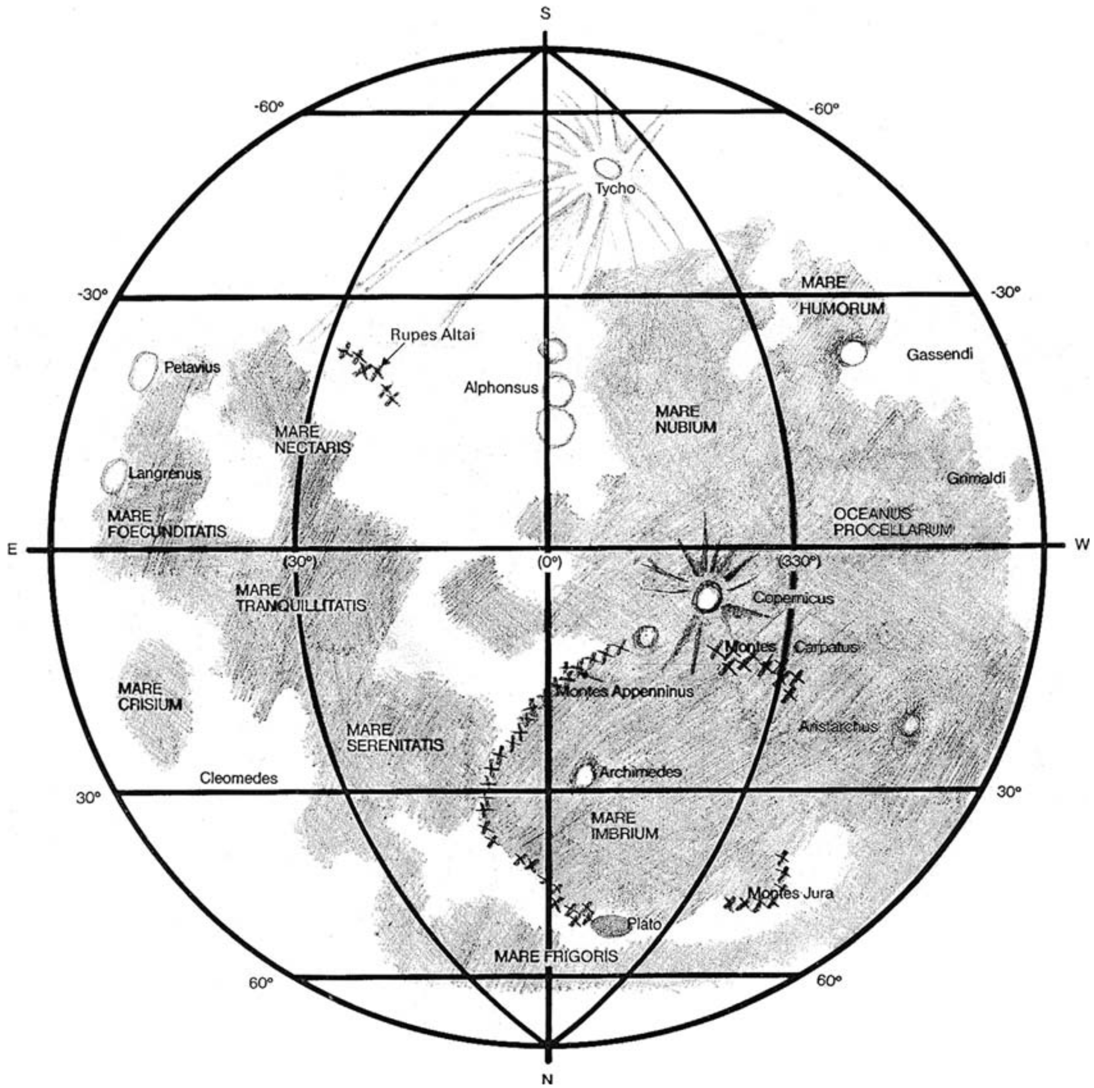


Figure 1.15 Outline map of the Moon, illustrating the modern system of co-ordinates as standardised by the International Astronomical Union.

One can go on to define the co-ordinates of the *terminator*, the boundary between the sunlit and dark portions of the Moon that shifts 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° when 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!

1.7 OCCULTATIONS

As the Moon sweeps around the Earth in its monthly orbit it may pass in front of the planets and stars far beyond. When the Moon hides a 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 the star suddenly 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 most of these objectives have been better met by other means. However, the long-term nature of occultation-timing data does lend 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 observing occultations, 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.

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, Leonard 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.

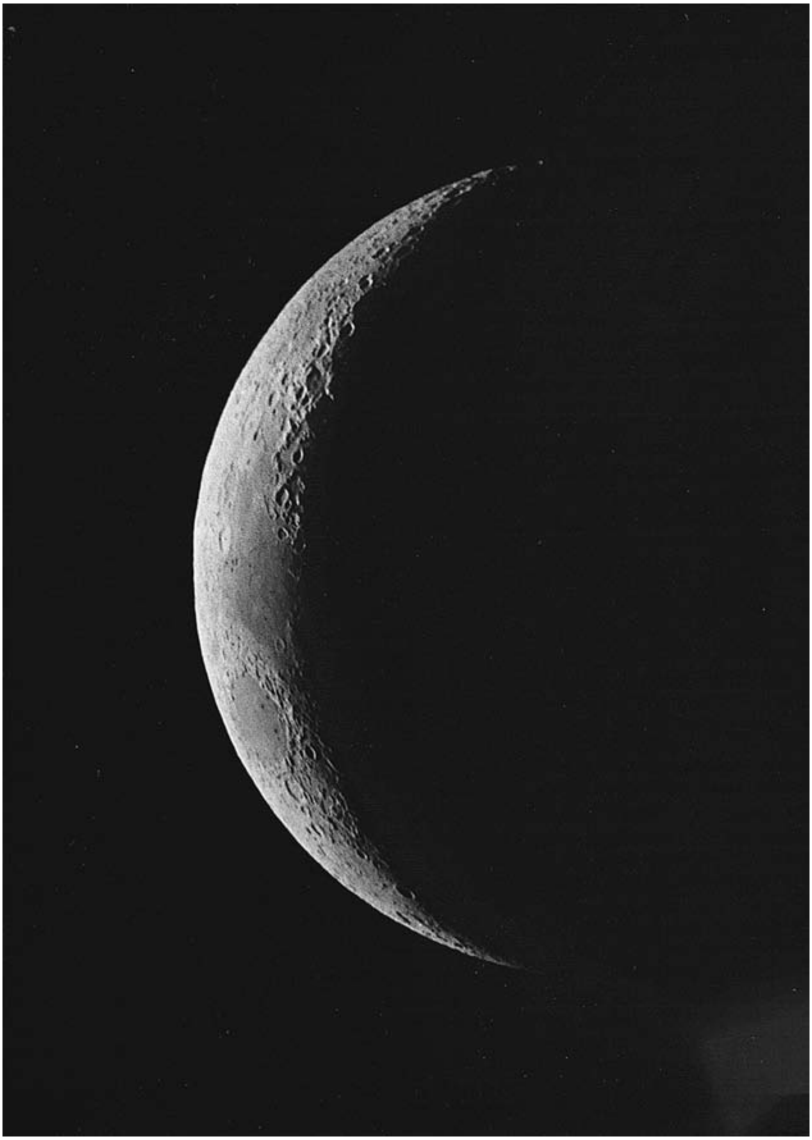
2.1 THE MOON IN FOCUS

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 folklores) effect which is so obvious around the time of the full Moon. Figures 2.1–2.4 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 it is expected that most of its readers will reside in the northern hemisphere, all the telescopic views of the Moon in this book are orientated with south at least approximately uppermost.

The main bright parts of the Moon are the rocky highlands, known as *terrae*. 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

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}.



recognised and the difference in hue was taken to indicate a difference in chemical composition. 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

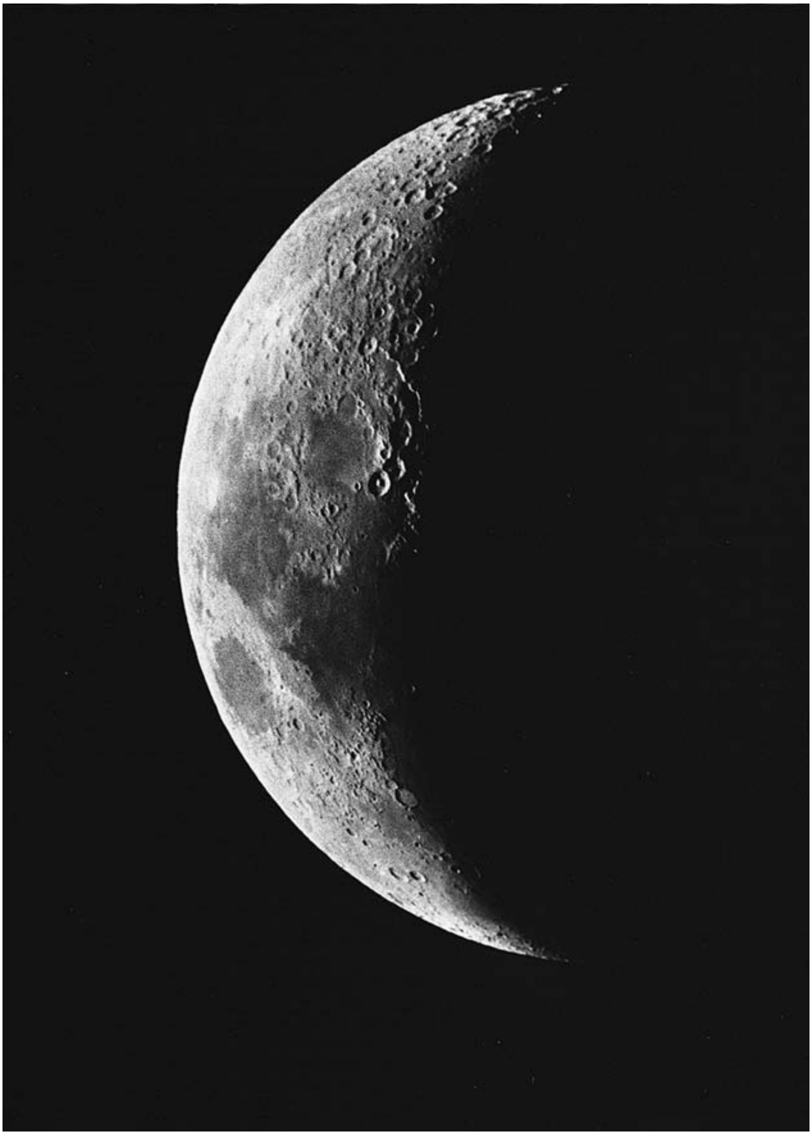


Figure 2.2 The 6-day-old Moon photographed by Tony Pacey. Same arrangement as for Figure 2.1 but he used a 1/60 second exposure on *Ilford* Pan F film, processed in ID11 developer. The photograph was taken on 1992 January $10^{d}\ 19^{h}\ 00^{m}$ UT.

example Lacus Mortis (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. 154) 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.

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 $\times100$, 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 15-day old Moon photographed by Michael Butcher on 2003 April 16^{d} 22^{h} 57^{m} UT. To take this image he simply held his *Canon* Powershot G2 compact digital camera, set to maximum zoom, up to a 40 mm Plössyl eyepiece which was plugged into his *Meade* ETX Maksutov telescope. The camera was set to automatic exposure and focus and an effective speed of 100 ISO.

When the Moon is close to full, as shown in Figure 2.4, 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.

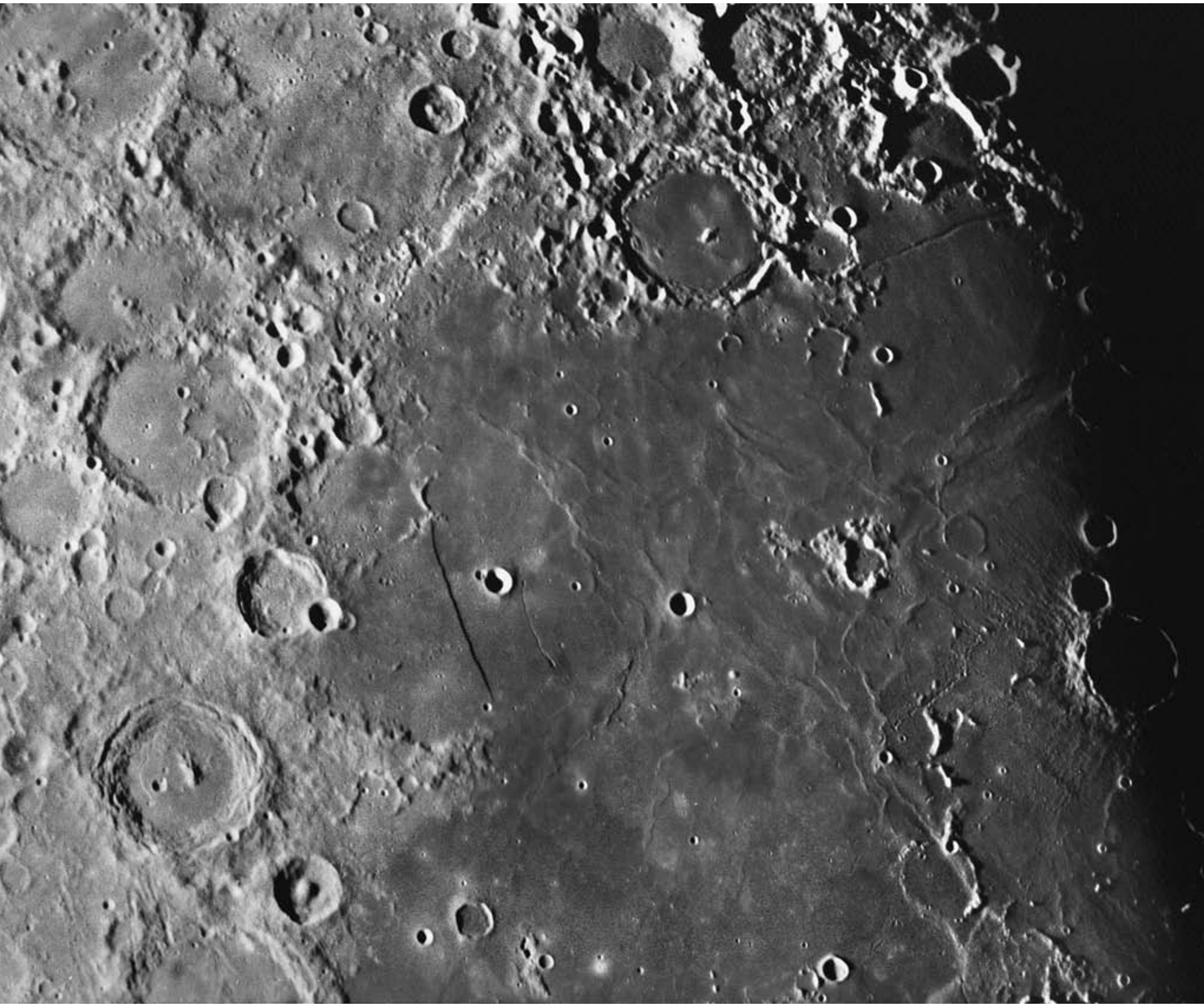
Away from the times when the Moon is full the effect is far less confusing. Shadowing then makes the lunar surface details stand out. This is especially so close to the terminator, where the sunlight is striking the Moon at a very shallow angle. This is evident even by comparing the wide-angle (and hence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

Under low-angle lighting even the lunar maria are shown to be less than perfectly smooth. *Dorsum*, networks of ridges crossing the maria,

Figure 2.5 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. (Courtesy Ewen A. Whitaker and the Lunar and Planetary Laboratory, Arizona.)

then become obvious (see Figure 2.5). *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.

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 features on the Moon. These saucer-shaped depressions range in size from the smallest resolvable in telescopes (and smaller, down to just a



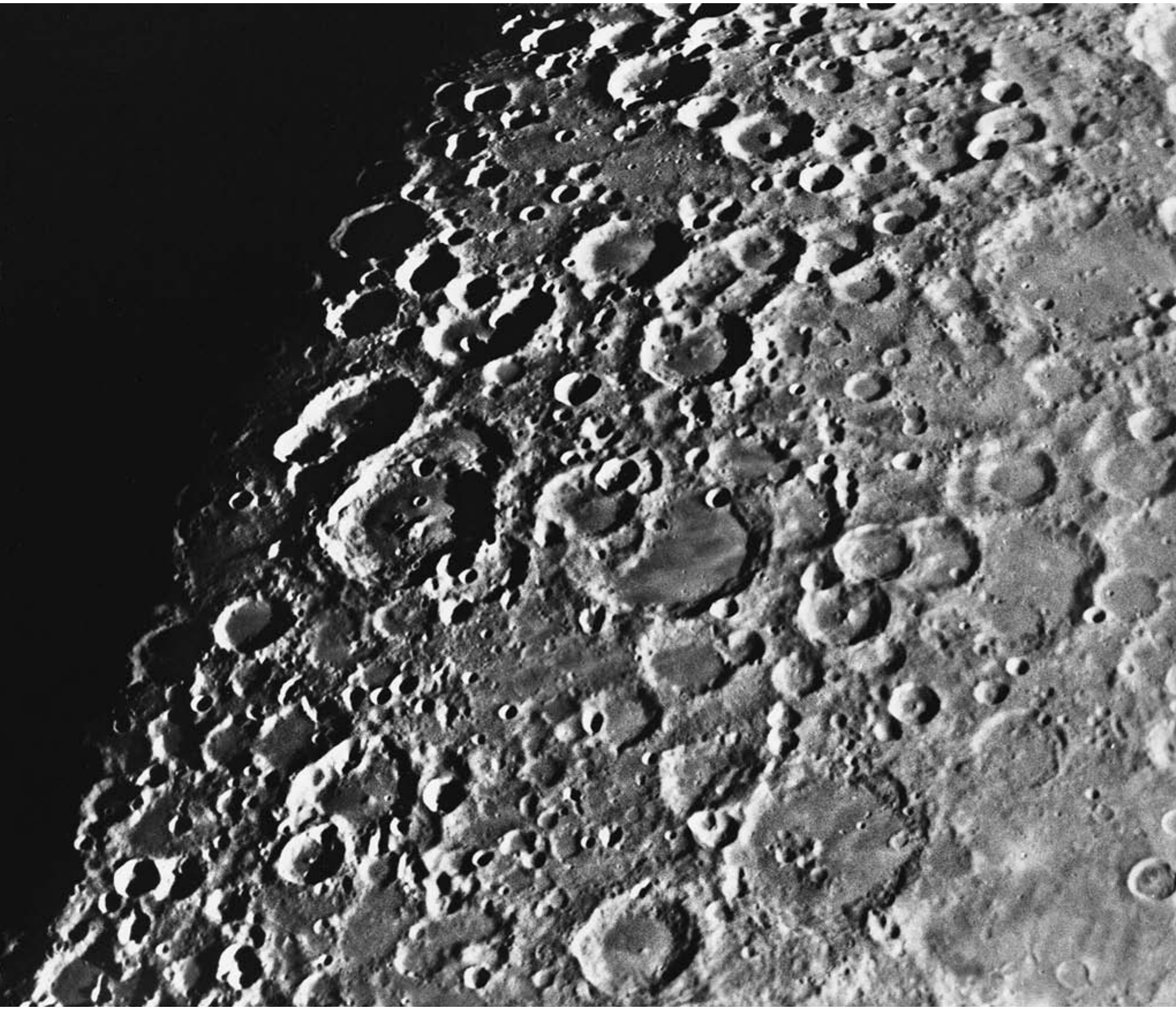


Figure 2.6 The crater-saturated southern highlands of the Moon, photographed using the 1.5 m reflector of the Catalina Observatory, Arizona, on 1966 September 5^{d} 11^{h} 30^{m} UT. (Courtesy Ewen A. Whitaker and the Lunar and Planetary Laboratory, Arizona.)

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 a different name on

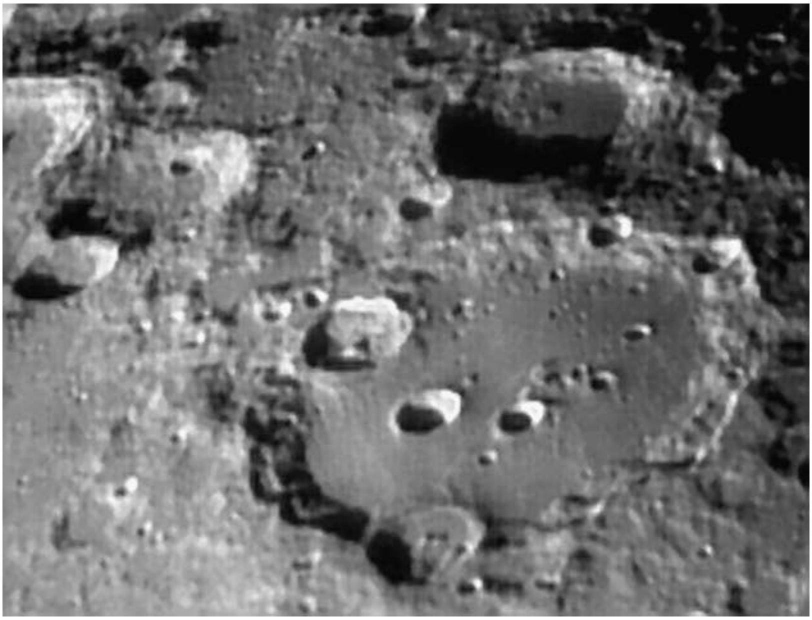


Figure 2.7 The lunar crater Clavius, imaged by the author on 2004 March 01^{d} 18^{h} 20^{m} UT. He used an *S-Big* STV camera in wide-field mode fitted into a ×2 Barlow lens, plugged into the 19½-inch (0.5 m) f/4.8 Newtonian reflector of the Breckland Astronomical Society, stopped to 8 inches (0.2 m) off-axis because the seeing was a rough ANT. IV at the time. The image was subsequently processed using *CCDOPS5* and *Image Editor* software.

different maps. Even more confusing, a particular name might refer to a different crater on different maps! Fortunately, the system has been overhauled by the International Astronomical Union (IAU) 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 2.6) but there is an obvious paucity of larger craters on the maria. An observer using 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