Gerald North

Observing the Solar System

The modern astronomer's guide

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The Modern Astronomer's Guide

Written by a well-known and experienced amateur astronomer, this is a practical primer for all aspiring observers of the planets and other Solar System objects. Whether you are a beginner or more advanced astronomer, you will find all you need in this book to help develop your knowledge and skills, and move on to the next level of observing.

This up-to-date, self-contained guide provides a detailed and wide-ranging background to Solar System astronomy, along with extensive practical advice and resources.

Topics covered include: traditional visual observing techniques using telescopes and ancillary equipment; how to go about imaging astronomical bodies; how to conduct measurements and research of scientifically useful quality; the latest observing and imaging techniques.

Whether your interests lie in observing aurorae, meteors, the Sun, the Moon, asteroids, comets, or any of the major planets, you will find all you need here to help you get started.

Gerald North graduated in physics and astronomy. He was a former teacher and lecturer in both subjects, a former Guest Observer at the Royal Greenwich Observatory, and is now a freelance astronomer and writer. He is a long-term member of the British Astronomical Association and has served in several senior posts in their Lunar Section. He has published widely over the years and is the author of this book's popular companion volume *Observing the Moon: The Modern Astronomer's Guide* (Cambridge University Press, Second Edition 2007).

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The modern astronomer's guide

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To

Mrs Joan E. North

my wonderful Mother

and to the memory of

Mr Gordon S. North

precision engineer,

horologist, man of many other skills,

and my much-missed Father.

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PREFACE

I still have my copy of the second edition of *Practical Amateur Astronomy*, the 'how to' book on astronomy that my parents bought me for the Christmas of 1971. The book was edited by Patrick Moore and contained chapters on practical astronomy written by British expert practitioners of the day covering their specialist fields. At the time I was thirteen years old and had already been interested in all the sciences, and particularly astronomy, for many years. However, my practical experience of astronomy at that time was limited to locating some of the more prominent astronomical objects and peering at them through the eyepieces of binoculars, a small terrestrial refractor, and a 3-inch (76 mm) Newtonian reflector. Back then that book seemed very advanced but I took what instruction I could from it and continued to pursue my interest in practical astronomy.

Practical Amateur Astronomy was a very useful book in 1971, giving the reader instruction in the then current activities of the more advanced amateur practitioners. In the main, the chapters were written by the directors of the various observing sections of the British Astronomical Association (BAA). Today that book looks very simple and quaintly old-fashioned, thanks to modern advances. A year earlier, I remember borrowing an early edition of Patrick Moore's *The Amateur Astronomer* from the local library. That book struck me as being extremely light on practical advice but it nonetheless provided a narrative of elementary general astronomy told from the perspective of the amateur. Despite my young age I had no trouble in understanding everything in that book, so it also helped me on my way. Other borrowed books, such as Nigel Calder's *Violent Universe* rounded out my knowledge and gave me some inkling as to professional astronomical researches carried out in the world-class observatories of the time.

Four decades later the whole amateur astronomical scene has changed beyond recognition. In addition, the gap in knowledge and expertise between beginners in astronomy and today's most-advanced practitioners has widened to a veritable chasm. A large range of equipment is now on offer to the prospective amateur astronomer at a vast range of prices. The unwary could waste much money if the wrong equipment is chosen for given types of observing. There is also the question of what observational projects are possible and how does one best go about them, anyway?

I have written this book with the intention of it being most useful to those who perhaps already have a limited amount of knowledge and experience but wish to move up to the next level of observing, to the point at which some scientifically useful observing projects can be undertaken.

I should add that you don't have to do serious research work to enjoy astronomy as a hobby. In fact, only a small minority of practising amateurs submit observations to the observing sections of any of the national astronomical societies. Even if you have no desire to submit your own observations, astronomy is a hobby which becomes so very much more interesting and rewarding with just a little increase in effort and sophistication of approach. So, whether you want to raise your game to the point where you can begin to submit scientifically useful observations, or just enjoy your hobby a whole lot more, I have written this book for you.

Mindful of my own introduction to practical amateur astronomy via the books of Patrick Moore and other authors, I decided at the outset that part of this book should be given over to a general account of Solar System astronomy, though heavily biased towards the viewpoint of the amateur observer. Such knowledge will give meaning and purpose to the observational tasks I describe. Without that background knowledge the practical work would be sterile and pointless. Of course the purpose of this book **is** to be a practical guide and so the majority of the material in it does actually concern the mechanics, equipment and techniques of observing.

As well as being a member of the BAA since the late 1970s, I have for the last decade also been a member of a large and active local astronomical society. That society contains many members – some old and some young, some advanced and some at the beginner level. It has been very instructive for me to witness how many enthusiastic beginners, especially the youngest of them, are great with computer software and all things Internet but are very lacking in some of the basic theory and practice of astronomy. They can very quickly learn a plethora of things technical but remain ignorant of many of the basics of setting up and handling telescopes.

Even what seemed to me to be obvious techniques that allowed me to see things to the best effect through telescopes back in the 1970s remain a closed book to many of today's apprentice astronomers. That is not due to any failing on their part. It is a combination of there being

so much to learn these days, blended with today's fashion for all things push-button and computer-related. If I was starting out today in astronomy I am sure I would be bewildered, maybe even intimidated, without some sage advice from a friend or perhaps a friendly book.

That observation has informed how I selected the material for this book and how I have organised that material within it. I have, for instance, given more space in this book to basic techniques of visual observing than would be justified if the book was proportioned to reflect the average of the activities of the more advanced amateurs today. Today's advanced practitioners heavily use imaging devices and computers with their computer-controlled telescopes and seldom, in many cases never, observe visually. However, even the most advanced of them started out as beginners, undoubtedly then spending a great many pleasurable hours peering through telescope eyepieces.

Please, dear reader, do not be insulted or irritated when you come across materials which you find very elementary, as I have no doubt you will. I have done my best to make this book useful for the maximum number of its readers – and that must include those who already know quite a lot, those who currently know not much, and those who know a lot but still have gaps in their knowledge and experience.

As much as is possible I have organised the book with the easiest topics first. Indeed, you can undertake the practical work described in Chapter 1 even if you do not own a telescope. To a large extent the chapters that follow each build on the earlier ones, in the process covering the fullest range of activities you might wish to undertake.

I have been observing the skies for four decades and still find the experience immensely enjoyable and rewarding. I hope that you, too, will enjoy the views of the alien worlds and other celestial bodies and phenomena that our Solar System has on offer. Perhaps this book can help along your way towards maximising that enjoyment. I hope that it may also help you undertake work that is scientifically useful, if that is your desire. It might even lead to a consuming interest that will last you for a very long time to come. Whatever your desires, I hope that you enjoy reading this book and I wish you the best of luck in your future endeavours.

Gerald North
Norfolk, UK

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I am very grateful to the following people for allowing me to reproduce examples of their superb work in this book: Ian Bennett, Peter Birtwhistle, Robert Bullen, Michael Clarke, Martin Crow, Roger Dymock, Nigel Evans, David Higgins, Nick James, Andrew Johnson, Dr Richard Miles, Martin Mobberley, Bob Neville, Damian Peach, Herbert Raab, Bob Samuel, Jonathan Shanklin, Peter Strugnell, Fiona Vincent, Brian Warner, and the Council of the British Astronomical Association. Erich Strach also gave his permission for me to use one of his excellent hydrogen-alpha filtergrams of the Sun and it is sad for me to record here his recent death.

In addition to allowing me to use his own observational materials, Roger Dymock has gone to considerable trouble to furnish me with helpful materials concerning asteroids, even to the extent of obtaining permissions for me to reproduce illustrative materials from some of the above noted contributors. Most certainly the chapter on observing asteroids would be diminished if it were not for Roger's efforts and contributions and I here offer him my special thanks. Finally, I must offer my special thanks to Zoë Lewin for her marvellous work. She is surely the best copy-editor in the business.

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Norfolk, UK

CHAPTER 1

Earth and sky

Almost all of this book is devoted to the practical methods we astronomers can use to study the great worlds and other celestial bodies in our Solar System we can see across millions of kilometres of space. To help us appreciate those other worlds it is as well to have to hand some basic facts about our own planet. Also there are some aspects of our Solar System we can observe and study without even using a telescope. So, let us begin our explorations right here, with a brief overview of our Earth and the phenomena that we can see and study without any optical aid . . .

1.1 PLANET EARTH

The Earth is a rocky globe, 12 800 km in diameter, orbiting the Sun at a mean distance of 150 million km and taking one year to complete one orbit. The Earth is not quite a perfect sphere but is rather an oblate spheroid, its polar diameter being 43 km less than its equatorial diameter. The difference is caused by the forces arising from the daily (technically *diurnal*) rotation of the planet on its axis.

The Earth is but one of eight major planets that orbit the Sun and they all rely on the Sun as a provider of light and heat. All the planets go round the Sun in the same direction and all keep close to the same plane as they orbit. The mean orbital radii of the major planets and their orbital periods are shown in Figure 1.1. The orbital period of a planet is referred to as its *sidereal period*. Hence the sidereal period of the Earth is one year.

The mass of the Earth is 6 million million million million kg. In scientific notation this is written as 6×10^{24} kg. Dividing the Earth's mass by its volume gives it a *mean density* of 5515 kg/m^3. The rocks near the surface of the Earth have measured densities of around 2500 kg/m^3

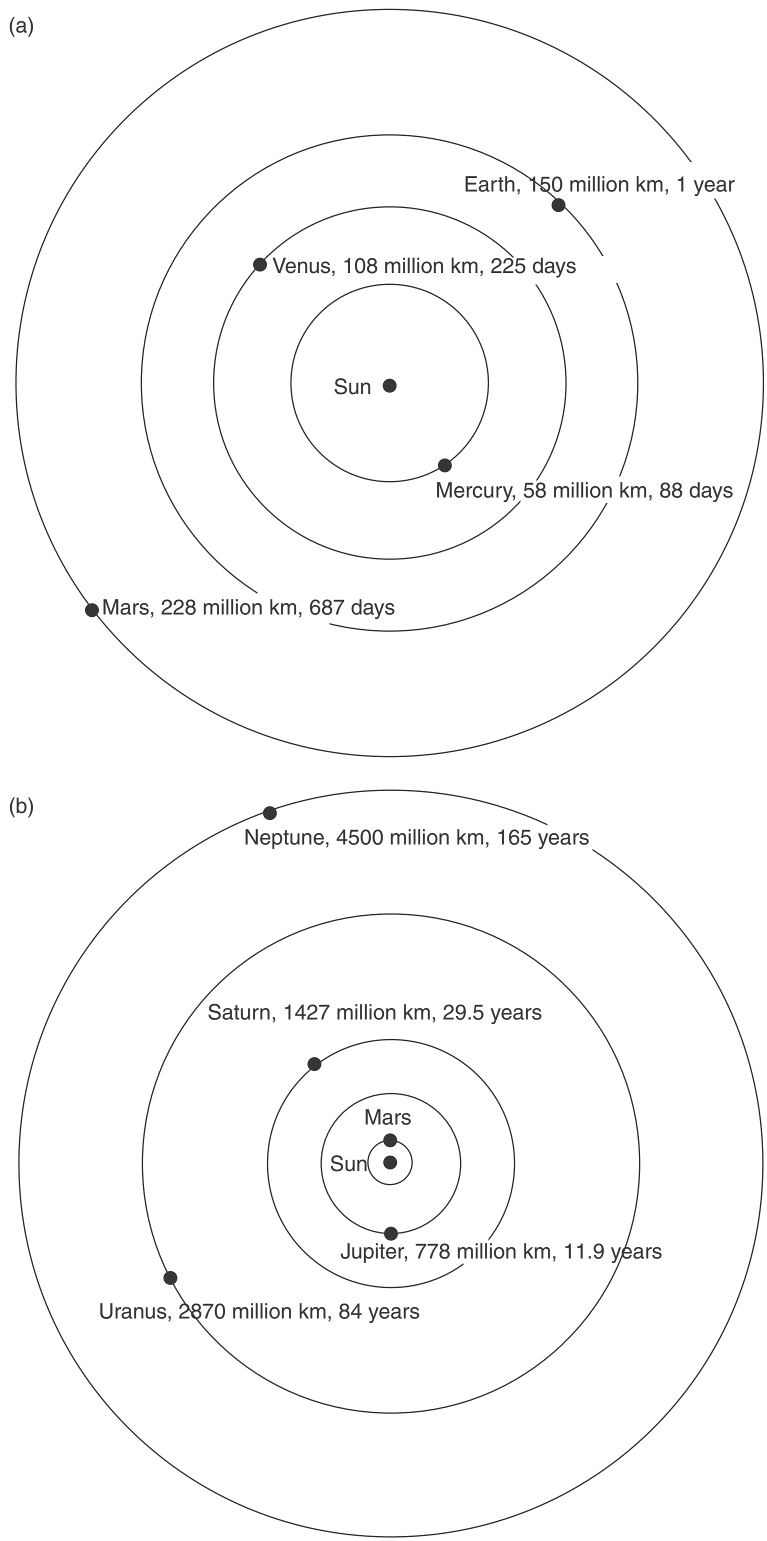


Figure 1.1 (a) The orbits of the inner planets;
(b) The orbits of the outer planets.

and so it is obvious that the Earth's density increases towards its centre. This is because the Earth is *chemically differentiated*, meaning that when the Earth was formed the lighter and more volatile substances rose to the surface while the heavier substances sank towards the its centre.

Seismographic studies have revealed that three distinct zones exist within the Earth. These are the *core*, the *mantle* and the *crust*. The core extends from the Earth's centre out to a radius of 3500 km and consists of two parts: a fluid outer core and a central solid core. The solid component has a radius of about 1250 km. The core is composed of iron and nickel, with some cobalt.

Over the core, extending out to a radius of about 6370 km, lies the mantle. It is mainly composed of silicates and is rather plastic in its mechanical nature. Overlying the mantle, with an average thickness of about 33 km, is the crust upon which we live. Radioactive decay, together with the heat left over from the formation of the Earth, causes the temperature to increase towards its centre. The temperature at the Earth's core is thought to be of the order of 5000°C.

The surface of the Earth is mainly composed of volcanic and *sedimentary* rocks. Sedimentary rocks are those deposited from an aqueous environment by any of various mechanical and biological mechanisms. Weathering, erosion and biological action turn these rocks into soils. Two-thirds of the Earth's surface is covered in water and most of this is saline.

A notable feature of this planet is that it is geologically active. Indeed, the very crust of the Earth resembles a huge broken eggshell with each of the pieces of shell floating on the mantle below it. These segments are called *plates* and the study of their movements is called *plate tectonics*.

Hundreds of millions of years ago there was just one major land mass above the level of the ocean. Since then tectonic activity, more commonly known as *continental drift*, has split this into parts and caused each to separate and spread over the Earth into their present locations.

Enormous forces build up at the boundaries between the crustal plates. Earthquakes are propagated along these *fault lines* when one plate slips against (or under, or over) another. Volcanoes are also active along fault lines.

The range of temperature that is experienced on the surface of the Earth is moderated by the blanketing effect of the atmosphere. Heat is retained during the night and the surface is shielded from the harshest of the Sun's rays during the daytime. The temperatures on the Earth range from a little below −50°C at night at the Earth's frozen poles to a little above +50°C during the hottest days near the Equator.

The sea-level pressure of the Earth's atmosphere is 101 325 N/m^2 (newtons per square metre). Air is a mixture of different gases. Its composition by volume is 78% nitrogen, 21% oxygen, with carbon dioxide and argon making up most of the remaining 1%. The lower portions of the Earth's atmosphere are also quite rich in water vapour.

There are traces of atmosphere hundreds of kilometres up but most of the mass of the air is concentrated in the first 10 km. As Figure 1.2 shows, the atmosphere can be divided up into distinct layers. These are marked by temperature variations. The lowest region is the *troposphere*, which is the region of weather.

The temperature of the atmosphere drops (as does the pressure) with increasing height until a region 12 km up, the *tropopause*, where the temperature levels off at about −60°C (with equator to pole variations – this figure also is subject to fluctuations over time). Cirrus clouds can extend up to a height of about 10 km.

Beyond the troposphere is the *stratosphere*, where the temperature begins to rise slowly until a region known as the *stratopause*, where the temperature levels off at about −40°C. It is in the stratosphere that most (about 90 per cent) of the atmospheric ozone is concentrated. Ozone is formed by chemical reactions between ionised atoms and molecules of oxygen. It is the short-wave radiations that the Sun sends us, along with the beneficial warmth and sunlight, which cause the ionisation of the normal molecules.

The stratopause lies at a height of 40 km and beyond this lies the *mesosphere*. In this region the temperature falls rapidly to a value of about −100°C or so at an altitude of 80 km: the *mesopause*. However, all of the foregoing temperatures are very much average values and are subject to seasonal and diurnal variations, as well as variations with latitude.

While all normal clouds reside below the tropopause, at the level of the mesopause a peculiar type of cloud exists composed of tiny ice crystals. These clouds are very tenuous in nature but can be seen from the ground at dusk from temperate latitudes during the summer months. This is because their height causes them still to be sunlit even when the Earth's surface and the tropospheric clouds have become submerged in the Earth's shadow. We call these gently shining night-time forms *noctilucent clouds*.

Above the mesopause lies the *thermosphere* where the temperature rapidly increases to somewhere around 1000°C at 600 km and then levels off in a region known as the *thermopause*. Finally, above the thermopause lies the *exosphere*, which consists mainly of hydrogen and extends to a height of about 5000 km where it merges with interplanetary space.

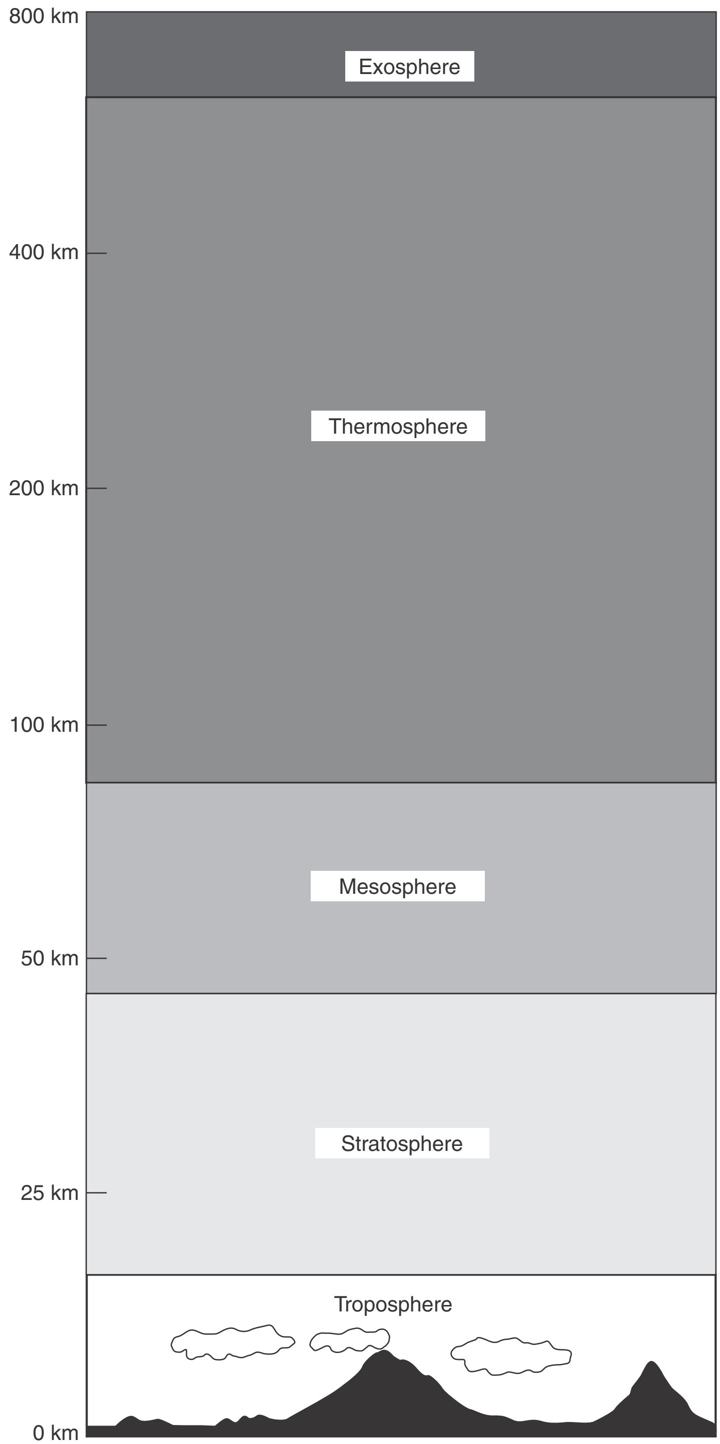


Figure 1.2 The Earth's atmosphere.

The short-wave radiations emitted by the Sun have the effect of ionising the rarefied gases in the upper atmosphere. The *ionosphere* is usually taken to exist between 80 km and 300 km above the Earth's surface, as a series of ionised regions and layers. These can reflect radio waves, so allowing radio reception far round the Earth's curved surface and much further from the transmitting station than would otherwise be the case. The gases above 300 km are also highly ionised but they are also extremely rarefied and so have less effect on radio waves.

1.2 THE EARTH'S MAGNETOSPHERE

The Earth has a magnetic field which is *dipolar* in form, like that of a simple bar magnet. As shown in Figure 1.3, the Earth's rotational and magnetic axes do not coincide. At present they are inclined at 11½° to each other.

The positions of the magnetic poles are not fixed but appear to be very slowly moving in a very roughly circular path. At present the north magnetic pole is moving westwards by about 0°.05 per year. In addition, the magnetic field is not constant in strength. It is currently decreasing

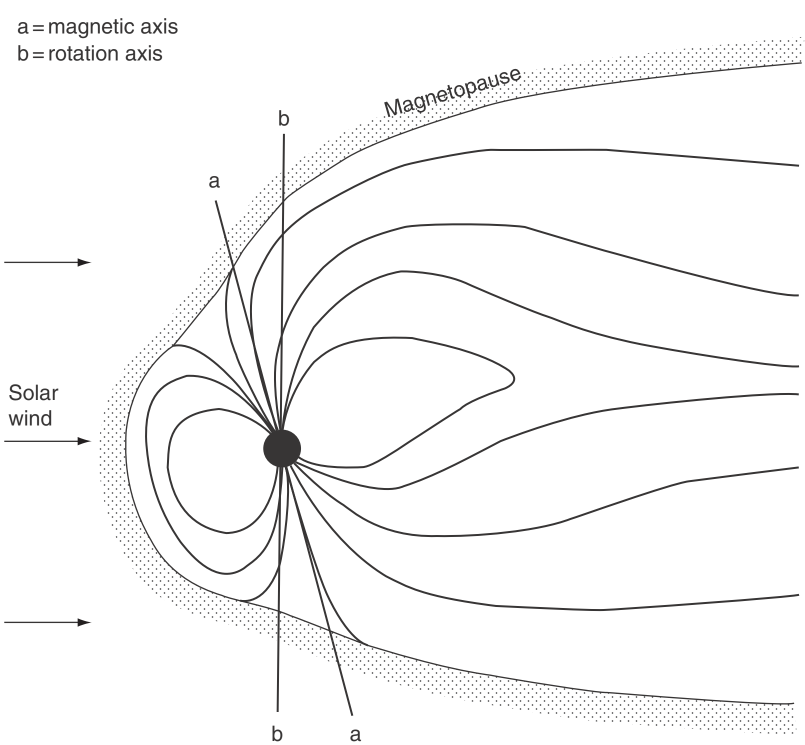


Figure 1.3 The Earth's magnetosphere.

at the rate of 1 per cent every 10 000 years. The Earth's magnetic field has even been known to reverse its polarity. This has happened several times in the past few million years, as revealed by studies of ferromagnetic rocks near the surface.

The terrestrial magnetic field is generated by a natural dynamo effect. The material of the Earth's core conducts electricity. Its churning motions, due to convection of the hot fluid and the spinning motion of the Earth, cause electric currents. These electric currents then generate the magnetic field.

As also shown in Figure 1.3, the Earth's magnetic field, or *magnetosphere*, is somewhat distorted on the large scale. The reasons for this are twofold. One is that the Sun has a very powerful and extensive magnetic field that extends outwards into the Solar System, interacting with the Earth's field. The other reason is that the Sun emits a stream of electrified particles that blow through the Solar System like a breeze: the *solar wind*. It is the fact that these particles are electrically charged that gives them the property of being able to distort the Earth's magnetosphere when they encounter it.

The Earth's magnetic field lines are flattened in the direction of the Sun and are extended in the antisolar direction. Near the Earth's globe its own magnetic field is strong and so it is only slightly distorted by solar interactions. However, the field strength decreases in accordance with an inverse-cube law and so the field strength at large distances from the Earth is low and the shape of the field is distorted much more.

At about 60 000 km from the Earth the magnetic-field lines no longer rejoin at the Earth's magnetic poles, this region being termed the *magnetopause*. Beyond the magnetopause lies a boundary layer where a large fraction of the particles from the Sun are deviated in their courses and pass round the Earth and out into the Solar System under the repulsive effect of the Earth's magnetic field. This layer is known as the *magnetosheath*.

However, some rather more energetic solar particles are trapped lower in the Earth's magnetosphere in two torroidal regions, the *Van Allen radiation belts*, named after James Van Allen who discovered them in 1958 as a result of experiments with rockets. They are depicted in Figure 1.4. The inner torus is filled with protons of energies ranging about 50 MeV (mega electronvolts) and lies at an average height of about 4000 km above the Earth's surface. The outer torus, which lies at an average height of about 17 000 km, is filled with electrons with energies ranging around 30 MeV. These energetic particles loop from end to end within the zones.

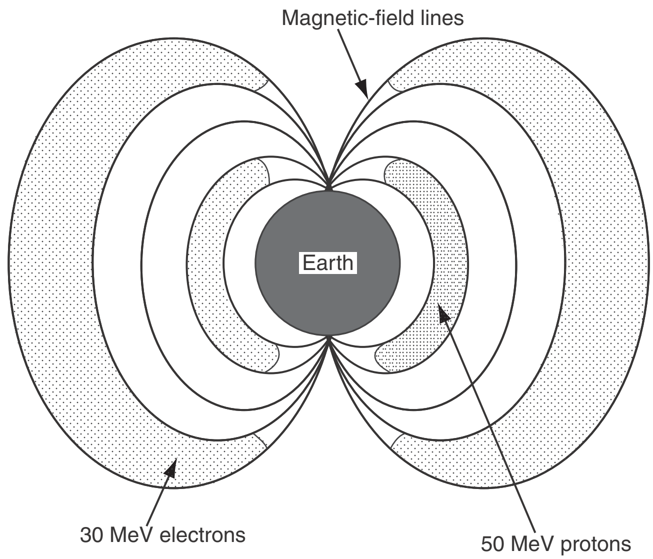


Figure 1.4 The Van Allen radiation belts.

1.3 AURORAE

Known since ancient times, *aurorae* take the form of beautifully coloured glows in the night sky. They are most often seen from far-northerly and far-southerly latitudes. In fact, they are visible on most nights from countries like Greenland and Alaska. They are least often seen from the equatorial regions of this planet.

The colours of the displays are chiefly shades of green and red, though yellow, blue and purple are sometimes seen. Most of the displays seen from temperate latitudes appear to the unaided eye as greyish-white because the auroral light is too dim to stimulate the eye's colour receptors.

A display may take the form of pulsating coloured glows in large, diffuse, patches of the sky, or perhaps just a steady glow. A major display may consist of ribbons and streamers of colour that pulsate and change their shapes in a matter of seconds. From mid-northern latitudes aurorae can sometimes be seen by looking towards the northern horizon, though town lights will completely swamp the effect. People living in mid-southern latitudes should look towards their southern horizon. The aurora concentrated toward the north pole is referred to as the *aurora borealis* – meaning 'northern dawn' – while that concentrated towards the south pole is called the *aurora australis* – 'southern dawn'.

The aurorae are caused by energetic solar wind particles finding their way into the Earth's inner magnetosphere. The precise details of the mechanisms that happen to allow this effect are still being investigated but certainly the most intense clouds of solar wind particles (erupted from the Sun by solar flares and coronal mass ejections – these terms are explained in Chapter 12) cause distortions in the magnetic field with field lines breaking and reconnecting. The normal protective sheath of the terrestrial magnetosphere is breached allowing the solar wind particles to enter. If you want an analogy, then it is a bit like powerful gusts of wind blowing open a door and allowing further blasts of wind to enter a dwelling. The solar wind particles spiral down the Earth's magnetic-field lines preferentially toward the poles.

The particles ploughing through the ionosphere constitute electrical currents that give rise to the coloured glows in the same manner as in the gases of the low-pressure fluorescent-tube discharge lamps so commonly used today. This is by particle collisions exciting electrons bound within gas atoms. On de-excitation the electrons re-emit the energy as photons of electromagnetic radiation – in other words light.

The gases causing the coloured glows are molecular nitrogen, atomic nitrogen, and atomic oxygen. The chief emissions originating in the atmosphere at heights below 100 km are from molecular nitrogen and these mostly produce red colourations. The strongest emissions in a display are normally produced by excited atoms of oxygen. These create green and red glows, originating mostly at heights above 150 km. In most displays it is the green light of oxygen that dominates. Sometimes purples glows are visible. Nitrogen is responsible for these, this time originating mostly at an altitude of the order of a thousand kilometres.

The probability of an auroral display happening, and the intensities of any displays that do occur, vary from year to year. This is because the Sun produces solar flares and coronal mass ejections with a frequency that also varies from year to year. There is much more about the Sun and how to observe it in Chapter 12, but suffice it to say here that the Sun's activity waxes and wanes with a period of about eleven years. It is at times of highest solar activity (actually often a year or so after the peak of the visible sunspot cycle) that auroral displays are at their most frequent and most spectacular.

The most spectacular auroral display I have ever seen was that of the night of 13/14 March 1989. At dusk on 13 March I was busy with one of the telescopes of the former Royal Greenwich Observatory at their Herstmonceux site. At one point early on I left the dome and noticed a peculiar glow along the northern horizon, like a row of searchlight beams fanning upwards. As I watched I could see the glow wavering slightly and changing in brightness.

I had observed the Sun earlier that day and had noted its high activity (it was then close to the time of maximum activity in its cycle). I realised what was happening and alerted the only other observer on site at that time, Peter Strugnell, who was preparing to operate the satellite-tracking camera in another dome. We climbed onto the roof of an adjoining building between two domes and watched and photographed as an

Figure 1.5 The brilliant auroral storm of 1989 March 13^{d} photographed by Peter Strugnell and the author. Peter's camera happened to be loaded with 100 ISO colour-print film (Kodak Gold 100) and 30 second exposures were made during the course of the display. The camera was fitted with a 35 mm focal length lens, set to f/2.4. This is looking east and the brightest star visible just above the dome is Arcturus. Notice the tropospheric clouds silhouetted against the bright auroral light visible in the lower left of this picture. [This image is also reproduced in colour as PLATE I (upper), between pages 304 and 305].

amazing auroral display unfolded (see Figure 1.5). At times, vast arches of blue-green light pulsed low down in the north, with upward shafts and wavering curtains of light becoming yellow higher up and finally a rich vibrant red extending to the zenith.

The display continued, showing amazing variations. For instance, at one point the whole sky became a vivid red colour and the scene around us became quite unearthly. At another point later in the display a white patch formed at the zenith, which then broke into moving ripples at the same time as tickertape-like darts of light formed in the south. The telephone lines to the observatory became jammed with callers and that aurora became an international news story. It was an awesome experience and yet it is rare to see the aurora at all from southern England.

1.4 VISUALLY OBSERVING AURORAE

The best way of ensuring that you know that an aurora might happen or is happening is by belonging to the aurora observing section of a national astronomical society. More about that in Section 1.12. The following websites may also be of use:

Aurorae	www.sec.noaa.gov/Aurora
Space Weather	www.spaceweather.com
Solar Terrestrial Dispatch	www.spacew.com

One basic piece of equipment is useful for all your visual observing – whether it is for observing aurorae or anything else – and that is an illuminated notepad or drawing board. You should be able to fashion something from the following materials: a small piece of hardboard, or a large stiff dinner mat; a switch; a torch bulb and holder; a small square box (to mount the bulb in its holder at the head of the board) made of metal, plastic, wood or even stout cardboard; some wire; a battery (perhaps mounted on the board by means of a Terry-clip) with terminal connections (or soldered joints).

Adding direct shielding from the bulb is also desirable and a small rheostat is also useful for brightness control. A red filter mounted over the bulb or across the front of the lamp housing will help preserve your dark-adaption. There is no need for anything elaborate. Most important is that it is handy and lightweight.

The Moon was in the sky during the great auroral storm of 1989 but the brilliance of this display made the moonlight pale into insignificance. Most aurorae visible from temperate latitudes are much feebler affairs. Normally you will require a dark sky well away from light pollution to have any real chance of successfully observing any aurorae that may be visible from time to time at your latitude. Unless you are lucky to live in a dark rural location you will have no choice but to travel to a dark site to do your aurorae patrolling and observing.

Whenever you intend to spend any significant time outside at night, whether for observing aurorae or anything else, please do dress appropriately against the cold. An uncomfortable observer is an inaccurate observer. Also feeling uncomfortably cold will extinguish the pleasure of your observing experience. It is also true that hypothermia can creep up without one fully realising it and the result of that can be fatal. Please do be careful.

In the coldest weather I put on an extra pair of thick woollen socks, sometimes an extra pair of trousers, a Balaclava **and** a thick woollen hat, in addition to the rest of the heavy clothing you would expect me to wear. I may look a silly but I enjoy feeling warm and comfortable as I walk across my lawn even when it is frozen as hard as concrete!

If you have to drive to a remote site to get a good view to the north free from artificial lights then it is a good idea to take with you a thermos of hot drink and maybe even a light snack. Don't forget to pack your torch and any other equipment you desire for your observing run. Perhaps it would be safest also to pack a sleeping bag just in case your car lets you down and you have to spend the night far from home. At the very least you should take a mobile phone with you. Be warm. Above all, be safe!

Make sure that you have a watch or other timepiece that is accurate to the nearest quarter minute and that you have a pen, pencil, and spares of these, and maybe an eraser, easily to hand. You might as well make yourself comfortable by sitting in a 'foldaway' lightweight chair to do your observing. Laying in a sleeping bag on a sunbed may be better in the coldest weather. A 'foldaway' small table will also prove useful.

Each auroral display is different but there are a small number of primary forms the auroral glows can take. A given display will have one or more of these forms as dominant features at any one time, often with significant changes in the relative dominance and shapes of the features as the display unfolds.

The six basic forms are *glow*, *patch*, *arc*, *band*, *ray* and *corona*. They are given the shorthand symbols *G*, *P*, *A*, *B*, *R* and *C*, respectively. The term *veil*, symbol *V*, is used for a weak background glow extending across almost the entire sky. This is only rarely noticeable. These basic forms can be modified by structure in ways described as: *homogeneous*, *rayed* or *striated*. Bands and arcs can be either homogeneous or rayed. A striated structure usually only manifests in wide bands seen high in the sky. The eight most common combinations of form and structure are illustrated in Figure 1.6. They are also briefly described as follows:

Glow (G)	This is a dawn-like glow extending upwards from the horizon. In this case, though, the glow appears due north for the aurora borealis. The light area does have to extend all the way down to the horizon for the term glow to be the correct one to use. See Figure 1.6(a).
Patch (P)	This is a cloud-like area of light. The boundaries of patches tend to be diffuse. Tropospheric clouds will show up as dark against an auroral glow, the opposite of genuine auroral patches. See Figure 1.6(b).
Homogeneous arc (HA)	This is an arch-like form of light, of reasonably even radius of curvature, spanning the north-eastern to the north-western sky. If the curvature sharply changes anywhere along its length then it is regarded as a band, rather than an arc. See Figure 1.6(c).

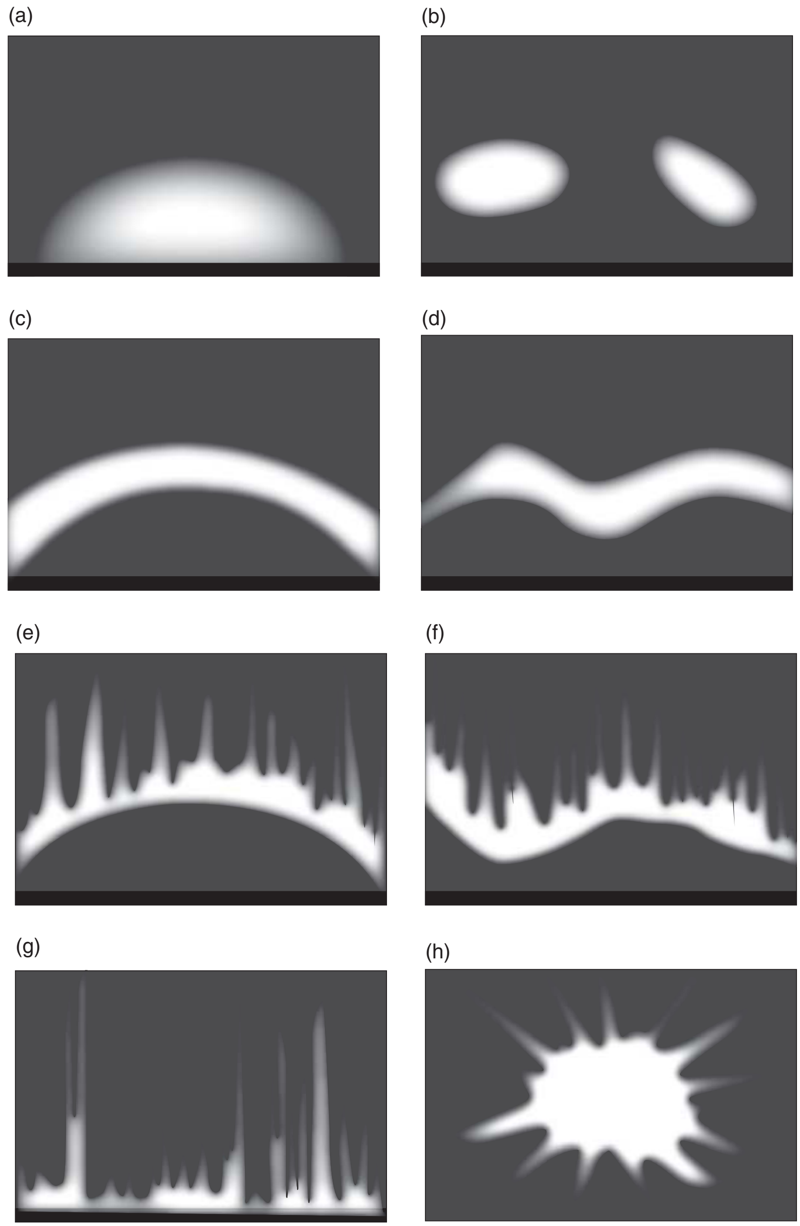


Figure 1.6 The most common combinations of auroral form and structure:
(a) glow;
(b) patches;
(c) arc;
(d) band;
(e) rayed arc;
(f) rayed band;
(g) rays; and
(h) corona.

Homogeneous band (HB)	This a wide ribbon of light, with one or more changes of curvature along its length. The band might even fold back on itself in places. See Figure 1.6(d).
Rayed arc (RA)	This is an arc which is the root for one or more upwardly extending shafts and/or spires of light. See Figure 1.6(e).
Rayed band (RB)	This is a band which is the root for one or more upwardly extending shafts and/or spires of light. See Figure 1.6(f).
Rays (R)	These are upwardly extending shafts and/or spires of light. See Figure 1.6(g)
Corona (C)	Meaning 'crown', a corona is formed when rays converge at the zenith, often blending to produce a bright area of light. See Figure 1.6(h).

The aurora observing section of your national astronomical society will be glad of any observations of aurorae you can submit. These might be in the form of a description, maybe with sketches or photographs. The most serious aurora observers use a standard shorthand format to record the appearance of the aurora at given times. This format is:

condition/qualifying/structure/form/brightness/colour

Each of these components is itself described by the choice of a code. The following codes are for each of the components (we have already discussed some of these):

Condition

q 'Quiet' – static appearance; no movement or changes.
a 'Active' – changes happening.
a1 Folding of bands.
a2 Rapid changes of shape of lower parts of glow.
a3 Rapid shifting of rays horizontally.
a4 Auroral shapes fading, other forms rapidly replacing.
p1 Pulsations affecting much of the auroral form.
p2 'Flaming'. Upward moving surges of brightness.
p3 'Flickering'. Very rapid irregular brightness changes.
p4 'Streaming'. Irregular variations in brightness horizontally.

Qualifying

m 'Multiple'. More than one group present of a stated form.
f 'Fragmentary'. Only one part of a standard auroral form visible.
c 'Coronal'. Convergence of rays resulting in a corona.

Structure

H ‘Homogenous’. Appearing uniform in shape and brightness.
S ‘Striated’. A pattern of light and dark lines visible.
R1 Short-length rays visible.
R2 Medium-length rays visible.
R3 Long rays visible.

Forms

G ‘Glow’. Brightness extends upwards all the way from the visible horizon. If the glow does not extend all the way down to the horizon then this descriptive term and code is not to be used.
A ‘Arc’. Uniformly curved arch-like band of light.
B ‘Band’. Like an arc but irregularly curved.
RA ‘Rayed arc’. Rays extending upwards from an arc.
RA ‘Rayed band’. Rays extending upwards from a band.
V ‘Veil’. Vaguely defined glow across much of the sky.
P ‘Patch’. An isolated cloud-like pall of light.
C ‘Corona’. Overhead convergence of rays into a pool of light.
N Shape of glow does not conform to the other defined types.

Brightness

1 Barely visible to the unaided eye.
2 Definitely visible but not particularly bright.
3 Bright.
4 Glow from aurora brilliant enough to cast shadows on a light surface (very rare in temperate latitudes).

Colour

a Red appearing in upper part of aurora.
b Red appearing in lowest part of aurora.
c Green, and/or yellow, and/or white.
d Red.
e Red appearing with greens.
f Blue and/or purple as the dominant colour.

As an example, if at a certain moment I saw a uniformly curved arch of pale bluish-green light extending from the north-east to the north-west, from which upward spikes of green light extended, the whole effect brightening erratically, with the brightness surges extending upwards in an effect reminiscent of what happens when somebody pokes a fire in a grate, then I would record the following against the date and time of the occurrence: p2/R1/RA/3/c.

If more than one distinct form of auroral activity is visible at any one time then separate entries should be made, each on its own line of your report form.

To do the job properly a new code should be entered with every change of the aurora, alongside the specific time that it had that appearance, going right through to the end of the observing session. Otherwise recording the appearance every 5 minutes would also be satisfactory.

The details and data you record could be entered onto a standard report form issued to you by the aurora observing section of the society you intend submitting your observations to (more about joining astronomical societies in Section 1.12).

Simple sketches are also valuable and on these you could mark other details such as the *altitude* and *azimuth* values of specific features of the display. These specific features could commonly be the highest point of the lower edge of an arc or the highest point of a ray, etc.

Altitude in this context refers to the angular distance of the feature above the horizon in degrees. The span of your wide-stretched hand from the tip of the thumb to the tip of the little finger spans about 10° when you hold your arm out straight in front of you. You could use that to help you make your estimate. Azimuth is measured around the horizon from true north (0°), increasing eastwards to 90° at due east, further increasing to 180° at due south, then to 270° at due west and further increasing to 360° (equal to 0°) once again due north.

Finally, make sure that your report also carries information on your own location, preferably including the latitude and longitude of your observation site each correct to the nearest degree.

1.5 OTHER METHODS OF OBSERVING AURORAE

A modern digital camera capable of exposures of at least a few seconds will be good enough to capture photographs of all but the faintest auroral displays. Best of all would be to use a *digital single lens reflex* (*DSLR*) camera fitted with a fairly wide angle lens. For the best results the camera should be mounted on a tripod and operated by a cable release. The camera lens should be set at its lowest f/number setting.

With the ISO set to 400 or above (the 'ISO' number indicates photographic speed/sensitivity), a ten to twenty second exposure will capture at least everything that can be seen with the naked eye and maybe a little more besides. Certainly the images will show colours in the faintest auroral forms that look merely greyish-white to the eye.

If you know the angular extent of the field of view of your images and you are precise about the pointing of the camera then you can use your images to work out the azimuths and altitudes of specific features of the auroral forms you record. As always when reporting astronomical observations be sure to include all relevant details, including the times of the beginning of the exposures to the nearest minute and the length of each exposure, details of the camera, its lens, and the observing conditions.

Since visible aurorae are chiefly formed in the ionosphere, you might imagine that auroral activity would affect radio propagations that rely on atmospheric reflection – and you would be right! A few readers of this book will undoubtedly be 'radio hams' and will need no instructions from me on their craft. Most readers will not want to get involved in this specialist activity. So, can I just say that those who might be interested can observe the effects of aurorae on radio propagation and leave it to them to investigate this subject further. The same goes for observing the radio effects of the ionisation trails produced by meteors.

Another specialist area is *magnetometry*, the monitoring of local disturbances to the Earth's magnetic field. Aurorae are a prime cause of such disturbances. It is possible to build your own magnetometer and many have done so. Lack of space demands that I must leave you to research this field for yourself if it interests you. For the same reason I must deal with the important, though minority-interest, subject of noctilucent clouds in the same brief manner . . .

1.6 NOCTILUCENT CLOUDS

The basic techniques for visually observing and photographing aurorae can also be used for studying noctilucent clouds. As before, a standard report form should be obtained and filled in according to the scheme devised by the form's originator. The data must include: the position (latitude and longitude) of your observing site, the date, time, azimuths, elevations, brightness, structure and observing conditions. Photographs are especially valuable.

1.7 DATES AND TIMES IN YOUR OBSERVATION REPORT

One can take time out to enjoy the sight of a starry sky or a celestial body through the telescope just for fun. Indeed, if you deprive yourself of this activity you will lose out on a big source of enjoyment. Once you consider doing anything serious, though, then making notes becomes a crucial part of observational practice. Routinely, your notes should include the date, time, atmospheric conditions and any other factors which affect, or otherwise have any bearing on, the observation.

Times should always be in UT (Universal Time), which is the equivalent of GMT (Greenwich Mean Time). Strictly this is UTC (Co-ordinated Universal Time), though you can take this to be the same as UT. There are other time systems you might come across but I don't propose going into any of them here. Record your observations in UT and you will be conforming to the standard adhered to by the rest of the astronomical community.

When making rough notes during the observation period you can record the time in whatever is in current operation at your observation site (Zone Time, maybe including Daylight Saving Time, etc.) if that proves easiest but you should always convert times to UT when making up the 'proper set' of notes after the observing session.

Sometimes the co-ordinator/director of whatever organisation you send your observational reports to will require you to enter the double date for the observing session, especially where your observation spans 0 hours UT ($\equiv$ 24 hours UT = midnight GMT); for example 2010 March 16/17. You should always provide your data in whatever format the co-ordinator/director wishes as he or she has the often mammoth task of collating and combining the observations of all the contributors.

Otherwise a strict adherence to the standard astronomical format of dates and times in UT will be sufficient to avoid possible confusion. The normal form is: year/month/day/hours/minutes/seconds expressed in the format (using a hypothetical example):

2012 April 19^{d} 23^{h} 45^{m} UT.

An observation that spans midnight Universal Time might be represented in the following ways:

2012 April 19^{d} 23^{h} 45^{m}–April 20^{d} 00^{h} 08^{m} UT,

or alternatively:

2012 April 19^{d} 23^{h} 45^{m}–24^{h} 08^{m} UT.

Firstly, note the use of the raised d, h, m, and s for days, hours, minutes, and seconds. Secondly, note the inclusion where necessary of zeroes in the first of a pair of digits (for hours or minutes) – a practice intended to minimise confusion or errors. Finally, note in the second example the use of times running beyond 24^{h} 00^{m} UT, in order to avoid changing the date. However, it is the format used in the first example which is normally preferred. The observational report for that night might well be given a heading like 'Visual Observation of Jupiter 2012 November 19/20', then listing the equipment used and the observing conditions, then going on to list times in the preferred format against notes of the details observed.

1.8 A CELESTIAL MENAGERIE

I am sure everybody reading these words will already know that the Sun is the massive orb around which the planets orbit. Mercury orbits closest to the Sun, Venus further out, then our Earth, beyond that Mars, then Jupiter, Saturn, and Uranus. The outermost of the major planets is Neptune. The Sun, these planets, their moons and a whole host of minor bodies go to make up the dynamic entity we call the Solar System.

Once the scientists of the sixteenth and seventeenth centuries had established that the Moon and planets orbit the Sun, rather than the Earth as had been previously believed, some were struck by the apparent large gap between Mars and Jupiter. It was almost as if there should have been a yet-to-be-found planet orbiting between these worlds. In 1766, Johann Titius even came up with a simple arithmetic rule that seemed to fit the sequence of known planetary orbits – and predicted a planet should exist orbiting between Mars and Jupiter. Few took any notice of Titius at the time. Johann Bode revisited the issue and, in 1772, also produced a numerical sequence using a 'law' only slightly modified from that of Titius. He also asserted that an undiscovered body must orbit between Mars and Jupiter. When Uranus was discovered in 1781 it also seemed to obey 'Bode's Law', prompting renewed speculation about the 'Bode Gap' between Mars and Jupiter.

A group of German astronomers instigated a practical search for the supposed missing world, enlisting astronomers in other continents to their cause. They became known as 'The Celestial Police'. The first of a new class of small rocky orbs, known either as *asteroids* or *minor planets*, were discovered at the beginning of the nineteenth century. As it happened, the first discovery was not made by a 'Celestial Policeman' but the next ones were. Subsequently, many more asteroids were discovered by others, especially after the advent of astronomical photography. The current discovery rate is tens of thousands every year and the discovered asteroids now number well over half a million.

Until late in the twentieth century we regarded the region between Mars and Jupiter as the main domicile for these small rocky bodies. Then discoveries were made which showed them also to thickly populate several zones further out, including a region known as the *Kuiper Belt* well beyond the outermost major planet Neptune. The most distant asteroids seem to be composed mostly of ices while those further in appear to be mostly rocky in nature. I take up the story of asteroids along with how to observe them in Chapter 10.

Theoretical scenarios of how the Solar System formed all start with a cloud of gas and dust collapsing under its own self-gravitation. Instabilities and vortexing during its inward collapse instigated a rotation, which was assumed by the whole cloud (though the rotation rates varied with radius from the centre – this being called *differential rotation*).

The cloud then flattened (particularly so in its innermost regions) and a central hub of matter formed which eventually became the Sun. The material in the flattened disk extending outwards from the Sun eventually collected and coagulated under self-gravitation to form the planets. It is because of the pre-planetary disk that all the major planets orbit the Sun in the same plane and all orbit in the same direction.

Modern dynamical models run on a super-computer suggest that the detailed scenario of the Solar System's formation is actually rather complex. It seems that the major bodies, once formed, could migrate thanks to complex gravity-driven interactions. This contrasts with our older, and perhaps naive, view that the planets were born into pretty much their current orbits.

The early Solar System was undoubtedly a highly chaotic place with objects forming and some even smashing into others. Theoretical models also predict that the formation of the most massive planets, especially Jupiter, inhibited the subsequent building of larger planets from the merging of numerous thousand-ish kilometre sized *planetesimals* in a zone inside the giant planet's orbit. Further, many of these planetesimals smashed together, fragmenting to create the vast population of asteroids we see today.

The first definite examples of planets orbiting other stars, known as *exoplanets*, were discovered in 1995. As I write these words, we know of hundreds of examples and new discoveries are being made at an ever accelerating rate. The first example of major collisions in a newly formed planetary system was discovered in 2009. The star concerned, HD 172555, lies about a hundred light years away. Though the collision could not be seen directly, theoretical modelling based on spectroscopic evidence suggests that a Moon-sized planetoid smashed into a Mercury-sized planet splashing hot debris across the system. HD 172555 is reckoned to be about 12 million years old and theory suggests such collisions are commonplace in young planetary systems.

Returning to our own planetary system, the ancients knew of the Sun, the Moon, Mercury, Venus, Mars, Jupiter and Saturn. Uranus was discovered in 1781 and the first of the asteroids was discovered in 1801. Then came the discovery of Neptune in 1846. Pluto was first recorded in 1930 as a result of a hunt for another major planet orbiting beyond Neptune. Now, though, we regard Pluto merely as a particularly large asteroid of the *Trans-Neptunian Object* (*TNO*) type (the orbit of a TNO lies close to, or crosses, that of Neptune). Under new rules issued by the International Astronomical Union, Pluto, Ceres and several other large objects we know of in the Kuiper Belt are now known as *dwarf planets*. By the spring of 2009 we knew of five dwarf planets but be aware that others might have been discovered by the time you are reading these words.

There is one other type of Solar System body that occasionally appears in the sky. This type of body was known to the ancients but was not properly understood until relatively modern times. Of course, I am referring to comets.

You might remember the spectacular comets of 1996 (Hyakutake) and 1997 (Hale-Bopp). Great comets such as those are rare. Most comets would pass unnoticed without some optical aid. Now we understand that the major part of a comet is a filmy mass of gas and dust so tenuous that in ordinary conditions it would be regarded as a vacuum. This envelope of dust and gas can sometimes extend over millions of kilometres. The source of this tenuous material is a small body, perhaps only a few kilometres across even in the large examples, made of ices and some more refractory materials. This body, the comet's *nucleus*, has been figuratively described as a 'dirty snowball'. I have a great deal more to say about comets and how to observe them in Chapter 11.

1.9 METEORS, METEORITES AND METEOR SHOWERS

To some extent, mutual collisions between asteroids continue to this day, supplying the Solar System with fresh dusty and grainy material. Some of this matter intersects the orbits of the planets. The smaller fragments burn up in planetary atmospheres as 'shooting stars' or, more properly *meteors*, while those large enough survive as *meteorites*.

Meteorites can be divided into three main classes, according to their compositions. The first are *siderites* – these are roughly 92% iron, 7% nickel and contain traces of cobalt and other minerals. The second class is the *lithosiderites* – containing mineral and metallic elements in various proportions. The third class is the *stony meteorites*. Most of the collected meteorites are of the lithosiderite variety.

Each of these types has now been subdivided into specific subtypes categorised by their chemical compositions. Actually, I should say that the terms siderites and lithosiderites have now largely gone out of fashion and meteorites are now mostly just known by their subtypes. Unfortunately this system is complicated and it would need many pages for me to explain things in detail – and this is not a book about meteorite taxonomy. Suffice it to say here, though, that there are six broad chemical classifications: *carbonaceous chondrites*, *ordinary chondrites*, *enstatite chondrites*, *stony irons*, *achondrites* and *irons* – with each of these in turn subdivided into further subtypes – and all denoted by a complicated system of numbers, letters and names.

The carbonaceous chondrites and ordinary chondrites are the most primitive materials and are thought to be relatively unprocessed since the birth of the Solar System. The other types are more chemically differentiated; various processes have operated on them during the history of the Solar System and particularly within the parent body of which they once were part.

Clearly, most of the meteorites that land on Earth originate from the asteroid belt. Whether ejected from the *Main Belt* (that orbiting between Mars and Jupiter) by a mutual collision, or by the orbit of the body becoming unstable owing to one-too-many tugs from Jupiter, or already in an orbit that brings it perilously close to the Earth's gravitational influence, somehow the body does find its way to Earth. The result is we get to study the materials that make up some asteroids first hand. I will not discuss hunting for meteorites in this book – but at least I can point you in the direction of a book that does cover this topic: *Field Guide to Meteors and Meteorites* authored by Richard O. Norton and Lawrence A. Chitwood and published by Springer-Verlag in 2008.

Micrometeorites continually rain down on the Earth. These are tiny granules, the largest of which are smaller than grains of sand. They are easiest to find deep on the ocean bed or in places like Antarctica, simply because they can lie undisturbed for thousands, or even (when frozen in ice) millions of years. Their extraterrestrial origin can be established by laboratory determinations of the ratios of certain isotopes they contain.

'Meteor' is the term for the visible effect of a particle burning up in our atmosphere. While the particle is in space before being swept up by our atmosphere it is properly known as a *meteoroid*. The speed at which a meteoroid enters the atmosphere can be as high as 70 km/s. Below a height of about 150 km the atmosphere is dense enough to reduce the speed of the particle, so converting its kinetic energy to heat energy. The temperature of the particle rises to thousands of degrees as a consequence. The high temperature causes ionisation of the air and it is this that produces the brilliant light – the meteor – which is visible from the ground.

A meteoroid the size of a grain of sand is enough produce a visible shooting star, and one with a mass of a gram will create one that flares as bright as the brightest (zero-magnitude) stars in the sky. A pebble-sized meteoroid will result in a brilliant fireball accompanied by a bright flaring trail that persists for several seconds. Some of the brighter meteors are distinctly coloured and many pulse, or 'sputter', in

Figure 1.7 A bright Perseid meteor captured by Nick James with a fixed camera fitted with a 50 mm lens. The film was Kodak Tri-X (nominally 400 ISO). Several small flares are evident in this photograph before the meteor reached magnitude -6^{m} (which qualifies it as a *fireball*) in its terminal burst. Several of the bright stars of Cassiopeia are also visible. The star trails appear slightly broken because of occasional interruptions by passing clouds during the 16-minute exposure taken on 1980 August 12^{d} 02^{h} 50^{m} UT.

brightness before they are extinguished (see Figure 1.7). Meteors that appear brighter than magnitude -5^{m} (the planet Venus is magnitude $-4^{m}.4$ when at its most brilliant) are rare occurrences technically known as *fireballs*. Some fireballs are seen to explode, rather than simply fizzle out, and these are termed *bolides*.

Fireballs and the brighter meteors leave *trains* which can persist for several seconds. Please note that a 'train' persists after the meteor itself is extinguished. Even quite faint meteors have *trails*, which is the normal luminous track extending behind the bright head of the meteor as it dashes across the sky. Only when that track persists after the demise of the meteor is it then known as a 'train'.

Some meteors appear singly and from any direction in the sky. These are termed *sporadic meteors*. They also occur in distinct shoals and these are termed *shower meteors*. In the case of shower meteors, the particles producing the shower are spread around an elliptical orbit around the Sun and the Earth then intersects the stream of particles once a year to produce an annual *meteor shower*.

There are many such showers that occur with great regularity each year. Since the particles of a given shower will be entering the Earth's atmosphere in approximately the same direction, they appear to emanate from a very definite patch of sky, termed the *radiant*. This is purely a perspective effect. The particles of the shower actually all enter our atmosphere parallel to each other.

Now, this radiant actually shifts about a degree per day either side of the date of main shower activity. However, the location of the radiant on the date of maximum activity is used to name the shower. For instance, the shower that occurs annually between 27 July and 17 August has its radiant in the constellation of Perseus when the shower activity is greatest and so this shower is known as the Perseid meteor shower.

That is not to say that the meteors all appear in this constellation but rather that if all of the directions of the meteors are plotted on a star map and produced backwards, then all the tracks appear to intersect closely in a patch of sky within Perseus. The other annual showers are each denoted by the name of the constellation in which the radiant lies on the date of shower maximum. Thus the shower that occurs between 15 October and 25 October is known as the Orionid – and so forth. Not all the annual showers are as intense as one another.

The characteristics of the meteors of particular showers vary quite considerably from each other. Some showers, like the Taurids of late October through to late November, produce slow-moving meteors. Others, such as the late April Lyrids, produce meteors which rapidly streak across the sky. Some showers are rich, while others consist of just a small number of meteors to be seen during a given night.

Also, showers of a particular annual display may, in some cases, be different in richness (the number of meteors falling in a given time) from one year to another. For instance, the Perseid shower tends to produce a steady stream of meteors from year to year. This indicates that the material that gives rise to this shower is evenly spread around its orbit. However, in the case of the Leonid shower, the activity varies quite considerably from one year to the next. In this case the material is bunched up in certain places around the orbit. Figure 1.8 shows a photograph taken by Nigel Evans of the particularly vigorous display of the Leonid meteor shower in 1999. His photograph clearly shows the convergence of the meteor tracks towards the radiant in Leo.

As a consequence of the rotation of the Earth, meteors are roughly twice as common and rather faster moving in the hours after midnight than in the hours before. Before midnight, a particular location on the Earth's surface is on the 'trailing face' of the Earth and the meteors have to 'catch Earth up', so to speak. After midnight, Earth meets the meteors 'head-on'.

I mentioned that asteroidal collisions are a source of meteoroids. Actually, so are comets. Indeed, it seems that the vast majority of annual meteor showers have either past or still-existing comets as their

Figure 1.8 The Leonid meteor shower photographed by Nigel Evans during a particularly strong maximum of 1999 November 18^{d} from the Sinai Desert. Nigel used a 200 mm lens on a DSLR camera fitted to a driven equatorial mount. This photograph is a mosaic of seven frames, each containing from one to three meteors, spanning 01^{h} 19^{m}–02^{h} 46^{m} UT. Thirteen meteors all emanate from a point about 10^{h} 15^{m} right ascension and +21°.7 declination.

originators. The Geminid meteor shower is unusual in that it is definitely linked to a very small asteroid called Phaethon. However, Phaethon may very well be the rocky remnant of a one-time large and icy comet nucleus.

It can be argued that the link between meteor showers and comets was first established thanks to the behaviour of a particular comet recovered by Captain Wilhelm von Biela in 1826. This comet was first discovered in 1772 by Charles Messier and had a period of 6.7 years. It was a totally unremarkable object and many of its subsequent returns were missed.

Friedrich Bessel predicted that this object should appear again in 1826. Bessel alerted many of his contemporaries, including Biela. Biela was first to recover the object, on 27 February 1826. From careful observations he also confirmed its period and it became known as Biela's Comet. It was one of the *Jovian family* of comets, meaning that the comet had been previously 'captured' by the gravitational field of the planet Jupiter and its original path had been altered.

The comet was recovered again on its next apparition in 1832. Conditions were unfavourable for its next return, in 1839, and so it was missed. It was predicted to next reach *perihelion* (closest point in its orbit to the Sun) in 1846 and it was recovered again near the end of 1845. However, astronomers received a shock – they saw two comets flying side-by-side through space! The amazed astronomers watched the comet throughout its apparition and eagerly awaited its next return.

In 1852, it, or rather they, were recovered once more. The distance between the comets had increased.

Having realised that the original comet had split into two pieces, astronomers eagerly awaited the next returns. Nothing was seen in 1859 but the conditions were very unfavourable. The situation was very much better in 1866 – but still nothing was seen. Still no Biela's Comet(s) in 1872. However, something did occur on November 27 that year: a spectacular meteor shower.

November 27 was the date that astronomers had calculated that the Earth would pass through the orbit of Biela's Comet. This confirmed the widely held suspicion of a link between meteor showers and comets. It was reasoned that debris shed by a comet would spread around its orbit. If the Earth intersected the comet orbit then the particles would produce shooting stars when they entered the Earth's atmosphere. Over the years, the shower has lost its vigour but a few Bielid meteors may still be seen in late November every year.

We now realise that Biela's Comet strayed too close to the planet Jupiter in 1842 and was disrupted by the strong tidal forces. Clearly, the nucleus of the comet was, at best, very weakly bound. This may be the case with many comets. Many others have since been seen to split into two or more pieces.

Even comets that do not completely break up shed material – and this material becomes spread around the comet's orbit. If the Earth's orbit intersects that of the comet then the Earth's atmosphere will sweep any cometary meteoroids present to form meteor showers. For instance, the Leonid shower, in mid-November each year, is associated with the comet known as 55P/Tempel–Tuttle and the Aquarid shower of May is associated with the famous Halley's Comet. Another example is the Draconid meteor shower in mid-October. Little is seen of these meteors except in years when the parent comet – known as 21P/Giacobini–Zinner – is near perihelion and, at the same time, near the Earth. For more about this you might like to refer to the book *Meteor Showers and Their Parent Comets*, written by Peter Jenniskens and published by Cambridge University Press in 2006.

There is a weak glow visible after dusk and before dawn that appears as a cone of light, widest near the horizon, and inclined along the line of the ecliptic. It is obvious in very dark and crystal-clear conditions but the slightest presence of haze and any light pollution is enough to completely swamp it. This glow is known as the *zodiacal light*. In exceptionally good conditions this glow, extending from both east and west horizons, meets at a point in the sky antipodal to the Sun. Here it forms a large and extremely tenuous glow called the *gegenschein*. I have seen the zodiacal light only occasionally and always imperfectly. I have never seen the gegenschein. This glow is caused by the dust shed from comets illuminated by sunlight in interplanetary space. Until recently, sunlit asteroidal dust was also thought to be responsible for the zodiacal light but modern dynamical studies have ruled out any major contribution from this cause.

1.10 VISUALLY OBSERVING METEORS

The first step is to obtain some knowledge of what showers are active on a given night and where the radiants for these showers are in the sky. There are published ephemerides (tables of positions, or other physical quantities, for given dates) that you could consult, such as the *Handbook of the British Astronomical Association*, issued free to members. An online resource, active at the time of writing, I can recommend is at www.namnmeteors.org. This provides a listing with notes of all major and many minor meteor showers, including the dates of the active periods, date and positions of the radiants at maximum and the daily drift of the radiant's co-ordinates, the velocities of the meteors, and the predicted *zenith hourly rate* (*ZHR*) of each shower.

The ZHR is the number of meteors that would be observed by a person whose eyes are fully dark-adapted on a night when stars of magnitude $6^{m}.5$ are visible, and the radiant appears at the zenith. In practice, these conditions can never be met and so the actual number of meteors seen per hour will be rather less than the predicted ZHR.

Almost all ephemerides will provide all the information you need to observe meteors. The International Meteor Organisation has its website at www.imo.net and you may also find the website www.meteorshowersonline.com of interest.

The basic equipment you need is the same as that for observing and recording aurorae. Once again a dark observing site helps and if your home lacks that then you will have no choice but to travel to a dark site with a wide view of the sky. I discuss this along with the minimum precautions you should take in Section 1.3.

Before going out you should arm yourself with star charts, ideally showing stars down to the fifth or sixth magnitude over a wide area of sky, on which you have marked the positions of the meteor shower radiant – or radiants as more than one shower will likely be active on any given night. Printouts from a piece of planetarium software will be found most convenient. *Starry Night Pro* is a favourite amongst most observers. Failing that, photocopies from a book-form general star atlas – maybe *Norton's 2000.0* – will do as well.

The meteor shower ephemeris data will give the right ascension and declination of the radiant at the time of the predicted peak of the shower, as well as the daily drift in declination and right ascension of that radiant. You will need to calculate the right ascension and declination of the radiant for the night you are observing. Simply multiply the daily drift figures by the number of days before or after the date of shower maximum and add or subtract these as appropriate to the co-ordinates given for the night of shower maximum.

Using the scales printed on the printout/atlas, or the readout from the cursor when running the planetarium software, mark the co-ordinates of the radiant(s) on the chart(s). Finally draw a circle of size equivalent to about 8° centred on each radiant co-ordinate. This circle represents the actual physical radiant for each shower on that particular night.

Meteors whose paths can be tracked back to within a specific 8° circle can be taken to be genuine shower members. Those that do not track back to specific radiants are either sporadic meteors, or meteors from unrecognised showers, or obscure showers which may be known about but you have not marked on your charts.

When you go outside, give yourself at the very least 10 minutes for your eyes to dark-adapt. You should then make a note of the magnitude of the dimmest stars you can see at an altitude of about 60° in the direction of the meteor radiant. Use the star chart to help you with this. Your meteor observing group director/co-ordinator may well prefer you to determine the limiting magnitude by another prescribed method. Perhaps you might be asked to count the stars visible in a certain defined area of sky, or by observing certain specified stars such as those known as the ‘North Polar Sequence’. Your director/co-ordinator will instruct you on what is required.

Also make a note of all other pertinent information – date, the start and end times for your observation period(s), presence of moonlight, any light pollution, general notes on the atmospheric transparency and the presence of mist. Can you see fifth- or even sixth-magnitude stars near the zenith but only third-magnitude stars at an altitude of 30°, for instance? Next, you ought to make sure that you correctly identify the positions of the radiants on the sky, with reference to your pre-prepared charts.

When you are ready and you are confident that your eyes are dark-adapted you can begin your observing session proper. Normally, you will be best advised to face the radiant of the main shower you intend observing and look mainly at the sky about 60° altitude above the horizon in this direction. In that way most of the meteors in that shower will appear somewhere in your field of vision.

The simplest useful activity you can undertake is to count the number of meteors you see in a given time period. The ideal length of this period does depend on the activity of the shower. An hour would be a suitable period for a weak shower but 10 minutes might be best for a vigorous one. Taking careful note of the beginning and ending times of your chosen periods, record the number of all the shower meteors that you see in each period.

Mentally project the path of the meteor backwards to see if it originated in the radiant. This is fairly easy to do if you adopt the viewing position I suggest.

If it is a help to you, you could immediately hold up something such as a thin piece of bamboo to the observed path of the meteor. This will give you some thinking time in which to establish whether or not it is a shower member.

You should separately record all instances of sporadic meteors. It is imperative that you record the start and stop times of any breaks you take – and the session must not re-start until you are properly dark-adapted once more.

Your meteor observing section director/co-ordinator will be pleased to have this as the main part of your observational report. However, you can always carry out more elaborate observations – even on a meteor-by-meteor basis – if you so wish.

You could undertake to record the time of each meteor you see, along with your determination of its type (specific shower meteor or a sporadic) and its visible brightness at its maximum (by comparison with the stars of known magnitude). You could record its colour and whether it has a visible trail. If it has a persistent train then you might record how long that train persists. You could record the meteor's altitude and direction, or even plot it on spare copies of your chart. Always record anything you are unsure of as a question mark. Never be tempted to give inaccurate information just to make your log look 'complete'.

You could even include a brief description of the meteor's appearance and behaviour. However, the more time you spend note-taking, the less you will be looking at the sky and the more chance you will have of missing meteors. Your initial note-taking could be in the form of abbreviations (invent your own but please make sure that you know what they mean afterwards!). Report-form filling is an activity that should be done in the warmth and light indoors after the observing session and not during it.

A portable voice recorder will prove invaluable for longer descriptions and may even be useful for recording most of the data during an observing session. Do, though, make sure that it is reliable in the damp and cold of night and that its batteries are fully charged before you begin each observing session. If the shower is so rich that you cannot record the details of individual meteors then stick to just making counts in specified time intervals.

You could even turn your observing session into a social gathering if you become part of an organised group. Each group member might be allocated an area of sky, for instance. There is a book authored by Robert Lunsford called *Meteors and how to observe them* published by Springer-Verlag in 2008 which expands on this field more than I have had space to do here. There is also a small book written by Mike D Reynolds called *Falling Stars – A guide to meteors and meteorites*, published by Stackpole Books in 2010, covering almost all aspects of this subject at an introductory level.

1.11 OTHER METHODS OF OBSERVING METEORS

You can photograph meteors using the same basic equipment and technique as for photographing the aurorae. However, meteor photography will normally involve longer exposures. Exposures longer than about 20 seconds with a wide-angle lens, or 10 seconds with a standard (*circa* 50 mm) lens, will produce star trails.

You can take a series of short exposures and combine then afterwards into a composite picture. This composite will show the meteors against stars which are not trailed by diurnal motion. How to do this is explained later in this book – principally in Chapter 4, Section 4.3 and in Chapter 11, Section 11.16.

You can also mount the camera on a telescope, or on a telescope mounting, or on a driven platform, in order to track the stars. Practical details for this are given in Chapter 11, Section 11.15.

There are two possible problems. One is that not all digital cameras are capable of long exposures. The other problem is that long exposures may produce a bright image of the background sky, in addition to producing a grainy image due to thermal noise in the sensor. You must choose a camera that is capable of multi-second exposures at the very least. The thermal-noise and background-brightness problems are both alleviated by selecting a lower ISO (sensitivity) setting. This is preferable to stopping the lens down. Experiment to find out what works best for your camera and for the sky conditions at your observing site before you begin meteor work in earnest.

Since the camera will have a far smaller field of view than will your eyes, the camera is best pointed towards a point near the zenith but angled towards the shower radiant. If money is no object, then you can have an array of cameras each looking at regions of the sky adjacent to each other to achieve wider sky coverage.

A more advanced project would be to photograph the meteors through a fast-rotating fan with wide blades. The meteor trails would then appear as broken lines. You will need to know the rotation rate of the fan so that you can work out how many times every second a blade passes in front of the camera lens. One way of doing this is to drive it using a synchronous motor of known fixed rotation rate. Another method is to set up a monitoring dim light and sensor set looking at each other through the fan blades alongside the camera body. The output of the sensor is then arranged to drive a pulse-counter.

Knowing the number of interruptions of the meteor trail every second and the image scale of the photograph, the angular speed of the meteor can be worked out. If another observer several tens of kilometres away, similarly equipped, also recorded the same meteor then its actual speed and height could be determined. Such group efforts become possible when you are a member of an observing team. A good first step to achieving that is to join an astronomical society . . .

1.12 JOIN AN ASTRONOMICAL SOCIETY

You will gain maximum enjoyment and satisfaction from your involvement in astronomy if you submit good-quality observations – properly carried out and recorded – to the wider astronomical community. The doorway to do that becomes open once you join a national astronomical association. The premier amateur association in the USA for observation-based research of the Solar System is ALPO (the American Lunar and Planetary Organisation, at www.alpo-astronomy.org). The equivalent in the UK is the BAA (the British Astronomical Association, www.britastro.org).

Other major countries have at least one equivalent organisation or association each. These organisations have separate observing sections devoted to specialist studies (solar, lunar, meteor, etc.) under the control of a director or co-ordinator. After joining the association you can get involved with whichever of the observing sections takes your interest. You get a lot for the small annual membership fee: well produced periodicals full of up-to-date news items and learned papers, access to members with great expertise and experience, access to meetings with keynote speakers and much more. You also get frequent circulars/periodicals and other methods of feedback from the observing sections you decide to join.

In order to access the webpages of specific observing sections of ALPO and the BAA, such as those of the aurorae and meteor observing sections, it is easiest to use the links you will find on their homepages.

I also strongly recommend giving your local-area astronomical society a try. You will make many like-minded friends. You will probably also become ‘plugged into’ the up-to-date world of telescopes and accessories because of the interests and activities of at least some of the society members. There is also much enjoyment to be got from joining in with group activities. A good local society will also have regular meetings, often addressed by outside speakers. It may even have its own well-equipped observatory available for members to use. Such is the case for the Breckland Astronomical Society, which I joined shortly after moving to my present home in 1999. The camaraderie you will likely experience on joining a local astronomical society will increase the pleasure of your hobby many-fold, if your experience turns out to be anything like mine.

CHAPTER 2

Moon and planet observer's hardware

Four decades ago, when I began practical astronomy, the range of equipment used by amateurs was rather limited. Newtonian reflectors dominated, with a very small number of amateurs using Cassegrain reflectors. Some also had 3-inch (76 mm) or 4-inch (102 mm) refractors. Mass-produced Schmidt–Cassegrain telescopes were yet to conquer even their home market of America. Accessories were limited to not much more than a few different types of eyepieces and some filters. Only a small percentage of even serious amateur astronomers carried out photography (using photographic film, of course). Another difference from today is that back then many amateur astronomers built much of their own equipment. Personal computers appeared only in science fiction and the Internet didn't exist even as a futuristic fantasy.

How things have changed! Now very few astronomers make their own equipment and the marketplace is replete with an almost bewildering variety of different types of telescope and accessories. Today's serious amateurs are able to undertake a vast range of observational projects. In most cases this involves the now ubiquitous personal computer or laptop and the Internet is now regarded as an indispensable resource.

Different designs of telescope and ancillary equipment vary enormously in their suitability for specific observational tasks and subjects for observation and this can be a major pitfall for the unwary. Most people have to spend their available funds carefully. Severe frustration, along with poor results and wasted money, can result from bad choices when selecting equipment.

In this chapter I will offer some information and advice about the suitability of particular items of equipment for visually observing the Moon and the major planets. In the course of the rest of this book I will build on the material given in this chapter and discuss specific equipment requirements for other tasks and other Solar System objects.

2.1 OPTICAL REQUIREMENTS FOR MOON AND PLANET OBSERVING

The imaging characteristics of a telescope which are most important for lunar and planetary observation are resolving power and contrast. In practice there is a degree of interrelation between these characteristics.

When the light from a star passes through the objective lens, or is reflected from the primary mirror, of a telescope it suffers an effect known as *diffraction* and any image formed from that light has a resultant *diffraction pattern* imposed upon it. The typical diffraction pattern of a star produced by an unobstructed circular aperture, such as a refractor's objective lens, is represented (at a very high magnification) in Figure 2.1(a).

Diffraction happens because the wave-like nature of light causes it to interact with the aperture it is passing through. Larger apertures produce smaller diffraction patterns. It is the size of these diffraction patterns that decides whether or not a telescope has the potential to resolve a close-together pair of stars. This is illustrated in Figure 2.1(b).

Of course, our interest is not so much in stars but rather in resolving details on extended bodies such as the Moon and planets. The principle of diffraction still applies. The image that the telescope forms of extended bodies 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 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-aperture telescope the individual diffraction patterns are smaller. This is the same as having the mosaic made up from smaller tiles.

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

$$R = 137/D,$$

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). You might also be familiar with Dawes Limit, a rule for splitting sixth-magnitude double stars. The formula takes the same form but the numerator would instead be 116. 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 defined.

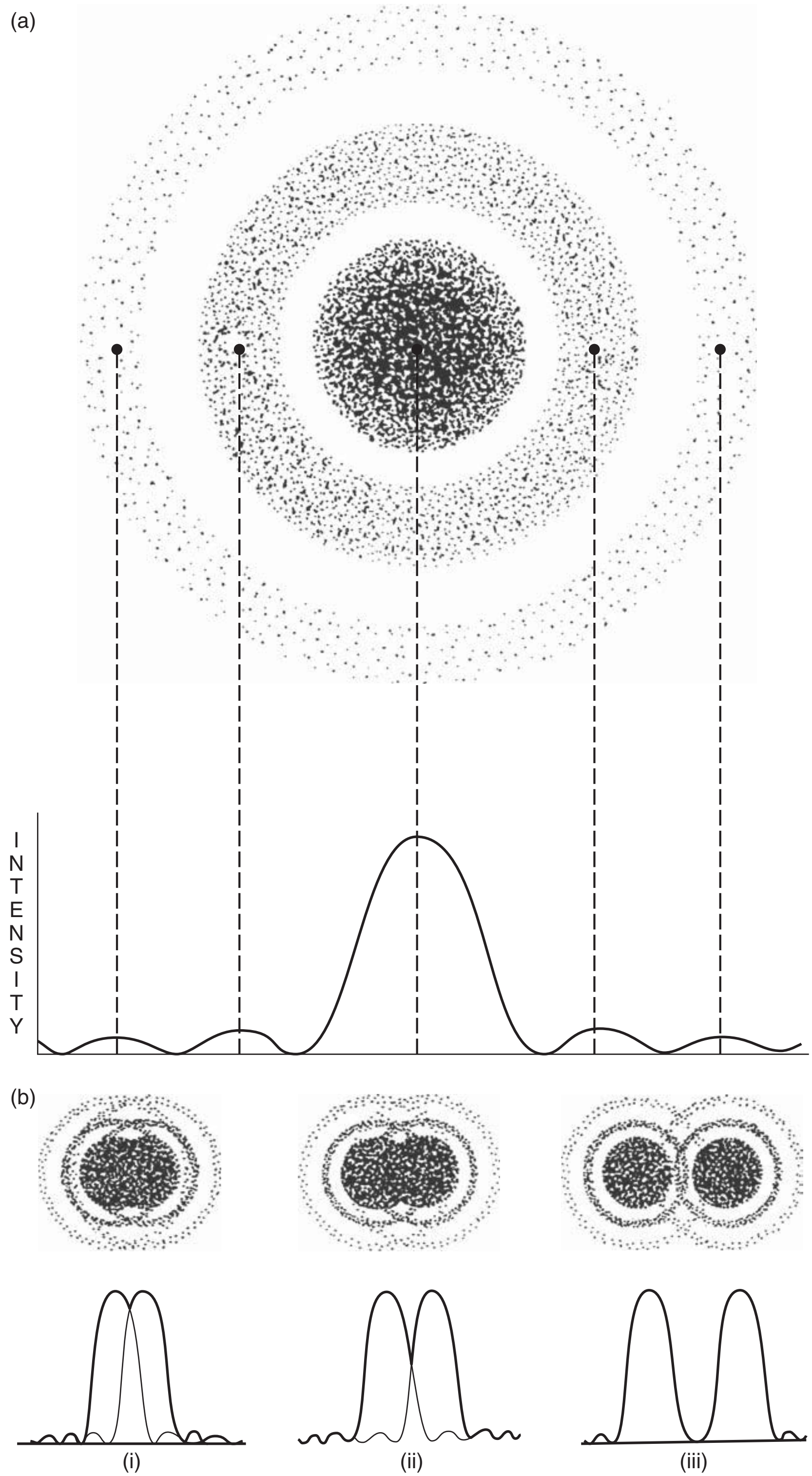


Figure 2.1 (a) Idealised representation of the diffraction pattern of a star produced by an unobstructed aperture (for example a refracting telescope's object glass). (b) In (i) a pair of stars are too close together for a given telescope to resolve them because the diffraction patterns merge. In (ii) the stars are just resolvable and in (iii) they are easily resolvable. The complex extended image that a telescope forms of any extended object can be, albeit simplistically, thought of as being composed of an array of star-like points, in order to understand the principle of resolution limited by the telescope's aperture.

So, we need a larger telescope to see finer details on the Moon and planets. Is that the end of the matter? Actually no, there is more to it than that. In practical telescopes the diffraction pattern is affected by instrumental design and the accuracy of manufacture of the optical surfaces. We also have to contend with the prevailing atmospheric conditions and thermal effects, both of which can spoil the images formed by telescopes.

On the point about accuracy of manufacture of the optics, 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 within ¼-wavelength of yellow-green light. This is often referred to as '¼-wave peak-to-valley', being the allowable deviation of the wavefronts of light by up to this amount. If the wavefronts deviate by more than this tiny amount, a linear distance of only 135 nm, then the diffraction pattern will be significantly spoilt and image resolution and contrast will both suffer.

Even the ¼-wave limit is not the ultimate for good performance. Trying to see faint markings on the bright globe of a planet is especially dependant on good optical quality and the ¼-wave limit should be considered as only the bare-minimum requirement for a telescope intended for planetary observation. There would be some improvement, especially in image contrast, if the telescope had optics of still greater accuracy. Go beyond 1/10-wave accuracy as measured at the telescope's focal plane, though, and you will be hard pressed to see any further real gain in the quality of the image. This is especially so for larger telescopes used in average seeing conditions. I say 'measured at the focal plane' in order to take account of all the optical components that comprise the telescope. I would consider any set of optics that produces a genuine 1/10 peak-to-valley (P–V) wave accuracy at the focal plane to be of truly excellent quality.

Not all manufacturers give a numerically defined figure of optical accuracy. Of those that do, some refer to an *rms*, or root mean square, wavelength figure. Actually, this a better measure of accuracy because it takes into account the area of the optical surface affected by errors as well as the amount of error present.

To take a rather unlikely example, a telescope advertised as having '¼-wave P–V' optics might have this amount of error generated by a very small zone near the centre of the main optical component, the rest of the optics having zero error. The actual performance of this telescope would be well-nigh perfect. To take the opposite extreme case, again very unlikely, a telescope of identical design and size might have '1/6-wave P–V' optics but in this case the majority of the optical surfaces may be generating this amount of error, especially so those zones near the outer edge of the optical components (perhaps one of the optical surfaces is somewhat corrugated). If you were to compare the two telescopes under identical excellent conditions you would find that it is the first telescope which produces images that are noticeably crisper and showing the most delicately contrasted features on planets with the greatest ease. The rms figures for the two telescopes would be a much better guide to their actual performance than their peak-to-valley figures. That for the first telescope might be something like $\frac{1}{30}$ wave rms, while that for the second telescope might be about $\frac{1}{8}$ wave rms.

As an aside, do beware that some manufacturers quote wavelength accuracy limits based on wavelengths longer than 540 nm (which corresponds to yellow-green light). For instance, 0.25 wave measured against light of wavelength, say, 630 nm is really 0.29 wave when measured at a wavelength of 540 nm.

In general, you can expect a telescope to perform passably well for visually observing the planets if it has an rms accuracy of about $\frac{1}{12}$ or $\frac{1}{14}$ wave, measured at 540 nm, but you will certainly see proportionate improvements in the crispness of images and your ability to see faint markings on the bright globes of planets with increasing quality up to about $\frac{1}{20}$ wave rms. You will even see still further, albeit diminishing, improvements with further increases in optical quality. Any such comparisons would have to be made when the observing conditions are at their very best, though. Poor conditions are a great leveller of a telescope's performance, whatever its size and optical quality.

2.2 WHAT TYPE OF TELESCOPE IS BEST FOR MOON AND PLANET OBSERVING?

We desire textbook diffraction-pattern structure in order that image resolution and contrast are at their best. Of the most common telescope designs (and putting aside any subsequent modifications by the telescope user), the instrument that potentially comes closest to providing this is the refractor. However, a refractor would not normally be my first choice for a telescope for Moon and planet observing, primarily because of monetary considerations, though there is more to it than that. To understand the issues, and in order that we can be in a position to make an informed choice, let us now consider each of the main telescope types in turn:

Refracting telescopes

The layout of the refractor is illustrated in Figure 2.2(a). The focal length – it is this which determines the image scale at the focus and the magnification you get when using a particular focal length of eyepiece – is simply the distance indicated as *F* on the diagram.

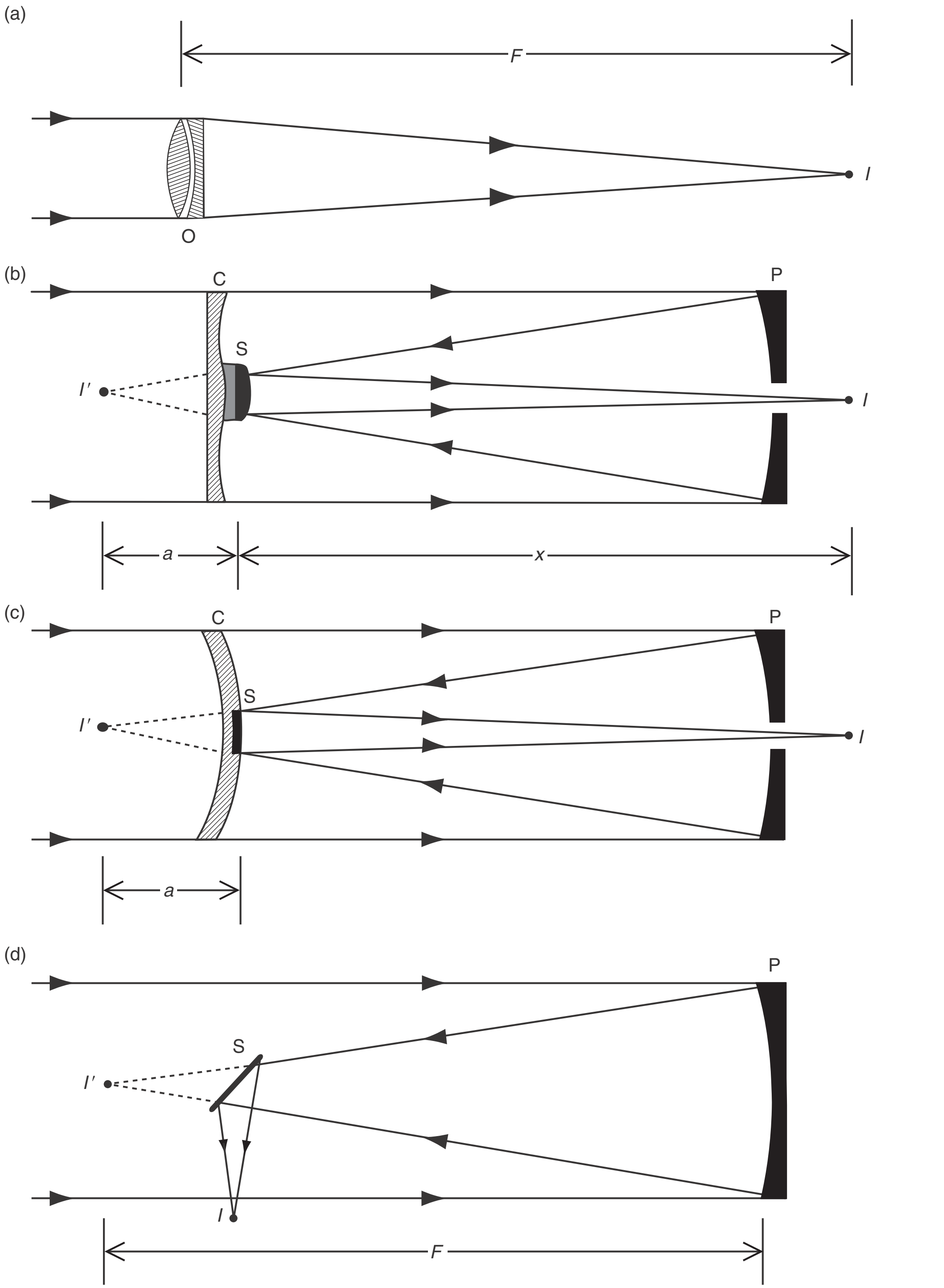

(a)
F
I
O
(b)
C
P
S
I′
I
a
x
(c)
C
P
S
I′
I
a
(d)
P
S
I′
I
F

Figure 2.2 The optical layouts of the four most common types of telescope used by amateur astronomers today.
(a) The refractor. The object glass, O, of the refractor forms an image on a distant object at the point shown as *I*. The image can be formed on a screen, or electronic detector, at this point, or alternatively viewed with an eyepiece (not shown).
(b) The Schmidt–Cassegrain telescope. The primary mirror, P, would form an image at *I*′ but for the intervention of the secondary mirror, S, which directs the rays back through the hole in the primary to reach a focus at *I*. The curve on the corrector plate, C, has been exaggerated here for the sake of clarity.
(c) The classical Maksutov–Cassegrain telescope. The Rumak version has a separately mounted secondary mirror.
(d) The Newtonian reflector. Here the secondary mirror directs the light from the primary mirror to the side where it reaches a focus at *I*. Without the secondary mirror the light would have reached a focus at *I*′.

The focal ratio of the telescope is *F* divided by the aperture (diameter of the objective lens) of the telescope, both being measured in the same units. The refractors of yesteryear tended to have focal ratios in the range f/12–f/16. The relatively gentle curves on optical surfaces with large focal ratios are easier to manufacture with accuracy and this is one reason why long-focus refractors do make good telescopes for Moon and planet observing. Actually, it is quite possible 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 another reason for large focal ratios delivering better images.

Refractors with object glasses made from two lens elements, typically of common crown and flint glasses, **should** be manufactured to have large focal ratios because of a generic problem with them. While the manufacturer has designed the object glass to bring the wavelength range to which the eye is most sensitive (*circa* 540 nm) to a minimum focus, inevitably the focal positions for the other wavelengths occupy a range of positions extending further from the lens than the minimum focus. This *secondary spectrum* shows itself as a softening of contours in the image, together with a reduction in image contrast. It even leads to visible colour-fringing when the problem is severe.

The effect of the secondary spectrum diminishes with the square of the focal ratio for the range of sizes and focal ratios normally encountered. As an aside, the wavefront error (change of focus) for red and violet light at the extreme ends of the spectrum compared to that for yellow-green light can be several times the ¼-wave limit tolerable for the seidal errors (spherical aberration, coma, astigmatism, field curvature and distortion) before becoming objectionable. This is because of the much-reduced sensitivity of the eye at wavelengths away from that of yellow-green light.

I have used a large variety of telescopes over the years, including a number of refractors. Based upon my experiences with them, I would say that for visual observation the 'old-fashioned' types of 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 severe. Even then the image will fall well short of perfection.

As a case in point, I often used the 12.8-inch (325 mm) f/16.4 'Mertz' refractor that was mounted on the 'Thompson' 26-inch (0.66 m) astrographic refractor at the Royal Greenwich Observatory, Herstmonceux. The Mertz object glass of this instrument was made in 1856 and was originally mounted in what at the time was the Observatory's premier telescope. Seen through the Mertz telescope at a magnification of ×240 the Moon's crater rims were fringed with yellow and the black interior shadows were filled in with a delicate blue haze! Planetary disks were similarly enveloped in an extended bluish haze that tended to overpower the faintest markings. 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') at the same observing site gave images that were very haze-free and completely free of false colour-fringing.

Until recently, few amateur astronomers owned refractors larger than 4 inches (102 mm) aperture. This was because refractors were very expensive compared to other types of telescope. That has now changed. Telescope manufacturers have attempted to sate a perceived appetite for refractors amongst the serious amateur astronomical community. There are now a large range of refractors on the market, commonly up to 6 inches (152 mm) in aperture. A few manufacturers even supply larger models. In response to the modern desire for compactness, these instruments are manufactured with much lower focal ratios than the refractors of yesteryear. A focal ratio of f/8 is now quite common, even for a 6-inch refractor. The cheapest of them (2010 prices range about \$350 for a 4-inch rising to about \$1300 for a 6-inch) have object glasses of old-fashioned design, that is composed of just two elements, one of common flint glass and the other of common crown glass.

If you intend buying one of these low-focal-ratio cheaper models please do be aware that the uncorrected secondary spectrum will be visible when you use the telescope to look at anything bright such as a planet or the Moon. You will see light–dark boundaries fringed with yellow and the image contrast will be reduced by a bluish-purple haze.

Some companies market refractors with one component of the two-element objectives made of a special glass (usually known as 'ED glass'). The result is a refractor with a much-reduced secondary spectrum compared to one of classical design of the same focal ratio. Again, they have focal ratios *circa* f/8. These are marketed as 'ED apochromatic refractors', and sometimes as 'apochromatic refractors', though that title really belongs to three-element objectives. They should really be called semi-apochromatic refractors. True apochromatic objectives have the smallest secondary spectrum, especially so if made utilising special glass types such as fluorite.

The two-element ED glass refractors are much more expensive than those with classically designed objective lenses, typically costing roughly \$3000 for a 4-inch rising to \$5000 for a 6-inch. True apochromatic refractors are **very** much more expensive. A 5-inch model may well set you back more than \$10 000. There are some tricks you can get up to in order to reduce the amount of secondary spectrum you see when looking through the cheapest low-focal-ratio refractors. I describe these in Section 2.7.

Schmidt–Cassegrain and Maksutov–Cassegrain telescopes

Schmidt–Cassegrain and Maksutov–Cassegrain telescopes are now extremely popular. They are optically more complex than refractors, as is shown in Figure 2.2 (b) and (c). The corrector plate at the front of the Schmidt–Cassegrain is a special shape in order to correct for the aberration (spherical aberration) that is produced by the simple-to-manufacture spheroidal primary and secondary mirrors. That in the Maksutov–Cassegrain is a thick meniscus, facing concave to the sky, and having spheroidal surfaces. In both cases the correctors have negligible optical power though, the mirrors doing all the real work in the telescope. In the classical Maksutov–Cassegrain telescope (shown here) the secondary mirror is actually formed from an aluminised spot at the centre of the corrector plate, but there is a 'Rumak' version of this telescope which has a separately mounted secondary mirror in the same manner as the Schmidt–Cassegrain telescope. The secondary's containing cell is usually bonded to the centre of the corrector plate in both the Schmidt–Cassegrain and Rumak Maksutov–Cassegrain telescopes.

Remove the corrector plate and instead support the secondary mirror cell with four thin vanes extending from the side wall of the tube and you have an 'old-fashioned' Cassegrain telescope. Here, though, one or both of the mirrors have to be some shape other than spheroidal. The classical Cassegrain telescope, to take just one of several variants, has a paraboloidal primary mirror and a hyperboloidal spherical mirror.

The focal length and focal ratio of the primary mirror (which is most usually around f/2 for Schmidt–Cassegrains, and often a little larger for the Maksutov–Cassegrains) are multiplied by the ratio of x/a, these distances being indicated on Figure 2.2. This is usually something close to a five-times multiplication in most commercial Schmidt–Cassegrain telescopes on the market and maybe a little higher for the Maksutov–Cassegrains. So, one gets a long effective focal length in a very short tube assembly. The effective focal ratio (the effective focal length divided by the aperture) is usually f/10 or f/11 for the Schmidt–Cassegrains produced by the market leaders Meade and Celestron and f/15 to f/20 for most Maksutov–Cassegrains.

Their compactness and relative portability suit the needs of the modern amateur astronomer very well. They are expensive but for the price you typically get an instrument of nearly double the aperture of an ED refractor and which can automatically set and track on any of thousands of celestial objects.

All very well, but how good are they for observing the Moon and planets? Of course, the portability and compactness aspects are just as much of an advantage to the Solar System observer. The downside is that, aperture-for-aperture, they do not give quite as good lunar and planetary images as some other types of telescope when used for visual observation.

The reasons are two-fold. One is that the steep curve on the primary mirror and the complex curve on the corrector plate (at least for the Schmidt–Cassegrain) 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 focal-plane wavefront error might be just a little larger than the desired minimum of the ¼-wavelength of yellow-green light.

Having said this, the latest models coming off the production lines are **very** much better than the oldest models. This is something to be aware of if you are contemplating buying an older second-hand telescope. In general, you can expect the image produced by a Maksutov–Cassegrain telescope to be superior to that from a Schmidt–Cassegrain of the same aperture. However, a lot does depend on the manufacturer.

The second reason for the shortfall 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 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 as is usually the case for seeing details on the planets.

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. Maksutov–Cassegrain telescopes tend to have smaller central obstructions, sometimes less than a quarter of the diameter of the aperture.

The two problems, any slight shortfall in optical accuracy (but you can expect at least fairly good optics in a recently manufactured instrument), and the large central obstruction, act additively to degrade the image. The common f/10 or f/11 Schmidt–Cassegrain telescopes on sale need to have apertures around twice as large as the very best apochromatic refractors in order to show the Moon and planets with equal fidelity under identical excellent conditions. The performance of the common f/15 to f/20 Maksutov–Cassegrains falls somewhere between these telescope types.

However, any lack of image contrast is much less of a problem to the lunar and planetary photographer as this can be restored (and even boosted way beyond what is real if so desired) in the subsequent image processing.

The experience of myself and many others is that Celestron's line of Schmidt–Cassegrain telescopes, and especially the 9¼-inch (235 mm) model, are particularly good examples of this type of instrument. Damian Peach, one of the best lunar and planetary imagers in the world, uses Celestron Schmidt–Cassegrains to produce his finest work.

The 9¼-inch Celestron is unusual in that the primary mirror is an f/2.5, rather than the more usual f/2. The secondary amplification is less (×4, rather than the usual ×5) and these factors are quite likely the reason for this telescope's better-than-average performance.

My experience of an older-model 9¼-inch Celestron Schmidt–Cassegrain telescope (one of the instruments at the Breckland Astronomical Society's observatory) is that it delivers images of high quality, though noticeably down in contrast, just as I would have expected from a reasonable-quality set of optics with a large central obstruction. It does, though, need frequent collimation. Even pointing the instrument to different parts of the sky is enough to disturb the collimation. This is because focusing is achieved by small movements of the primary mirror and the mechanism and supports allow varying amounts of drooping of the mirror.

The collimation of a Schmidt–Cassegrain is, though, very quick and easy – just a tweak on one of three screws (see Appendix 1 for methods of collimating all the main types of available telescope). The very latest Schmidt–Cassegrains have much improved mirror mountings and so the collimation-drift problem should no longer be an issue if you buy a brand-new telescope (but always carefully check the specifications and, particularly, independent reviews). This is something you should bear in mind, though, if you buy a second-hand unit.

Newtonian reflectors

Although they have somewhat fallen out of fashion, the telescope that gives the observer the best value for money is still the Newtonian reflector. See Figure 2.2(d) for the optical layout of this type of telescope. The focal length is simply F, as shown on the diagram and the focal ratio is F divided by the diameter of the primary mirror. In the Newtonian, as well as in the Schmidt–Cassegrain and Maksutov–Cassegrain telescopes, the diameter of the secondary mirror (the minor axis of the elliptical secondary mirror in the case of the Newtonian telescope) has to be equal to at least a/F times the diameter of the primary mirror in order that all the light collected by the primary mirror from the celestial body fully illuminates at least the centre of the field of view.

Any manufacturer can produce a poor Newtonian reflector but at least it is not very difficult for the manufacturer to produce a good one. The obstruction due to the secondary mirror tends to be about 20–25 per cent of the telescope aperture, higher focal ratios on larger apertures allowing smaller-percentage secondary obstructions. 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. The Newtonian's image quality may be roughly equivalent to that of a Maksutov–Cassegrain (at least in the smaller sizes), though still a little down on what the very best apochromatic refractor of the same aperture can show. However, the Newtonian will be much cheaper aperture-for-aperture than any other type of telescope.

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! Actually, a modern manufacturing trend for medium-sized off-the-peg reflecting telescopes is to make their focal lengths not much more than 1.6 metres, anyway. It seems that manufacturers have decided that people prefer compact telescopes these days. For purely visual work, the telescope need not be driven. Of course, a drive is always an advantage as long as it works properly and a drive is generally necessary for photography.

One long-standing question: 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 helps prevent this. 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 help matters.

My 18¼-inch (0.46 m) reflector used to have an open-framework tube, while my 8½-inch (216 mm) has a solid tube (see Figure 2.3 (a) and (b)). Long ago, I realised that on some nights the images produced by the 8½-inch were poor and star images betrayed the obvious presence of a tube current (see Appendix 2). There is a door installed in the tube close to the primary mirror to gain access to the mirror cover (see Figure 2.4). I found that opening this door significantly improved the images on those nights, since it allows much of the warm air convecting from the primary mirror to escape, rather than to flow up the entire length of the tube. Now I always leave this door open during observing sessions.

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. I am currently rebuilding my largest telescope. It will have a solid tube, provided with good ventilation around the mirror cell and across the face of the primary mirror (probably with fan assistance).

Nowadays, Newtonian reflectors tend to be sold with solid tubes and these often have poor ventilation. Compounding the problems, the tube diameters are often only very slightly bigger than the primary mirror. The convecting currents of air generated by the primary mirror and its cell are thereby forced to move up the tube partially sharing the path that the light has to take, consequently producing the worst-possible effect on the image.

Closed optical systems, such as refractors and Schmidt–Cassegrain telescopes, are usually less troubled by tube currents, though even these need to cool off for a while if brought out from indoors before observing. The shear mass of Maksutov–Cassegrain telescopes (they have thick and

(a)

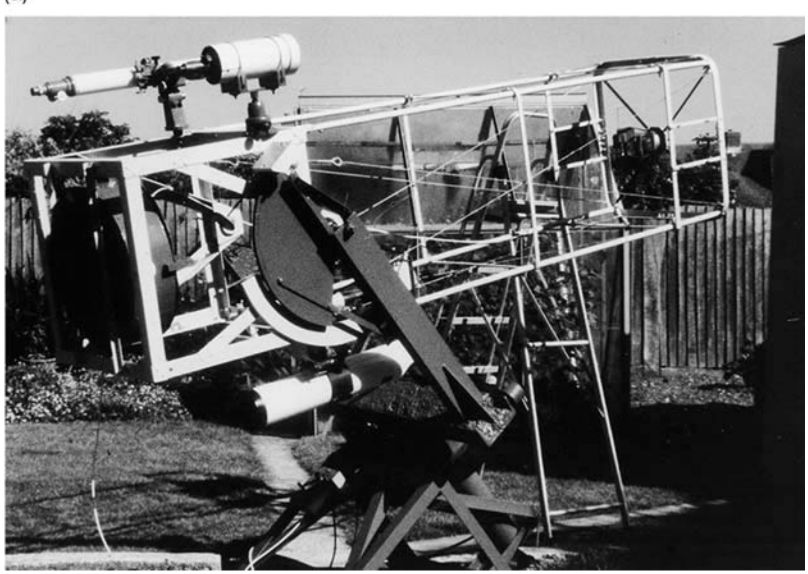


Figure 2.3 (a) The author's 18¼-inch (0.46 m) Newtonian reflector, here sited at Seaford, on the south coast of England, in the 1970s. It has a skeleton tube and a fork equatorial mounting.

(b)

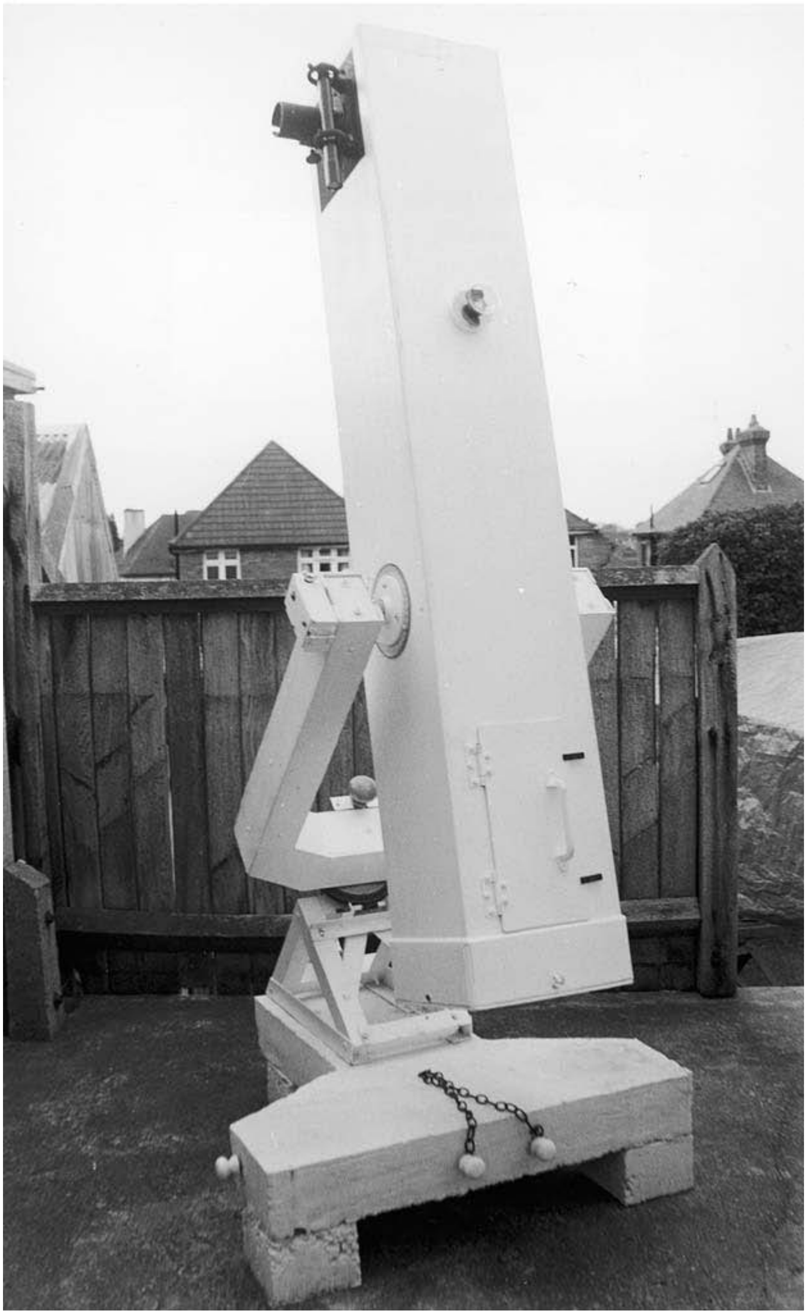


Figure 2.3 (*cont.*) (b) The author's 8½-inch (216 mm) solid-tubed Newtonian reflector sited at Bexhill-on-sea in the 1990s. It also has a fork equatorial mounting but this is fixed onto a cast concrete plinth resting on cast concrete blocks.

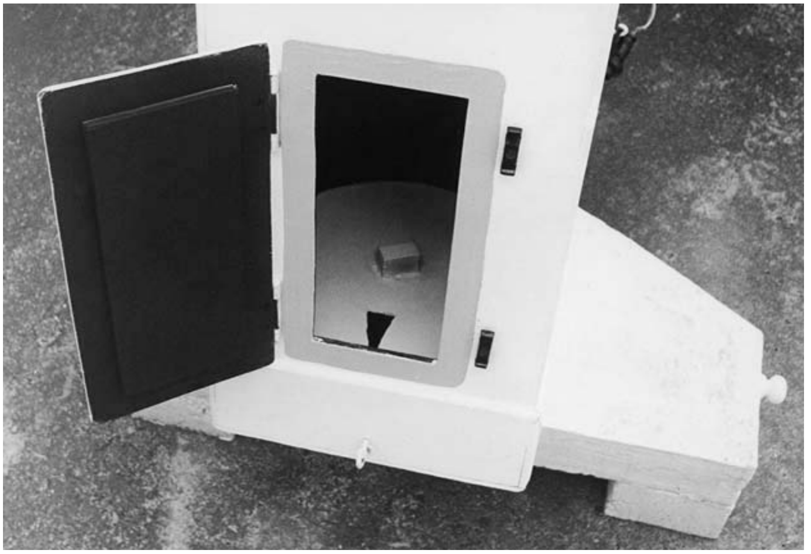


Figure 2.4 The door in the tube of the author's 8½-inch (216 mm) Newtonian reflector gives access to the primary mirror cover. It is also useful in ventilating the mirror and cell, so minimising tube currents.

heavy corrector plates at one end of an enclosed tube with the heavy primary mirror at the other end, along with the heavy metalwork needed to keep these heavy optics rigidly aligned) makes them prone to thermal problems, though models up to 8 inches (203 mm), or even 10 inches (254 mm), aperture are generally very highly thought of by their users. The same thermal inertia problem can afflict the Schmidt–Cassegrain telescope, especially so in the largest sizes of instrument.

Maksutov–Newtonian and Schmidt–Newtonian telescopes

Imagine a Newtonian reflector with a primary mirror whose reflecting surface is shaped as part of a sphere instead of the usual paraboloid. Unless its focal length is maybe a dozen times its diameter the images it will produce will be spoiled with spherical aberration. However, imagine now the effect of adding a corrector plate placed at the sky end of the telescope tube. If this corrector plate is shaped almost exactly like that on a Schmidt–Cassegrain telescope then the spherical primary mirror can have a focal ratio of as low as f/4 and the telescope will still deliver images that are good enough for some tasks. The resulting instrument is called a Schmidt–Newtonian telescope. They make fairly good wide-field telescopes suitable for the comet observer or those who like to observe the star clusters, nebulae and galaxies beyond our Solar System. They are not marvellous as planetary telescopes, though.

Exchanging the Schmidt-type corrector plate for a Maksutov-type one produces a good planetary observer's telescope provided the minimum focal ratio of the primary mirror is a little higher, say around f/6 or more. A higher focal ratio also allows the secondary mirror to be a little smaller, which helps the telescope deliver higher-contrast planetary images. Also, the secondary mirror can be mounted onto the corrector plate without the usual spider-support vanes – again helping with image fidelity. The company Intes-Micro produce some particularly fine examples of these Maksutov–Newtonian telescopes. However they are, size for size, very much more expensive than straightforward Newtonian reflectors. A question you must decide for yourself is, are you a connoisseur of fine instruments or is achieving the best value for money your most important aim?

2.3 WHAT SIZE OF TELESCOPE IS BEST FOR MOON AND PLANET OBSERVING?

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 recommend you put quality above sheer size when it comes to selecting telescopic equipment. You will have a great deal more success and 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 poor-quality 'light-bucket'.

What if one is wealthy enough to have quality and size? Will a bigger telescope always outperform a smaller one of equal quality? Based on my experience of observing with a large variety of telescopes of differing size and design (ranging from a 2.4-inch (60 mm) refractor to a 36-inch (0.91 m) Cassegrain reflector), my answer to that question is a qualified 'No'. In fact, sometimes even the reverse is true. Understanding why this should be so is not very difficult. There are two main reasons.

The first reason is that the column of atmosphere 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 cells that affect the telescopist to the greatest extent are from 10 to 20 cm in diameter and can occur from just in front of the telescope to high up in the troposphere. Each of these cells disturbs the passage of light rays passing through 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, many do not appreciate just how severe this limitation really is. From most backyard sites the seeing rarely allows details to be glimpsed by a human eye looking through the eyepiece 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 1.6 km. At the distance of the planet Jupiter this corresponds to roughly 3000 km, even when the planet is favourably placed for observation.

A good-quality 6-inch (152 mm) telescope will potentially 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 is not as great as one might expect. While I have experienced rare nights where my 18¼-inch (0.46 m) telescope shows fabulously detailed views of the Moon and planets, I must say that the vast majority of the time the images it delivers are much fuzzier and lower in contrast. On those normal nights I find that my 8½-inch (216 mm) telescope can show these bodies pretty much as well as my 18¼-inch.

Indeed, **sometimes** the bigger telescope will even 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 gyrate around its mean position and 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 well-defined, but admittedly gyrating and distorting, image rather than the confused mess.

The second reason why a bigger telescope is not always better was mentioned in the last section – thermal effects. The smaller the mass of the telescope, the quicker will it cool to the ambient temperature and so not be troubled by currents of warmed air convecting from its optics and fittings.

2.4 SO, WHAT TELESCOPE SHOULD I OBTAIN FOR MOON AND PLANET OBSERVING?

All in all, if you can afford it, and if you have the room to house it permanently in some sort of observatory (perhaps a run-off shed), I would say go for a Newtonian reflector of 10–14-inch (254–356 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 unless your observing site is unusually good. Also remember that thermal problems increase rapidly with increasing telescope size. A particularly good observing site and attention to thermal issues are necessary before you can really benefit from a large-aperture telescope for Moon and planet observing. If you can't afford a 10-inch then go for a smaller Newtonian reflector. Remember, this type of telescope is the cheapest of any but please do not compromise on quality for the sake of size.

My second choice for an instrument intended for visual observation of the Moon and planets would be a refractor of at least 5 inches (127 mm) in aperture. However, it would have to be either an achromatic refractor of focal ratio at least f/12 (which would then imply an older second-hand instrument) or a modern (and consequently *circa* f/8) one with an 'ED apochromatic' objective as the bare minimum requirement.

Not far behind the refractor in the pecking order on my preferred telescope-list would be either a Maksutov–Cassegrain telescope or a Maksutov–Newtonian telescope provided it had an aperture of at least 6 inches (152 mm) but no greater than 10 inches (254 mm) because of potential thermal problems. The Schmidt–Cassegrain telescope would trail in fifth position; I would not be happy with one of those smaller than 8 inches (203 mm) aperture, nor bigger than 14 inches (356 mm). As far as a Schmidt–Cassegrain telescope goes, I would definitely choose the 9¼-inch (235 mm) model marketed by Celestron above all others.

Remember, this list reflects my recommendation for types of telescope suitable for **visual** observation of the Moon and planets. My list would certainly be re-arranged were I to consider preferred telescopes for other tasks, such as photography, and other subjects for observation such as comets and deep-sky objects.

There are other types of telescope that can be used but the ones I have discussed here are by far the most common currently found in the marketplace and in amateur observatories. I offer notes on how to adjust various types of telescope to get the best optical performance from them in Appendix 1. Once you have your telescope performing as well as it can, you can evaluate its optical quality under normal observing conditions by means of some simple tests I describe in Appendix 2.

When buying second-hand equipment remember the old adage: **buyer beware**. Unless the price is so low that the vendor is virtually making a present of the equipment to you, insist on checking it out under field conditions. If necessary take an experienced astronomer friend with you.

You even need to be careful when buying new equipment. For one thing, the quality of a company's advertising does not always reflect the quality of their goods. Make use of the Internet in researching out other people's experiences (via discussion groups and forums) with the equipment before you buy it. Are there any recurrent problems, or shortfalls in performance? Equipment reviews abound online. Use your favourite search engine, specifying the item of equipment under question and take careful note of what appears.

I have to limit my advice on equipment in this book to just a few aspects of particular relevance to the Solar System observer. If you want more, can I refer you to my book *Advanced Amateur Astronomy*, the second edition of which was published by Cambridge University Press in 1997. Another you might like to consult is Martin Mobberley's *Astronomical Equipment for Amateurs*, published by Springer-Verlag in 1999. Despite their ages, both books are still in print and the former one is now also available in various online and electronic formats.

2.5 EYEPIECE CHARACTERISTICS

Time and time again, someone has enthusiastically shown me the view through their telescope and I have straight away recognised that the instrument is not performing as it should. The most common reason and the easiest to put right is poor collimation (see Appendix 1). The next most common reason is the use of an eyepiece of inappropriate design for the telescope or for the type of observation intended. Surprisingly, this inappropriate eyepiece has often been supplied by the manufacturer with the purchased telescope! So, please forgive the following 'back to basics' notes about eyepieces.

In all eyepieces the quality of the image deteriorates to some extent with increasing distance from the centre of the field of view. Manufacturers mask off the images of unacceptable quality by means of a circular aperture, known as a *field stop*, positioned in the eyepiece's focal plane. As you peer through the *eyelens* of an eyepiece, the angle through which you would have to swivel your eye to look directly from one edge of the field of view to the other is known as the *apparent field* of the eyepiece. The apparent fields of different designs of eyepiece can range from about 30° to about 100° (120° in one exceptional case). The most commonly purchased eyepieces have apparent fields of about 45° to 55°.

Another quantity of interest to the observer is the value of the *real field*. This is the angular extent of the sky the observer actually sees when using a particular eyepiece–telescope combination. A rough figure for the size of the Moon is 32 arcminutes (slightly over half a degree). If the real field of the eyepiece–telescope is bigger than this value then all the Moon can be seen at once. If the real field is smaller then the observer will only be able to see part of the Moon in one go. Even though the planets can always be seen in their entirety due to their very small images, a large field of view is still an advantage if using a telescope without a sidereal drive and especially when you are trying to get your telescope pointed to the planet.

The value of the real field obtained depends upon the values of the apparent field of the eyepiece (fixed by the manufacturer) and the magnification that it produces with the telescope. The relationship is:

$$\text{real field} = \text{apparent field}/\text{magnification}$$

For the equation to work the values of real and apparent field must be expressed in the same units, for instance both in degrees or both in arcminutes, etc.

Eyepieces for amateur telescopes now come in two standard sizes; those which fit drawtubes of diameter 1¼ inches (31.7 mm) and those which fit drawtubes of diameter 2 inches (50.8 mm). Eyepieces with 0.96-inch (24.5 mm) diameter barrels used to be common, especially in telescopes imported from the Asian continent, and so you might still encounter them in the second-hand market.

For an eyepiece of apparent field 57°.3 the field-stop aperture has the same diameter as the focal length of the eyepiece. This means that a wide-field eyepiece of long focal length cannot be accommodated in a '1¼-inch fitting' barrel. As one example, an eyepiece of 32 mm focal length and 80° apparent field will have a field-stop aperture of 44.7 mm diameter. So, the manufacturer would have to build that eyepiece into a '2-inch barrel' body.

Most modern eyepieces have external markings which indicate their type and focal length (for instance MA 20 mm, Or 18 mm, etc.). Those you may well encounter, including some now almost obsolete but which you might come across in the second-hand market, include: Huygenian (H), Huygens–Mittenzwey (HM), Ramsden (R), Achromatic Ramsden (AR or SR), Modified Achromatic (MA), Kellner (K), Orthoscopic (Or), Monocentric, Plössl and Radian (these last three usually named in full).

There are also a variety of wide-field eyepieces which may be useful to you. Until recently I would have urged any planetary observer to avoid the majority of them, due to their lack of critical definition and the haze of scattered light caused by the many lens elements they contain. Some of the latest generation of wide-field eyepieces, though, do make very good planetary eyepieces. A recent example is the Speers-WALER Super Wide Field eyepieces. I must say straight away that I have never had the opportunity to look through one of these. However, a review by Steve Ringwood in the August 2010 issue of *Astronomy Now* magazine paints a picture of an eyepiece with an 82° apparent field that is very good for both planetary and deep-sky observing. One problem does remain with wide-field eyepieces, though, and that is their cost of several times that of their medium-field cousins.

One characteristic of eyepieces that varies with design and often varies with focal length is the *eye-relief*. This is the distance between the eye lens and the *exit pupil*, which is the position you need steer your eye pupil to in order to see the whole of the field of view. A generous eye-relief will be needed if you wear glasses at the telescope, for instance.

As an aside, I should say that you should not need to use glasses at your telescope if you suffer from simple long sight or short sight. The normal action of adjusting the telescope focuser should be enough to compensate. If you suffer from astigmatism then you will either need to wear your glasses or to use a compensating device such as the Tele Vue Dioptrx, which is an attachment that fits onto the eyepiece.

All modern eyepieces should have *bloomed* (anti-reflection coated) lenses. Blooming is highly desirable in order to avoid inter-glass reflections causing annoying ghost images and a general reduction of image contrast. The most modern eyepieces have sophisticated multi-layer coatings on most of their component lenses (which are generally referred to as lens *elements*) and are superior in that respect to the eyepieces of twenty-five or more years ago. This is something to be born in mind if you are buying second-hand equipment.

2.6 SPECIFIC EYEPIECE TYPES, BARLOW LENSES AND MAGNIFICATION

In general, if the effective focal ratio of the telescope is f/8 or more then any of the simpler types currently in production will be suitable for Moon and planet observing. Developed from the now-obsolete simple two-element Ramsden eyepiece, the three-element modern Achromatic Ramsden, Modified Achromatic and Kellner eyepieces are commonly available. They generally have apparent fields of about 40–45° and in focal lengths longer than about 12 mm will give good images when plugged into f/6 telescopes. A general softening of the image and even colour-fringing will be visible, particularly near the outermost regions of the field of view, when used with telescopes of lower focal ratio. Though the eye-relief of the textbook Kellner eyepiece (recognised by it having an eyelens with a concave surface facing the eye) is uncomfortably small, all modern ones share a similar design to the MA and AR eyepieces and all of these have a moderate eye-relief of about half the focal length of the eyepiece.

The two-element classical Huygenian eyepieces are another obsolete type. In common with the Ramsdens, they could not deliver good images when used with focal ratios of less than about f/10. However, until the late 1990s, imported Asian telescopes were often supplied with Huygenian eyepieces of modified design. You will recognise one of these by the fact that the eyelens is biconvex, the classical type having a plano-convex eyelens with the flat side facing the eye. These work acceptably with focal ratios down to about f/8. They have apparent fields of view around 30° and deliver images which are very free of ghosts and scattered light. Their eye-relief is only about a third of their focal length but I find no real difficulty in using one of 6 mm focal length.

You might come across these eyepieces second-hand, most likely with 24.5 mm diameter barrels and so needing an adapter to fit them into your modern eyepiece focuser. Their main advantage is that they are (or at least should be!) extremely cheap if you can pick them up second-hand. Beware, though, any eyepiece marked 'HM'. This denotes the Huygens–Mittenzwey design. It is a three-element eyepiece (doublet eye-lens, converging-meniscus field lens) which delivers a 50° apparent field. It used to be supplied with f/15 refractors and is quite unusable for use with lower focal ratios.

An eyepiece of yesteryear that used to be a firm favourite with Moon and planet observers was the Monocentric. This cemented triplet gives crisp and false-colour-free images even with f/5 telescopes and is especially notable for its freedom from scattered light in the image, the main disadvantage being a smallish apparent field of about 30°. A Monocentric's eye-relief is usually about three quarters of its focal length.

For many decades this design of eyepiece went out of production. Now one optical company, TMB, produce a current line of Monocentric eyepieces which they call 'Super Monocentric'. The August 2004 issue of *Sky & Telescope* magazine carries a review of these eyepieces by Gary Seronik. He compared them in use to other high-quality modern eyepieces and concluded that they only just better the best of the modern alternatives for image quality at the centre of the field of view. He reports that the image quality remains excellent at the centre of the field of view even when used with an f/4.5 telescope. However, on such a low focal ratio the image quality does noticeably fall off towards the edge of the already narrow (32°) field of view. Super Monocentrics cost around $230, which is two or three times the price of a good alternative eyepiece.

If you want modern eyepieces for lunar and planetary observation for about $80 each, then you will be best served by the widely available Plössl type. They typically have apparent fields of view of around 50–55° and produce high-quality images with any telescope of focal ratio around f/6 or more (in longer focal lengths, say 20 mm, they are fine even with f/4.5 telescopes). 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 to the finest of the Plössl type, except in their apparent-field diameters of 40–45°. The eye-relief of Orthoscopic and Plössl eyepieces is each about three quarters of the focal length.

If buying second-hand, do beware of the Asian so-called 'Plössl' eyepieces, which have replaced the Huygenian eyepieces once supplied with these telescopes. These give dismal performance even with f/8 telescopes and the images are noticeably degraded well before the outside of the 40° apparent field of view is reached.

If you can stretch your budget to about $230 per eyepiece then you can have what is probably the best type of planet observing eyepiece of all. I refer to the Radian eyepieces introduced by Tele Vue in 1999. As well as excellent image quality they deliver a 60° apparent field of view and 20 mm eye-relief in all focal lengths (the range available goes from 18 mm down to 3 mm). It is true that there is a little bit of lateral colour-fringing visible close to the very edge of the field of view but the image contrast and sharpness is particularly good over the majority of it.

The one problem with Radian eyepieces is that they are unforgiving when it comes to the positioning of your eye. Move your eye pupil slightly out of position and a 'black-curtain' effect sweeps across your line of vision and cuts off your view. Each eyepiece has a built-in extendible click-stop eye-shield that helps guide your eye into the proper position. Even so, if you have difficulty in holding yourself still at the eyepiece then you might find a Radian a bit tiresome to use.

With the exception of the Speers-WALER Super Wide Field eyepieces, or Tele Vue's very expensive Nagler, Delos or Ethos eyepieces (which can also work well with focal ratios down to f/4.5) I would not recommend using any of the wide-field eyepieces for lunar and planetary observation, as most lack critical definition even at the centre of the field of view. Many are also troubled by scattered light and ghost images despite blooming. This is because they contain from six to eight lens elements.

Barlow lenses can be useful. The most common form of this accessory consists of a diverging (biconcave or plano-concave) doublet lens set into one end of a tube, or series of tubes. This end is plugged into the telescope drawtube 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 $\times 2$ 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 $\times 2$ Barlow. As well as the obvious multiplication of the magnification of the telescope by a given eyepiece, using the Barlow lens allows the cheapest simple 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. Mind you, if you have a cheap low-focal-ratio refracting telescope then a cheap short-focus achromatic Barlow lens may actually help it deliver better images, as I describe in the next section.

Some manufacturers supply ED doublet or 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 introducing a tiny amount of 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 $0^\circ.6$. This means a magnification of no more than about $\times 66$ (for an eyepiece with a 40° apparent field) to $\times 86$ (for a 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. I have measured the resolution of my own preferred observing eye as 100 arcseconds. This means that I need to use a magnification of at least $\times 100$ on my telescope if I am to see details of an arcsecond extent in the sky. Another way of looking at this is that to see the finest details possible I must use a minimum magnification of around $\times 20$ per inch ($\times 0.8$ per millimetre) of telescope aperture on any occasion when the telescope aperture and not the seeing conditions or optical quality is the limiting factor. Your eyes will quite likely be similar to mine in their limiting resolution.

Of course, that is the minimum magnification to see the finest details and not the maximum that can be used. Go much higher than needed, though, and image contrast suffers. A balance has to be struck. If the observing conditions are excellent and the telescope 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 or intricate markings on Mars, might be better appreciated with higher powers, perhaps even up to $\times 2$ per millimetre of aperture for use during rare first-class observing conditions. Poorer conditions demand lower powers, of course, as do broad features of low contrast.

I only occasionally use magnifications higher than about $\times 200$ 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. It has been only on very rare nights that I have enjoyed wonderful views at more than $\times 400$ with my largest telescope. Of course your eyesight may be better than mine, or not as good. Consequently I cannot be prescriptive when it comes to magnifications you will find best to use. Maybe my experience will help get you started and in time you will find your own favourite eyepieces to best suit you and your telescope.

2.7 MAKING THE BEST OF WHAT YOU ALREADY HAVE

Most of us have limited funds to spend on astronomy. We often have to make the best we can out of whatever pieces of equipment we already have, or have been able to acquire at limited cost. Fortunately, there are often ways of making apparently unsuitable equipment perform reasonably for our chosen task – in this case Moon and planet observing. Let us discuss a few examples . . .

It might be that you own a great big 'light-bucket' of a Newtonian reflector with a low focal ratio and mediocre optics. Perhaps it is one of the cheaply produced large Dobsonian-mounted telescopes (though these days some companies manufacture Dobsonian telescopes with truly excellent optics). A cheap Dobsonian will probably come supplied with one or more low-cost eyepieces. You find it gives very bright but disappointingly blurred images of the Moon and planets. In particular, planetary disks seem very lacking in detail. Can you improve matters without having to buy another telescope? I am glad to say that you can.

Eyepieces

Let us consider the eyepieces. The set that the light-bucket has, probably Kellners, or Modified Achromats, will undoubtedly work better with a telescope of higher focal ratio. If your telescope has a focal ratio lower than f/6, you might be advised to obtain an apochromatic Barlow lens in order to raise its effective focal ratio. A more expensive alternative is, of course, to buy a higher-quality set of eyepieces. Perhaps the foregoing notes might help you make the choice.

Off-axis stops?

You might be able to improve matters by reducing the telescope's aperture. The advantages of using off-axis stops over a telescope aperture are hotly disputed. My own experience is that stopping my 18¼-inch (0.46 m) telescope down to 6 inches (152 mm) off-axis with a cardboard diaphragm **sometimes** improves the images that 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 I described earlier. I have had the same experiences using aperture stops on other large telescopes, for instance applying a 200 mm stop on the 19½-inch (0.50 m) reflector at the Breckland Astronomical Society observatory.

If the optics of the telescope are of poor quality or are in poor collimation then stopping the instrument down will improve 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. The hole in the diaphragm should be made and positioned to avoid the secondary mirror and its support vanes (see Figure 2.5). A 16-inch to 20-inch light-bucket may be made to perform like a high-quality 5-inch to 8-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 on the occasions 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 often gets even on poor nights.

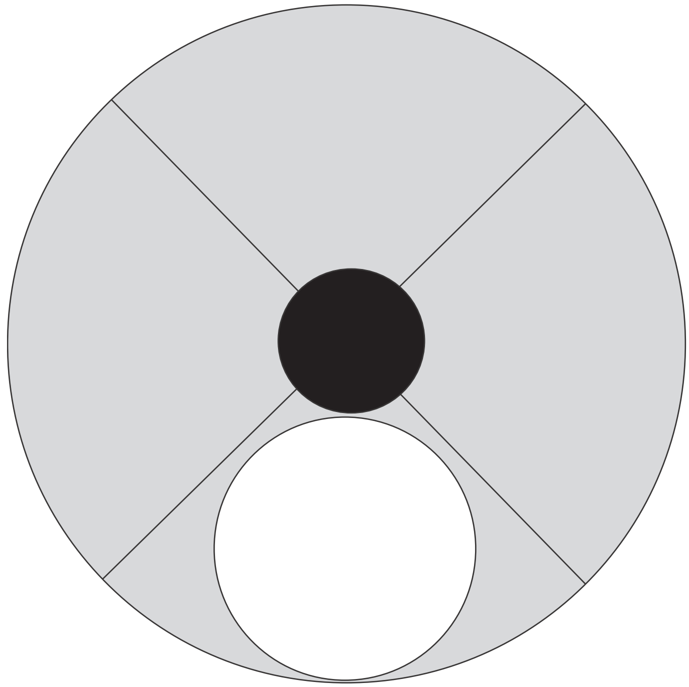


Figure 2.5 An off-axis stop for a reflecting telescope. Unless the mirror is thin enough to distort along its lower edge (unlikely in amateur-sized telescopes) positioning the aperture to expose the lower part of the mirror will normally provide the best images. This is because all of the mirror surface 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.

Apodising screens?

There is a device, called an *apodising screen*, you will have to make for yourself if you wish to try it. A very small minority of observers use these and claim a very significant increase in the contrast of planetary images their telescopes deliver along with an apparent reduction in the effects of atmospheric turbulence. Others dismiss apodising screens as useless.

A particular size of telescope aperture produces a particular size of stellar diffraction pattern in the telescope's focal plane. As I described in Section 2.1, that diffraction pattern consists of a central disk of light surrounded by concentric rings. The general idea behind apodisation is to modify this pattern to suit the observer's specific requirements. One can have various designs of apodising screen.

Here we will just consider an apodising screen that may boost the contrast of details on a bright planetary disk. The theoretical ideal would be to place a large filter at the end of the telescope tube that spans the full aperture of the telescope. This filter should be completely clear at its centre but get darker and darker with increasing distance from the centre. Moreover, to be fully effective the filter should darken in a mathematically precise way with increasing distance from its centre. At the outer edge the filter should be completely dark – in other words transmit no light at all.

To explain how this could be of any use to the observer, let me simplify our hypothetical filter. Imagine for the moment that it has a central circular area that is completely clear (100 per cent transmittance). Let us imagine that this area is surrounded by a concentric zone, which is uniformly light grey (the transmittance of light might be, say, 50 per cent). Finally, imagine that this grey zone is surrounded by a zone of uniform dark grey (the transmittance here might be, for example, 25 per cent). This dark-grey zone extends out to the edge of the filter.

So, this simplified filter has three sharply defined concentric zones of transmittance – 100 per cent at the centre, 50 per cent in an intermediate concentric zone and 25 per cent in the outermost zone. Each one of these zones will produce its own diffraction pattern when the telescope is used to image a star. The innermost one will produce the largest pattern, the intermediate zone will produce an intermediate-sized diffraction pattern, and the outermost zone will produce the smallest diffraction pattern.

The real trick here is that each of these differently sized diffraction patterns are superimposed one on top of the other. They combine to form a broad central area of light with all the concentric rings tending to blend together into a halo of light.

Now consider the theoretically ideal graded filter. This time we have what is effectively a continuous set of diffraction patterns going from small to large, all blended together. The theoretically ideal filter will generate a broad central area of light surrounded by a weak blurred halo of light.

The bright rings in the normal diffraction pattern produced by a telescope have the effect of harming the contrast of faint details seen against a bright background (this is exactly what we don't want when we are trying to see details on planets). Our theoretical apodising screen reduces this harm by turning these prominent rings into a less prominent halo. However, the downside is that the broader central disk that the apodising screen creates means that the telescope resolution is now reduced. A theoretically ideal apodising screen would actually cause the telescope's potential resolution to be halved.

So much for theory, what about actual practice? Firstly, an optical-quality filter that varies in transmittance in exactly the right way from its centre to its edge, and that is large enough to go over the end of your telescope, would be prohibitively expensive. Currently there is no such filter on the market. So, the best that you could do is to construct something that will at least approximate the function of the theoretically ideal apodising screen. One way is to use several layers of metal or plastic mesh cut into disks and stacked together to make an assembly for fitting to the end of your telescope.

The first disk of mesh has a central circular hole cut in it. The next has a bigger hole; the next a still bigger hole, and so on. When stacked together the central circular zone is then clear. The next concentric zone has just one layer of mesh, the next has two layers, and so on right up to the outermost zone, which has a stack of all the layers of mesh. The mesh screens should each be orientated to one another in order that the patterns of meshwork criss-cross each other. Ideally each of the zones created ought to pass something close to equal shares of light into the telescope.

Of course, only refractors and certain telescopes of unusual design are free of central obstructions. The central obstructions of other telescope types work against the desired effect of the apodising screen.

This type of crude apodising screen is exactly what a few amateurs have actually made for their telescopes. The usual is to use just three layers of mesh. How effective are they in practice? ‘Not very’ according to some who have tried them. Others insist they are extremely beneficial.

One downside is that the meshwork creates its own prominent diffraction patterns consisting of radiating thin coloured lines around stars and radiating coloured bands (each of width equal to the diameter of the planetary image) around planets. Anything large in the field of view is swamped by a mess of diffracted light. Look at the Moon through an apodising screen and the contrast of the view is heavily reduced by this fog of diffracted light, exactly opposite to the effect desired.

On the plus side, apodising screens certainly reduce the glare of a bright planetary disc seen against a dark sky and this does help with seeing low-contrast details. Also, cutting some of the light in the image contributed from the outer zones of the primary optic can improve the image in the same sort of way that an off-axis mask can help, as I described earlier. Perhaps these are the real main reasons that some astronomers find them an advantage in practical observing.

So, what is my advice? Well, I don’t use an apodising screen. Most other observers don’t, either. However, my mind is not closed to their potential benefits. If you have the time and you can find yourself a quantity of some material in mesh form, you might like to have a go at making your own apodising screen and try it out on your telescope. The materials you could use, the ideal sizes of the holes in the mesh (it occurs to me that stacking meshes of different hole sizes might be worth trying) and the best combination of relative areas of each of the zones you create from your stack of meshes . . . all of these factors I must leave you to experiment with for yourself.

Reducing a refractor's secondary spectrum

The secondary spectrum apparent in the images produced by a cheap achromatic refractor can be reduced by stopping the lens down. However, since the refractor is unlikely to have an aperture greater than 6 inches to start with, reducing it still further is undesirable.

There are other ways of alleviating the effects of the secondary spectrum in the cheaper refractors. One way is to try an optical trick that occurred to me years ago and which I have tried with some success. Surely other people must have tried the same thing for themselves but I have not seen the method written down before.

My idea (I'll call it that even if I am reinventing the wheel!) is to use a cheap achromatic Barlow lens, best of all one of particularly short focal length (often marketed as a 'dumpy' Barlow lens), plugged into the telescope before the eyepiece. Its own secondary spectrum will be of the opposite sense to that produced by the telescope's object glass (the Barlow's focus for yellow-green light is furthest from the lens, the other colours reaching focus closer to the lens). Although the Barlow's secondary spectrum is very unlikely to be strong enough to completely cancel the refractor's secondary spectrum, it will at least reduce it.

The situation can be further helped by lengthening the barrel of the Barlow lens (by plugging in an extension tube that goes in before the eyepiece). Along with further increasing the magnification of the Barlow lens, this will significantly increase the amount of secondary spectrum generated by it, so cancelling out rather more of the dominant secondary spectrum of the refractor's objective.

However, this cannot be carried too far. For one thing, the magnification may become greater than desirable, though one can bring the magnification down by swapping the chosen eyepiece for a longer-focus one. For another, any seidal aberration generated by the Barlow lens (particularly spherical aberration) may then become itself great enough to spoil the image. A final reason not to lengthen the Barlow tube too much is that to deliver a focused image the Barlow lens may wind up so far inside the telescope's focus that it begins to vignette the rays from the object glass, effectively stopping the telescope's aperture down.

An alternative way of reducing the effect of the secondary spectrum is to attach a strongly coloured filter to the eyepiece before you plug into the telescope. You will have to put up with a planet or the Moon that appears the colour of the filter but at least the image will appear sharp (provided the filter is of good quality) and colour-fringe free.

One step up from that is a filter which is specially designed to reduce the visibility of the secondary spectrum of refractors. Companies that make these include Baader Planetarium, Orion Telescopes and Binoculars, and Sirius Optics. You might like to refer to an article 'Curing the Refractor Blues', in the April 2004 issue of *Sky & Telescope* magazine, where Thomas A. Dobbins compares the effects of a number of different filters on views through his Chinese-made achromatic 6-inch f/8 refractor. Of those he tested he liked the effect of Baader's Fringe-Killer and Neodymium filters stacked together the best. The main advantage of any of these special filters is that they reduce the appearance of a refractor's secondary spectrum while only imparting a relatively weak colour-cast (yellowish-green in most cases) to the image.

Mechanical deficiencies

In this chapter I have concentrated on matters optical but I must at least give mention to some matters mechanical. A common fault with telescopes, either homemade or purchased, is an eyepiece focuser that is sloppy and cannot be adjusted precisely. Worst of all, though, is a telescope mounting that is tremulous. If every touch, or even a breeze, makes a planet appear to rattle like a dice in a shaker then your observing experience will be marred by disappointment and frustration.

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 largely rebuilding the telescope and just incorporating some of the parts of the original. At the same time you can make any changes that will improve the instrument's thermal characteristics. I do realise that this might seem like a quaintly old-fashioned approach. I also know that spare time is a rare and precious commodity these days but the end result – a sturdy telescope that functions just as you wish it should – is surely an ample reward for any time and effort you spend.

2.8 PERMANENTLY HOUSING A TELESCOPE

Today's marketed telescopes are much more portable than the bulky and heavy instruments of yesteryear. The downside is that they tend to be much less rigid. Nonetheless, a modern telescope that is large enough to carry out serious observing of the Moon and planets is quite likely to be portable, even if only just so.

It is, though, an undeniable convenience to have a telescope permanently mounted in the grounds of one's home. Such a telescope can be brought into operation very quickly and it will suffer far less from the sort of thermal problems that arise from bringing a telescope outdoors from a warm house and delay it delivering good images.

Lugging equipment out of the house and setting it up for an evening's observing takes valuable time and effort. The prospect of having to dismantle everything and lug it all indoors once more at the end of the session can also be a bit of an enthusiasm killer in the early evening when you are eyeing up a sky consisting of a mixture of clear areas and some scudding clouds. Take it from me, how much you observe in the long term will be largely affected by how quick and easy you find both setting up for an observing session and packing everything away again after it.

I obtained the parts of a wrecked, 1970s-vintage, 10-foot (3 metre) diameter fibreglass observatory dome some years ago, after moving to my present home in Norfolk, and had to spend many months repairing and renovating it. The effort was very worthwhile as I now very much enjoy using the 10-inch (254 mm) reflector presently housed within it. Domes can be purchased new but they are expensive. Making one is a cheaper alternative and a large variety of materials and construction methods can be used.

A much cheaper and simpler alternative to a dome is a run-off shed. I built one of those for my largest telescope back in the 1970s when it was sited in my parents' large garden at Seaford. The whole of the north end of the shed functioned as a door. This door was opened and the shed then pushed off to the south. This was the best arrangement for the position of my telescope in the garden, taking into account the sky access allowed by tall hedges to the south over which I had no control. My shed rolled on large wheels on wooden rails but angle irons and pulley wheels are a common alternative. You can just see part of the northern end of my shed, the door having been closed once more after the telescope had been exposed, at the far right of Figure 2.3(a).

Another alternative, and one that is especially good for tall mounted telescopes such as refractors and catadioptric telescopes, is to have a shed with fixed walls and a roof that can run off on rails. Do make sure that any fixed-walled structure is spacious enough for you to work safely and easily in it in the dark.

You will need to be aware of planning regulations. Find out what is allowable and what requires special planning permission in the grounds of your home. On the subject of regulations, please be aware that installing mains electricity to the observatory and fitting plug sockets and lights normally requires either that a certified electrician does the work or that a local planning authority inspector has to pay you one or more visits to check up on your own work. If doing your own electrical fitting, never, **never**, **NEVER take chances with mains electricity. Beware damp, especially that caused by condensation and leaking**

rainwater, and make sure everything is properly earthed. Also ensure that the observatory is supplied via a safety cut-out device, such as an earth-leak trip system.

Actually there is a lot to be said for running your equipment and observatory lighting from a low-voltage power supply. The transformer can be installed in your house or garage and only a 12–24 volt supply need emerge from it to cross under the lawn and enter your observatory. If you choose this option I advise using a heavy gauge of cable to supply the observatory, even though its cost is much higher than a thinner cable. Domestic-kitchen cooker cable (typically rated for 30 ampere) would be suitable. The electrical resistance of a long length of thin cable would significantly reduce the voltage delivered to the dome from that produced by the transformer. The lights would shine less bright in your observatory as a result and you might even have problems with any voltage-critical electronic devices you use. The voltage drop increases in proportion to the current drawn by the lights and/or other devices running in the dome. The heavier the gauge of cable used the lower its resistance per unit length will be and so the less the volts lost per ampere drawn.

One consideration that is especially important for the Moon and planet observer is the local seeing conditions. Swirling warm air will wreck the views through your telescope. The worst possible design combination would be an un-insulated sheet metal dome with a narrow slit, painted on its outside in a dark colour, while inside having a naked multi-tonne concrete floor. A dark colour outside together with a lack of insulation will turn the interior into an oven during a sunny day. A concrete floor will get hot and stay hot long into the night, generating seething currents of turbulent warm air to stream out through the narrow slit.

A white or silver colour is thermally best for the exterior but a light green can look very garden friendly and is a reasonable compromise. The rotating hemispherical section of my dome is a pale mid-green and the walls a slightly stronger greengage hue. The effect is very pleasing and takes off the 'oil tank' appearance that a dome can have in a garden (see Figure 2.6).

A suspended wooden floor is best in a fixed building. Remember, though, to ensure that its underside is also well ventilated otherwise it will rot. I also recommend the liberal use of wood preservative underneath and a good varnish on its uppermost surface.

Failing a suspended floor, at least have any concrete thermally insulated by being well covered in laminated or vinyl floor covering, and/or carpeting. Do, though, beware of fabrics getting damp and going

Figure 2.6 The 10-foot (3 metre) dome the author renovated and which now houses a 10-inch reflector. Manufactured from fibreglass (GRP) in the 1970s it was originally a very dark green colour. The author painted it light colours to improve its thermal characteristics and to protect its sunlight-crazed surface from further degradation. The colours are garden friendly as is shown in the colour version of this figure, later on in this book. [This image is also reproduced in colour as PLATE I (lower) between pages 304 and 305].

mouldy given that the observatory is unheated. The concrete should first be heavily painted with a waterproofing stabiliser solution to limit rising damp.

The telescope must have a firm base, perhaps a concrete plinth set into the ground. No part of the telescope or its base should touch any part of the suspended floor in order to avoid transmitting vibrations to the instrument. For the same reason there should be a gap between the telescope plinth and any surrounding concrete flooring.

Ventilation is also important to avoid a build-up of mould and spores inside the observatory, as well as for keeping down condensation and moderating the temperature difference between the interior and outside. An observatory is far from being an essential – but a well-designed housing for the telescope will certainly increase the pleasure of your observing experience and your productivity.

CHAPTER 3

The Solar System framed

Nowadays a large proportion of amateur astronomers are astrophotographers. In fact, I am fairly sure that **most** amateur astronomers do at least some astronomical photography. This was not the case until relatively recently. I was certainly aware of being in a minority of practising amateur astronomers when I began astrophotography in the early 1970s. Back then, most commercial film processors and printers did not do a good job with astronomical subjects. So, to get the best results normally required the aspiring astrophotographer to set up a darkroom and get involved with the chemicals and operations needed for processing films and creating the final prints. I happened to love doing all that but for most other amateur astronomers that was a step too far.

The recent availability of a range of electronic imaging devices, all fairly easily used with laptops or PCs to give immediate results, has resulted in a veritable explosion of practising astrophotographers. Also, I must say that the quality of the images now routinely achieved using electronic imaging with the best amateur equipment would have been the envy of even the professional astronomers of yesteryear who used light-sensitive emulsions on film or glass plates as their recording medium.

In this chapter and the next I summarise the basics of how you can set about taking your own photographs of the various Solar System objects. I provide additional advice for photographing specific planets in each of the relevant chapters later in this book. Further, the equipment and techniques needed for photographing asteroids and comets (and carrying out astrometric and photometric measures of them based on the captured images) is covered in detail in Chapters 10 and 11. **The specialist field of solar photography involves potential dangers for both observer and equipment and should not be attempted until**

Chapter 12 has been read – and even then only if the greatest care is taken and all precautions are strictly observed.

3.1 CHOICES

Mobile telephones and other low-end electronic wares that can take pictures or videos have been pressed into service by some people to take pictures of bright Solar System objects through their telescopes. However the quality of the results is often wanting, so I will not be discussing those devices in this book.

The imaging devices most commonly used by serious amateur astronomers are the *CCD astrocamera*, *the digital camera* (preferably a *digital single lens reflex* camera – usually known as a *DSLR* camera) and the *fast-frame-rate video camera* (this category includes the humble *webcam* at the cheapest end of the market). All these can be used with your telescope for photographing the various celestial bodies that make up our Solar System.

However, they are not equally good for every subject. Generally the DSLR camera is best for wide-angle shots, for instance encompassing the whole of the Moon's disk (or the Sun's – but please remember the warning I gave in the introduction whenever I mention solar photography in this chapter and the next).

The CCD astrocamera can also be used for wide-field imaging if it has a large enough active imaging area. In addition, it can be used for fairly high-resolution imaging of the Sun, Moon and planets, though it will not produce the very best results if only single frames are taken. Many amateurs like to undertake deep-sky photography and this is the field in which the CCD astrocamera reigns supreme. The same characteristics that make the CCD astrocamera particularly good for deep-sky astrophotography also make it good for asteroid and comet imaging.

The fast-frame-rate video camera, when used with appropriate software, is the best choice for obtaining the highest resolution views of the planets or of small areas of the Sun or Moon. On the downside, the associated software and techniques are a bit involved, so I have given over the next chapter to this important topic. Nonetheless, there is much in this chapter which is relevant to the material in the next, so I recommend that you treat this chapter as the foundation for all the astronomical photography described in the rest of this book.

3.2 CCD ASTROCAMERAS AND DIGITAL CAMERAS

In the majority of cases the best quality imaging devices have at their heart a device called a *CCD* (the letters standing for *charge-coupled device*), as the image collector. A cheaper alternative to a CCD is a *CMOS* (*complementary metal oxide semiconductor*) detector. The Nikon range of DSLR cameras use these, as do some other devices such as the cheapest webcams. The Nikon cameras are extremely good for their price. In general, though, you get what you pay for and so I recommend choosing devices with CCD detectors wherever possible.

A CCD consists of an array of light-collecting units, called *pixels*. Each pixel on the CCD has the same size and shape as its neighbours. That size can range from about 5 μm to about 25 μm (5 micrometres to 25 micrometres) square. Today's professional astronomers mostly use large CCDs, having an array of 2048×2048 or more (often many times more) pixels each of around 25 μm square. These are hugely expensive. Amateur astronomers use smaller versions. Though much cheaper than the professional observatory astrocameras, they still cost from a few hundred to several thousand dollars/pounds.

I recently acquired a Starlight Xpress HX916 astrocamera (see Figure 3.1(a)) Although it is an older (2001) model, it can still be considered to lie within the rather wide compass of what constitutes a typical amateur's astrocamera of today. It has an array of 1030×1300 pixels each 6.7 μm square. So, the total active imaging area of the CCD is 6.90 mm × 8.71 mm.

It cost its original owner about £1800 (roughly $2700). Until recently, you could expect to pay about the same for the latest equivalent model. Then the Santa Barbara Imaging Group – usually known as SBIG – marketed their ST-8300M astrocamera. Its Kodak KAF 8300 CCD has 2504×3326 pixels, each 5.4 μm square, so the light-receiving surface of the CCD measures 13.5 mm × 18.0 mm. Its introductory price was $1995, considerably less than previous cooled astrocameras of equivalent specification. Other manucturers such as Atik and Starlight Xpress have since produced their own versions of this camera based around the same Kodak CCD, while undercutting SBIG's price. I expect that you can look forward to rather more for your money with the very latest generation of astrocameras when the time arrives for you to go shopping. In theory, this price reduction should also filter down to older models of astrocameras on the second-hand market.

How the CCD works

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 brighter the light (the

Figure 3.1 (a) The author's Starlight Xpress HX916 camera system. To the left of the camera head is the USB interface that connects between the camera head and the computer. To the right is a camera lens adapter. The power unit can be partially seen in the background. (b) The author's Starlight Xpress SX camera system. To the left of the camera head is the 15 metre reel of cable that goes between the camera and the power and interface unit. This unit is partially shown to the right.

more photons per second) falling on a given pixel, the faster electrical charges are liberated within it.

Let us consider an image focused onto the picture-receiving area of the CCD. The pixels illuminated by the brightest parts of the image have charges liberated in them at the greatest rate. Meanwhile, the dimmest parts of the image generate the slowest rate of charge build-up in those corresponding pixels.

If you let the process continue charges would continue to build up all the while the light is falling until each and every pixel becomes 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 old 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 accumulated while those associated with the brightest parts of the image have lots of charge, though ideally a little less than the amount that would cause saturation. Thus, a representation of the image as an array of electrical charges is created on the CCD.

Next, the array of charges are sequentially read off the chip and sent as a representative data stream to a computer, or other electronic devices to deal with in order to recreate the image on a monitor or television.

DQE and the wavelength responses of CCDs

A convenient unit for expressing wavelengths of light is the nanometre. A nanometre is one thousand millionth of a metre. As an example, green light has a wavelength of *circa* 500 nanometres. This could be written as 500 nm or 5×10^{-7} m.

A CCD is not equally sensitive to all wavelengths of light. The percentage of the total number of photons of light falling on the CCD at any given wavelength that is detected by it is properly known as the *DQE* of the CCD at that wavelength; DQE stands for *detector quantum efficiency*. I have noticed in the latest literature that the 'D' or 'detector' part of this term is often dropped.

A DQE of 100 per cent is the best that one could possibly have, all the incoming photons then being detected. The earliest examples of CCDs all tended to have their maximum sensitivity in 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 both shorter and longer wavelengths to become zero at about 400 nm (violet) and at about 1100 nm (near-infrared). 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, falling to zero at about 380 nm (deep violet) and at about 700 nm (deep red).

Many of the later generations of CCDs have coatings which enhance their response to light at the blue end of the spectrum. To take an early example, the Philips FT12 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 quite a lot of its sensitivity, having a peak DQE of only 30 per cent. Coming a little more up to date, the Sony ICX085 CCD in my Starlight Xpress HX916 astrocamera has its DQE peaking at 47 per cent in the green.

The reason I mention older astrocameras and their CCD detectors here is that you might well wish to buy one second-hand, rather than lay out the considerable cost for a new one. If so, as well as taking all the usual precautions that you would naturally do as a purchaser, I recommend that you investigate (maybe online, or at least within the supplied paperwork) the characteristics of the CCD installed in it. It would be a shame to waste money on a unit that you would find disappointing in use. If it is a really old astrocamera you ought also to check that its controlling software will run on your computer. For instance, the camera control software of a Starlight Xpress SX system (see Figure 3.1(b)) I was given will not run in anything later than *Windows 98*.

Digital cameras have CCDs which are designed to mimic the response of the human eye. They also have an array of red, green and blue filters (called a *Bayer matrix*) layered on top of the CCD so the camera can record images in colour. For these reasons domestic digital cameras have rather lower values of DQE than do astrocameras.

The DQE is a very important factor when imaging the faintest deep-sky objects. Nonetheless, many amateurs produce spectacularly good full-colour images of even very faint deep-sky objects using DSLRs and they are easily sensitive enough to produce nice images of the Sun, Moon and planets. I should add that there are also small numbers of CCD astrocameras which you can buy that are 'one-shot colour' cameras. They produce their coloured images in the same way as do the detectors in DSLR cameras.

More CCD characteristics

There are a number of variations in the design of modern CCD detectors. Look at the literature and you will come across terms such as *progressive scan*, *interline transfer* and *frame transfer*. These refer to the way the CCD is structured and, consequently, how the image is read from the chip. You may also come across *back-illuminated* and *front-illuminated* CCDs. These terms also relate 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) and different imaging devices use different types of CCD. You can do your Solar System photography pretty much just as well with any of these types, so I don't propose to spend pages detailing all these terms. After all, when you purchase a motor car do you worry much about the engineering design and technical fine details of its engine? In the real world, rather than in the theoretical realm, considerations of cost, pixel size and imaging area are of the greatest importance to you if you are to equip yourself to do astrophotography on a limited budget.

One problem afflicting CCDs of all types is something called *dark current*. While an integration is underway thermally liberated charges build up in each of the pixels along with those liberated by the incident light. At room temperature, these charges can build up to fully saturate each pixel in just a few seconds for the older models of CCD and not always a lot longer for the latest versions (at least for those at the cheaper end of the market).

Even before the point of saturation the thermally liberated charges are reducing the total *dynamic range* (range of brightness levels) recordable – for instance if the pixel becomes half full of thermally generated charges then only half of it is left to fill with light-generated charges. The effects are negligible for very short integration times, say a fraction of a second. However, integrations longer than a few seconds produce images afflicted with a 'noise' of random apparent brightness variations at the pixel level of detail superimposed on the otherwise pure image. With longer integrations this can even build to a snowstorm effect as more and more of the pixels fully saturate.

Practical CCD astrocameras have built-in thermoelectric coolers to reduce this problem. An astronomer wishing to record a faint galaxy on a CCD will need to use an integration time of minutes, maybe even stretching into hours. Cooling the CCD is then essential. We photographers of the Sun, Moon and planets are fortunate in that these celestial bodies are usually bright enough for integration times of less than a second. Photography of asteroids and comets will normally demand exposure lengths somewhere in-between, and CCD cooling is usually needed, unless a series of short exposures are taken in order to create the effect of a single long exposure (using software to combine the exposures).

Many medium-cost digital cameras are fitted with CCDs capable of reasonable results with exposures as long as several tens of seconds. The one-shot colour versions of CCD astrocameras have cooled CCDs and so are superior in their imaging characteristics to DSLR cameras and all the lesser versions of digital cameras.

CCD astrocameras in practice

If you take another look at the Starlight Xpress astrocamera head shown in Figure 3.1(a) you will notice the small grey square that appears just inside the facing end. This small square is the Sony ICX085 CCD. Of course the unit also contains some electronics but the major part of the mass of the camera head (about half a kilogram) is associated with the cooling unit.

Unlike the first generation of CCD astrocameras, even this fairly old model is connected by a USB (Universal Serial Bus) cable to the computer (albeit via an adapter in this model). It does have a separate power-supply module. All functions of camera control and image acquisition are controlled from the computer. You can expect any recently manufactured second-hand or newly purchased astrocamera to have provision for either direct USB or a Firewire connection to the controlling computer. My museum-piece (1996) Starlight Xpress SX camera connects via RS232 plugs and a 15 metre long cable to a box of electronics. This in turn connects via a ribbon cable to a 25-pin 'D' connector to the computer's printer port!

When you purchase an astrocamera system the camera head will come with a telescope adapter that screws into the front of it. This is to enable it to be plugged into the telescope drawtube (or Barlow lens, or other amplifying system used on the telescope) in the same manner as one would plug in an eyepiece.

One can also use the camera head with a photographic lens if desired. If you already have or wish to buy second-hand photographic lenses that formerly were used with single-lens reflex (SLR) film cameras – and there are a lot of them about at bargain prices – then these can be attached to CCD astrocameras with the appropriate adapter ring between the camera body and the lens. Consult the manufacturer/supplier for advice on the specific adapter needed. As well as the obvious requirement for thread/bayonet-matching, the adapter has to set the lens at the correct distance from the CCD. My Starlight Xpress HX916 unit requires a 27 mm spacer, for instance.

In most cases when using old camera lenses, you will also need an infrared-blocking filter to attach to the front of the lens (usually by the conventional 48 mm threaded fitting filter-mount) because the focus for the near-infrared light that the CCD is also sensitive to differs from that of the visual wavelengths the lens was designed for. This filter usually also incorporates ultraviolet (UV) blockage. Most photographic films were barely sensitive to deep red light and were totally insensitive to the infrared. A late-generation CCD may have sufficient UV sensitivity to warrant also blocking the UV end of the spectrum.

With the camera plugged into the telescope, the weight of the camera head will necessitate re-balancing the telescope tube, perhaps using additional counterweights and maybe sliding the tube along in its cradles or using strap-on weights, etc. A DSLR camera will probably weigh even more than a CCD astrocamera head.

Current manufacturers of CCD astrocameras include Atik, Finger Lakes Instrumentation, SBIG, Starlight Xpress, Opticstar, and QHY. They all proffer a range of models that come with different price tags. Of course you get what you pay for – but at least you can get started for as little as about £300 (about $500) for a cooled camera with a small sub-megapixel chip.

I recommend searching out advertisements in astronomy magazines current at the time you decide to purchase the camera. In addition, spend time on the Internet trying to find out as much as you can. Online chat groups and forums are useful for uncovering the pros and cons of any advertised camera before you make your own purchase. Also, take the time you need to obtain further information direct from the manufacturers.

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 acceptable results. There will be variations in operation between one system and the next so I will confine myself to offering general comments on matters relating to operating the camera with your telescope. First, though, we should consider how much of the sky you can expect to image in one go as this is fundamental when choosing the equipment that best suits your needs.

3.3 THE IMAGING AREA OF A CCD WHEN USED WITH A CAMERA LENS OR TELESCOPE

The basic characteristics of a CCD astrocamera for imaging Solar System bodies that we need to concern ourselves with are the size of the imaging area of the CCD and resolution in the image (number of pixels height × number of pixels width comprising the image). I will defer discussing the image resolution until Section 3.5. The complication is that what these quantities produce in practice depends on the focal length of the telescope or the camera lens that the astrocamera happens to be plugged into. Here 'telescope' and 'camera lens' can be used interchangeably – it is only the focal length that is relevant – so please let me just refer to 'telescope' in the following ...

The image scale (in arcseconds per millimetre) at the focal plane of a telescope is given by:

$$\text{image scale} = 206265/f,$$

where f is the *effective focal length* of the telescope, taking into account the effect of the amplifying secondary mirror of a compound telescope. The figure used for the effective focal length must also take into account any additional optics (Barlow lenses, etc.) in the light path before the focal plane. More about that later.

The literature that comes with the camera should certainly state the size of the active area of the CCD. In the case of my Starlight Xpress HX916 camera it is 6.90 mm × 8.71 mm. If that figure is missing, then surely the literature ought to state the number of pixels in height and width in the imaging area and the size of each pixel. In the case of my camera it is 1030 pixels$\times$1300 pixels, each pixel being 6.7 μm square. 6.7 μm is 6.7×10^{-6} m. Multiply 6.7×10^{-6}m$\times$1030 pixels and you get 6.90×10^{-3}m. This is the (as it happens already known) 6.90 mm height of the active area. Similarly multiplying 6.7×10^{-6}m by the 1300 pixels gives the 8.71 mm width of the active area.

Knowing how many arcseconds of sky is covered by every millimetre of image and the height and width of the active area of the CCD in millimetres allows you to easily calculate the height and width of the image in arcseconds.

Let us say I plugged my camera into a standard 8-inch (203 mm) aperture f/10 Schmidt–Cassegrain telescope. In practice, the effective focal length of this type of telescope happens to vary a little with the precise position of the focal plane – focusing is achieved by moving the primary mirror, and this alters the focal plane's position. So, for the purpose of this example, please let me pick a round figure of 2000 mm for the effective focal length for this particular telescope. In practice, the variation is very small anyway, so our simple calculation will still give a good idea of what to expect.

To begin our calculation, a focal length of 2000 mm produces an image scale at the telescope's focal plane of 103.14 arcseconds per millimetre. The height of the image contained on the CCD in arcseconds is then simply: 103.14$\times$6.90. This equals 712 arcseconds. The width of the image in arcseconds is 103.14$\times$8.71. This equals 898 arcseconds. To summarise, my Starlight Xpress camera if plugged into an 8-inch f/10 telescope would produce an image covering an amount of sky equal to 712 arcseconds$\times$898 arcseconds.

Is this the area of sky you actually desire to image? Let us say that you want to image the Moon's entire disk during an eclipse. The Moon's apparent diameter varies a little as it orbits the Earth but it averages at about 1870 arcseconds. I am sure that you can see that you will only be able to image a very small section of the Moon in one go with this particular combination of telescope and camera.

If you wanted to image the whole of the Moon in one shot with that model of astrocamera, you would need to plug it into an optical device with a focal length (or at least an effective focal length) no greater than about 760 mm. Some modern refracting telescopes have focal lengths close to that figure. Of the optical equipment you have at your disposal, perhaps a telephoto lens of reasonably long focal length (maybe with the addition of a tele-extender lens if you have one) would be best to capture those whole-disk images of the Moon you want?

The Sun's disk is very similar in size to that of the Moon but the planets present very much smaller targets. Even the biggest of them, the planet Venus at the brief times when it is very near inferior conjunction, spans only 65 arcseconds. Most of the time Venus is very much smaller and then Jupiter takes over the crown as the planet that appears largest, at up to 50 arcseconds in diameter. The other planets are always smaller than this. So, at an image scale that shows the whole of the Moon's vista in one go a planet will appear as a tiny disk and the picture area will be mostly filled with blank sky.

Rather than each time plodding step-by-step through the calculations as I have done in the foregoing example, you might find the following general equations useful to have to hand:

$$\text{width of the image (in arcseconds) on the CCD} = 206265X.\mathrm{d}/1000f,$$

and

$$\text{height of the image (in arcseconds) on the CCD} = 206265Y.\mathrm{d}/1000f,$$

where X and Y are the numbers of pixels comprising the width and height of the CCD, respectively, d is the size of one pixel in micrometres (μm) and f is the focal length of the telescope (or camera lens) in millimetres. If the CCD pixels are not square (they usually are in modern astrocameras) then the appropriate values of d have to be used in each case, of course.

If you want to photograph the widest area of sky using your standard telescope, a telecompressor lens – these days usually called a *focal reducer* – will give you a proportionate increase in the field of view you can image with it. These accessories are usually optional extras with many commercial telescopes, especially so Schmidt–Cassegrains.

Do be aware, though, that the standard ×0.33 focal reducer (delivering an effective focal ratio of f/3.3) for the Meade and Celestron f/10 Schmidt–Cassegrains will only give a good image across the full extent of a CCD of no more than about 1 cm square. As it happens, this would be fine for the small CCDs on each of my own Starlight Xpress astrocameras. In fact, if I plugged my HX916 camera into the same 8-inch f/10 telescope as before but this time using the ×0.33 focal reducer, I would now be able to image a patch of sky of area equal to 2136 arcseconds × 2694 arcseconds. This would easily encompass the whole of the disk of the Moon, framed by just a little blank sky around the disk. Another, albeit much more expensive, alternative to a focal reducer is to buy an astrocamera with a bigger CCD.

This is where a DSLR camera really scores. One costing no more than $600 will often have a large CCD, perhaps about 17 mm × 25 mm across covered in at least six million pixels. A higher expenditure will allow the purchase of a new DSLR camera with perhaps a 23 mm × 37 mm CCD containing somewhere around twelve million pixels. We get a large imaging area along with a very fine resolution. Hence, DSLR cameras are great for imaging the whole of the Moon or the Sun in one go. This is very useful for events such as eclipses, when one-shot colour imaging is also a great advantage.

Though the CCD astrocamera is more sensitive and can take longer single exposures thanks to the CCD being cooled, the DSLR camera is still a powerful deep-sky imaging device, especially if you combine the results of several exposures. Therefore, it is also good for photographing starfields containing asteroids. For the same reason a DSLR camera is also very good for obtaining spectacular colour portraits of even fairly minor comets.

A handy rough rule of thumb that will serve to give an idea of the size of the full Moon's, or the Sun's, image on the CCD of either an astrocamera or a DSLR camera is:

$$\text{Moon image diameter} = \text{effective focal length}/107;$$

$$\text{Sun image diameter} = \text{effective focal length}/110.$$

As an example, plugging a DSLR camera with a 6 megapixel 17 mm $\times$ 25 mm CCD into a telescope of 1800 mm focal length will enable the whole Moon, or the whole Sun, to just fit within the imaging area. The Moon's or the Sun's image will then span approximately 2000 pixels at a scale of roughly 1 arcsecond per pixel.

3.4 PRACTICAL PHOTOGRAPHY THROUGH THE TELESCOPE – AT THE PRINCIPAL FOCUS

Some people mean 'principal focus' when they incorrectly say 'prime focus'. Amateur reflecting telescopes with no secondary mirror and equipment mounted at the true prime focus position are extremely rare. In many cases the principle focus will be the Newtonian focus, though the first focal plane of the refractor, the Cassegrain reflector or the catadioptric telescope also counts as 'the principal focus'.

The CCD chip's imaging surface is positioned at the principal focus in each case with no additional optics to further enlarge the image. Image scale and, from that, the height and width of the patch of sky imaged on the CCD are calculated just as before.

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 awkward. Many telescope suppliers provide a wide range of accessories you can purchase, including 'T-ring' adapters that can fit your lensless DSLR camera body into the telescope drawtube. Similarly, your purchased astrocamera will normally be supplied with an adapter to enable it to plug into your telescope's drawtube.

However, the CCD's surface within the camera will usually be approximately two centimetres back from the T-ring for a CCD astrocamera (maybe a little less, maybe a little more, the precise figure varying with the camera model) and about four and a half centimetres back in the case of a DSLR. You might well find that the focuser will not rack inwards far enough to allow the CCD to reach the telescope's 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 in your telescope's tube. For instance, with a Newtonian reflector you might move the primary mirror cell a little up the tube towards the secondary mirror.

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 that you can safely store the telescope's optics while carrying out the work**. Just to pick out one hazard, you will ruin the reflective film on any telescope mirror in any place you allow your fingers or palms to touch. I would hate to think of any enthusiast damaging their expensive telescope because of anything I have written, so please forgive me including this elementary warning.

Remember that if you bring a reflecting telescope's mirrors a little closer together the secondary mirror will then intercept a larger area of the cone of rays delivered from the primary. Make sure that the secondary mirror is large enough to still intercept all the rays. It might work fine in its original position but could easily vignette the field of view if you move it too close to the primary mirror. The rays of light from the outer zones of the primary mirror would be blocked from contributing to the image. The effect would be the same as stopping down the telescope's aperture. Please see Section 2.2 in the last chapter for formulae you can use to calculate the minimum size of secondary mirror needed for a given telescope focal ratio and distance between the secondary mirror and telescope focal plane.

Vignetting might also be caused by the drawtube in telescopes of low focal ratio. Try to avoid vignetting if you can, or at least do your best to minimise it. It causes the picture to darken away from the centre and more and more towards the corners. At least you can correct this problem in the subsequent processing of your captured image.

In most cases your telescope will need to be driven to follow the diurnal motion of the celestial bodies if you are to obtain sharp images. It is true that anything bright enough to allow it to be photographed with an exposure of a small fraction of a second can be captured through an undriven telescope. However, having the image 'stay put' while you are attaching the camera and then adjusting the focus would make life a great deal easier. I go into some quantitative detail about the need for having the telescope track the stars in Section 3.7.

3.5 LIMITS ON THE POTENTIAL RESOLUTION OF DETAIL IN THE IMAGE

Sometimes we will want to image the whole of the Moon or the Sun in one go. Even then we desire to see as much detail as possible but have to put up with the limits imposed by the image scale. Perhaps more often we will be photographing a planet or a part of the Moon or Sun for the sole purpose of recording the finest details possible. In that case we will need to use a telescope with some additional optics to enlarge the primary image. More about how to do that shortly. First, let us consider how much detail we can potentially deliver in an image using whatever equipment we have to hand.

There are seven factors that will limit the fineness of detail we can resolve:

1. Deficiencies in the optical system.
2. Deficiencies in the mechanics – most often the drive system.
3. Errors in focusing.
4. Atmospheric turbulence (and atmospheric dispersion may further degrade the image, even if it is not actually a limiting factor).
5. The aperture of the telescope.
6. The size of the pixels on the CCD.
7. The effective focal length of the imaging system.

The first two items on the list might be ameliorated by careful technique, such as stopping down a poor quality set of optics, etc. In mechanical deficiencies I include poor collimation, which again is under your control, as is poor polar alignment if the exposures are long enough for bad tracking to be a factor. Appendices 1, 2, and 3 near the end of this book may help you with these matters. Errors of focusing can be reduced by a painstaking approach and a delicate touch on your part, though matters can be helped very considerably by the fitting of a high-quality focuser. Better still, a high-quality motorised focuser.

Atmospheric turbulence is something you will have to put up with. The best you can do is to ensure conditions in the environment close to the telescope are as favourable as you can make them. In particular, you should do your best to ensure the temperature of your telescope is as close to the ambient temperature as possible at the time you wish to perform your photography. Open up your observatory, or take portable equipment outside well before hand – an hour or more if at all possible.

If you are lucky enough to have any choice, select an observing site of known good seeing. Ace planet imager Damian Peach packs up his equipment and takes vacations on the island of Barbados to produce his very finest images. Having said that, his imaging runs from England still generate world-class results, so please don't use less-than-perfect seeing as an excuse for not bothering!

I mentioned atmospheric dispersion along with atmospheric turbulence. Dispersion will almost never be a factor that on its own limits the image resolution but may well further degrade an image. One remedy is to purchase an atmospheric-dispersion corrector (available from Adirondack Video Astronomy, in the USA – www.astrovid.com). Another is to take your photograph through a coloured filter. I recommend a red filter as the effects of atmospheric turbulence appear least destructive in longer wavelengths and most CCDs have good sensitivity to red light.

If you want a colour photograph through your digital camera but the image is smeared vertically by atmospheric dispersion you could take repeated exposures through coloured filters and combine them (the red, green and blue images will each be slightly separated – that is what causes the image degradation) using software such as *Adobe Photoshop*. You should only be troubled by atmospheric dispersion when imaging objects close to the horizon. The degrading effects of atmospheric turbulence will also be prominent at the same time.

Next we come to the aperture of the telescope. The reason I have not put this at the head of the list is that one or more of the other factors will likely prove to be the limiting factor. A high-quality telescope with an aperture of 6 inches (152 mm), used on the very best nights, should enable you to see (and potentially to resolve in your photographs) detail that is 0.9 arcseconds in extent. On most nights, atmospheric turbulence smears the image so that at best you get infrequent brief glimpses of detail that fine. You will be doing well to image sub-arcsecond details during a **single exposure** however large your telescope may be.

The reason I emphasised 'single exposure' is that the video techniques described in the next chapter will give you the best chance of recording the finest detail, however good or bad the observing conditions. These techniques will often allow you to break through the 1 arcsecond limit, whereas taking single images will achieve that only rarely.

Next, we should consider the interrelation between the size of the CCD's pixels and the effective focal length of the telescope (or camera lens if that is what is used). Let us re-use the hypothetical example of my Starlight Xpress HX916 camera plugged into a standard 8-inch f/10 Schmidt–Cassegrain telescope.

As before, the telescope's 2 metre focal length produces an image scale of 103.14 arcseconds per millimetre. The CCD in the camera has pixels which are 6.7 μm (6.7×10^{-6} m) square. Now 1 millimetre is 1×10^{-3} m. So, the CCD has $(1 \times 10^{-3})/(6.7 \times 10^{-6})$ pixels spanning every millimetre. This is 151.5 pixels per millimetre. If you are not happy working with numbers in the '6.7×10^{-6}' style then simply remember that there are 1000 micrometres in a millimetre – hence the calculation would then be: number of pixels spanning every millimetre = 1000/6.7 = 151.5.

Dividing the number of arcseconds per millimetre that the telescope produces in its image by the number of pixels that spans a millimetre on the CCD gives us the number of arcseconds per pixel on the CCD. In our example this is 103.14/151.5, which equals 0.68 arcseconds per pixel.

Rather than going through the calculation step-by-step each time, you might like to have to hand just one formula for getting straight to the answer of how many arcseconds per pixel you can expect when you image with your chosen telescope and camera:

$$\text{image scale in arcseconds per pixel} = 206265d/1000f.$$

As before d is the size of the pixels in micrometres and f is the focal length of the telescope or camera lens in millimetres.

Obviously no details finer than the size of one pixel can be represented in an image (think about a picture on a mosaic made from individual plain tiles). In fact any piece of detail in the image that happened to fall on the boundaries between two adjacent pixels would actually be recorded on both of them, effectively diluting this detail and spreading it between both pixels.

Hence, if you desire to image details down to, for example, one arcsecond in the image then you should amplify the image to such a size that one pixel spans half an arcsecond. Using a lower amplification of the image than that would *undersample* the image, meaning that you would not be realising all of the potential resolution.

This reasoning is encapsulated into the *Nyquist theorem*. In order not to undersample an image one should choose an image scale such that the angular extent of the finest detail that you desire, or at least can expect to realise in the given conditions and with the equipment you are using, spans **two** pixels. In fact there is some advantage to be gained by enlarging even further, though this advantage rapidly diminishes with further enlargement. For one thing, the diagonal distance across the pixels is 1.4 times greater than the distance measured along one side.

If you are using a telescope under conditions in which its quality and diffraction limit are fully realised (a rare occurrence when using a telescope bigger than 6-inch aperture to take single exposures) then you might profitably enlarge the image to as much as twice the amount set by the Nyquist limit. This is to wring out the very last bit of the visibility of the finest details, almost all of which would be realised anyway by just attaining the Nyquist limit. Of course the rub is the more you enlarge the image, the more you lengthen the necessary exposure time with the attendant problems that brings.

The image scale at the 2.59 m principal (Newtonian) focus of my 18¼-inch (0.46 m) telescope is 80 arcseconds per millimetre. In perfect conditions the telescope should allow details as fine as 0.3 arcsecond to be seen. Granted, the chances that the seeing will be that good are virtually zero on any given night but that is no reason to forego trying to get the best resolution possible in one's photographs. However, a CCD of 5.6 μm pixels (typical of many cameras and webcams) will only provide a theoretical resolution that satisfies the Nyquist theorem of 0.9 arcsecond on that telescope (in other words, two adjacent pixels would span 0.9 arcsecond). Going back to the numbered list of limiting factors at the beginning of this section, factors 6 and 7 (the size of the pixels and the focal length of the telescope) are in this example limiting the potential resolution.

The inescapable conclusion is that to have the best chance of recording images of the highest theoretical resolution possible one must enlarge the primary image. In this example, I should have to enlarge the primary image by a factor of at least three in order to have any chance of resolving details as fine as 0.3 arcsecond in the image. So, let us now discuss the methods we might employ to enlarge the primary image . . .

3.6 ENLARGING THE TELESCOPE'S PRIMARY IMAGE

There are three main methods of doing this: projection using a Barlow lens (or Powermate); projection using an eyepiece; and for any camera with its own lens in place there is the afocal (or 'infinity to infinity') method. The afocal method is the one you are forced to use if you wish to mount your domestic video camera, or any other camera with a non-removable lens, on your telescope. The following notes detail each of these methods.

Barlow (or Powermate) projection

Figure 3.2 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). They are still fine with delivering images a little higher or a little lower than the manufacturer intended. Go too far away from the stated amplification value, though, and the lens will begin to introduce aberrations to the image.

Often the Barlow's lowly amplification may not be enough to match the potential resolution of the telescope to the CCD. More powerful alternatives to Barlow lenses are the range of amplifying lenses marketed as Powermate by Tele Vue. They come in amplification values

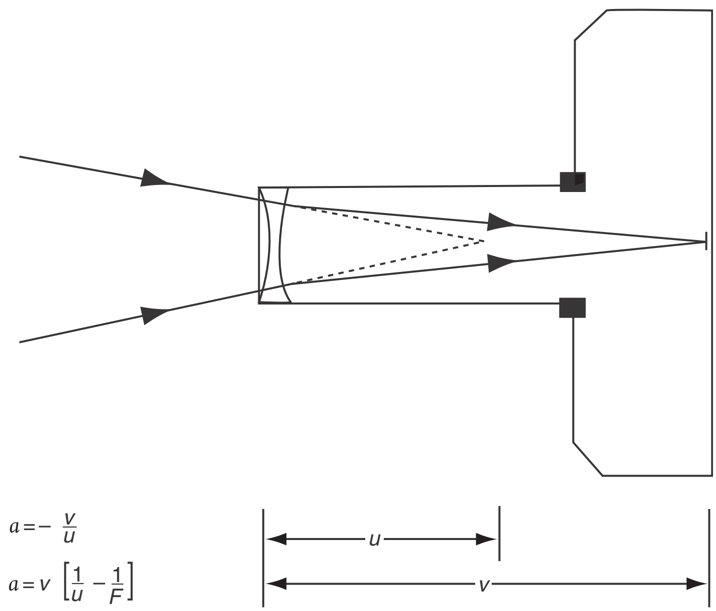


Figure 3.2 The optical configuration for projecting (and enlarging) the primary image by means of a Barlow lens. Alternative formulae are given for calculating the amplification factor, *a*. The focal length of the Barlow lens is *F*. It is entered in the equation as a negative quantity.

of $\times 2.5$, $\times 4$ and $\times 5$ and are the market leaders in terms of quality. Other companies market their own versions, such as Meade's TelexTender series, of $\times 2$, $\times 3$, and $\times 5$.

One thing I should point out is that the Powermate or Barlow is designed to produce the amount of magnification it does with an eyepiece plugged in to it – and so with the new focal plane situated just a little inside the top of the unit. Attaching your camera to the unit will involve racking the telescope focuser just a little further inwards in order to bring the focal plane a few centimetres out beyond the end of the unit in order to reach the imaging surface of the CCD. As a result you will get a little more amplification from the unit used this way than the manufacturer states. For instance a $\times 5$ Powermate used in this way might well actually deliver something close to a $\times 6$ enlargement of the primary image; perhaps even a little more depending on the back focus the camera requires.

It is prudent to check for vignetting when using a Barlow lens, especially in cases where the focal plane is extended much further back from the lens than the manufacturer intended. The minimum diameter, *D*, of 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:

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

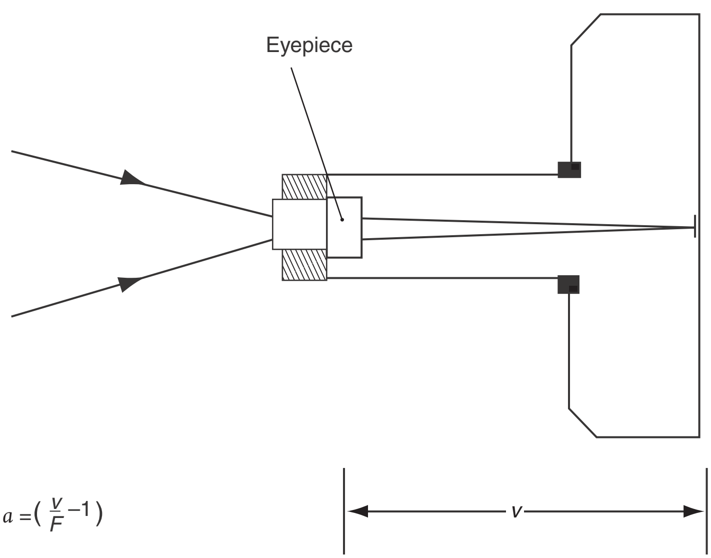
where a is the amplification factor, u is the distance the lens is set inside the telescope's focus, and f is the focal ratio of the telescope without the Barlow in position. The parameter f has no units, since it is a ratio, but the units of all the other quantities in the equation must be the same for the equation to work. For instance, all must be in millimetres, or all must be in inches, etc.

With DSLR cameras, fast-frame-rate video cameras and astrocameras with small pixels, a $\times 5$ Powermate will normally provide all the additional amplification the Solar System photographer will need on most amateur telescopes.

Eyepiece projection

As Figure 3.3 shows, the eyepiece can be mounted so that the rays emerging from the eyelens converge to form a focused image on the CCD. However, this is not what the eyepiece was designed to do. Sets of parallel rays emerge from the eyelens to enter the observer's eye when the eyepiece is being 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. The problem is that this causes an increase in the optical aberrations produced by the eyepiece. Good eyepieces will still produce sharp images within a small area of the centre of the CCD but the outer zones can be very blurred.

Figure 3.4 shows one of my early experiments with eyepiece projection onto photographic film. Notice the horrendous outfield blurring



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

Figure 3.3 The optical configuration 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 can only derive an approximate value as explained in the text.

Figure 3.4 Using eyepiece projection to provide low amplification factors onto a large imaging area will result in severe blurring of the outer zones of the image, as illustrated here. This photograph of the Moon was taken by the author on 1977 September 02^{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 an effective focal ratio of f/17 onto a 24 mm × 36 mm frame of Ilford Pan F film, for an exposure of 1/30 second.

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 effect is greatly reduced when using the eyepiece to create larger amplification factors. The reasons for this are two-fold. First, the rays emerging from the eyelens are less convergent (and so the paths of rays through the eyepiece are nearer to what the designer/manufacturer intended). Also, the size of the 'sweet spot' of sharply focused image is increased by virtue of the greater magnification, anyway. I should also say that outfield blurring only manifests when the detector the image is projected onto is large. In the case shown in Figure 3.4 the detector was a frame of photographic film of size 24 mm × 36 mm. The problem virtually disappears when imaging onto a CCD smaller than a centimetre across.

Afocal imaging 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 CCD, and have nightmares about multiple reflections and a 'fog' of light swamping the dimmed image, keeping both the telescope eyepiece and the digital camera's lens in place can actually work really well. With today's multi-coated eyepieces and camera lenses the amounts of light scattered, reflected, and absorbed by them are very much less 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.

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 the digital camera's display screen and focusing manually. It is obviously then an advantage if your camera has a display with an 'enlarge part of the picture for fine focusing' facility.

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

$$a = F_c/F_e.$$

One advantage of this method is that both eyepiece and camera lens are being used well within their manufacturer's intended parameters and so can be expected to deliver good-quality images.

While it is always best to firmly attach the camera to the telescope (see Figure 3.5(a) and (b)), another advantage of the afocal method is that tolerable, indeed sometimes very good, results can be obtained by hand-holding the camera to the eyepiece. My first photographs of the Moon were taken this way through my 3-inch reflector. That was back in 1972. In the years since, I often used this method when I wanted to take quick (albeit low-resolution) photographs without going to the trouble of setting up the equipment to attach the camera to the telescope. Recently I was given an old and discarded 'point-and-shoot' digital camera and thought I would try it out for hand-held afocal photography of the Moon through my 8½-inch (216 mm) reflecting telescope. The camera's lens is tiny and proved difficult to align with the eyepiece. It had no manual exposure and focus settings. Yet the results shown in Figure 3.6(a) and (b) are pleasing, especially as the camera couldn't have been any less suitable for this task. You should be able to do much better with almost any recently manufactured and halfway-decent digital camera.

In order to get consistently sharp photographs, hand-holding the camera demands that the exposures should certainly be shorter than 1/30 second and better 1/60 second or less. 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 with a digital camera set to ISO 800, provided the effective focal ratio is no higher than about f/20. With Moon at a fuller phase you will be able either to increase the effective focal ratio a bit further (and so enlarge the image) or to set the camera to a lower ISO, or give a shorter exposure. The Moon's brilliance increases very rapidly as its illuminated phase expands. The full Moon is fully

(a)

(b)

Figure 3.5 (a) The afocal arrangement the author used to attach his, now-obsolete, analogue-tape video camera to his telescope. The camera was rigidly attached to a moveable platform that could be racked back and forth to that the camera lens could be moved up close to the eyepiece. Counterweights (not shown) were needed, positioned near the bottom of the telescope tube.
(b) A still from a video obtained using this arrangement. The date and time are shown to the bottom left. The author simply photographed his television screen while the video was playing to obtain this image! Using modern digital equipment brings the potential to produce much superior results.

twelve times as bright as the Moon at first or last quarter. The brightest planets can also be photographed using the afocal arrangement; however, their images will appear rather small. I discuss the exposures needed for each of them in Section 3.7.

If you feel that attaching your camera to your telescope and arranging to project the image onto the CCD is just too much hassle, then

I urge you to try some hand-held 'snapshots' using the afocal technique. You may be surprised at just how good your photos will turn out. Go on – have a go! You might even be spurred on to more serious efforts afterwards.

Effective focal ratio related to focal ratio and required exposures

When we amplify the image by any of the methods discussed we are effectively also increasing the focal length of the telescope. For instance, using a Barlow lens to project a planet's image to make it twice as big has the same effect as if we had somehow magically doubled the focal length

(a)

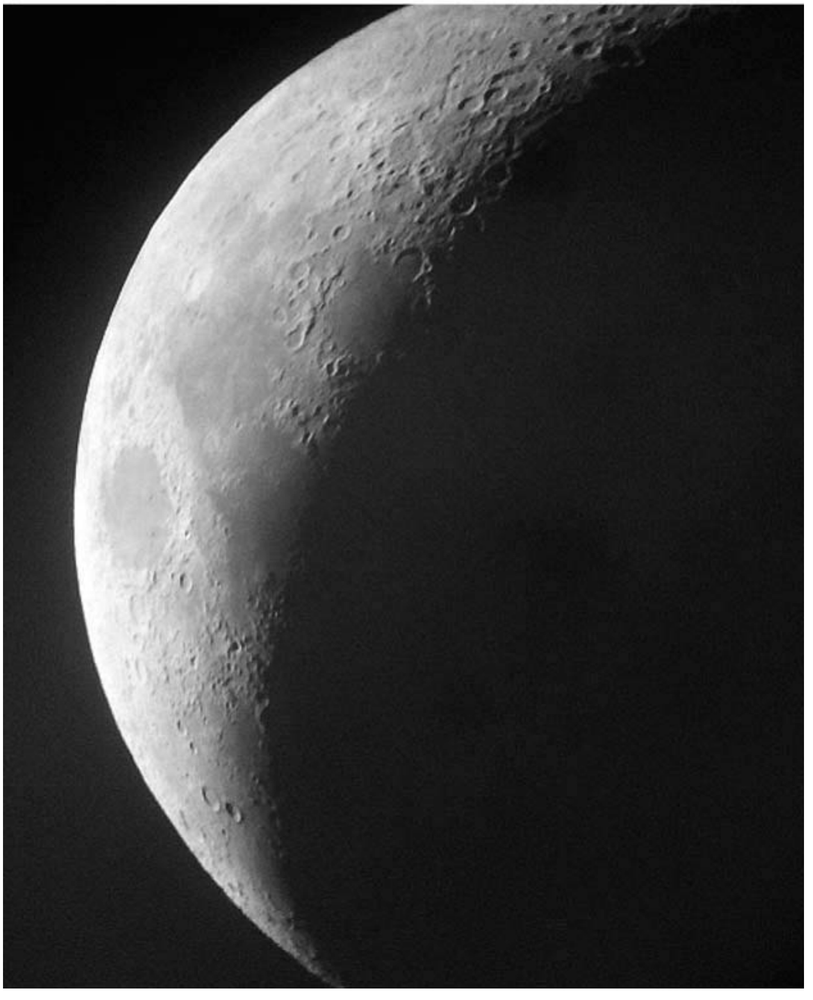


Figure 3.6 (a) The author obtained this image of the Moon by hand-holding a Kodak CX7300 (low-end 'point-and-shoot') camera up to the eyepiece (a 25 mm Plössl) of his 8½-inch (216 mm) f/7.74 Newtonian reflector on 2011 January 09^{d} 16^{h} 03^{m} UT.

(b)

Figure 3.6 (*cont.*) (b) This close-up of the Mare Nectaris region, taken 11 minutes later, was obtained by adding a ×2.5 Barlow lens. Both images were cropped, more so the image in (b), and both only very mildly sharpened and contrast-enhanced by the author using *Image Editor* software.

of the telescope. In this example the focal length of the telescope has been optically amplified to an *effective focal length* that is twice the original.

Let us work through a numerical example. Suppose our telescope is a 200 mm aperture Newtonian reflector of 1.2 metres focal length. If we used a Barlow lens in the manner just described we would create an effective focal length of 2.4 metres. In general:

$$\text{effective focal length} = \text{focal length} \times \text{amplification factor}.$$

There is something else. The focal ratio of the telescope is equal to its focal length divided by its aperture The 200 mm telescope of 1200 mm focal length in our example is therefore an f/6. If we have changed that focal length to a new effective focal length then we have at the time changed its focal ratio to a new *effective focal ratio*. In our example, by using the Barlow lens to double the size of the image, we have doubled the focal ratio to a new effective focal ratio of f/12. To summarise:

$$\text{effective focal ratio} = \text{effective focal length/aperture};$$

and also

$$\text{effective focal ratio} = \text{focal ratio} \times \text{amplification factor}.$$

Why bother to think about the effective focal ratio? Well, the reason is that the integration time (aka exposure) required for a given extended body such as the Sun, Moon or a planet, is inversely proportional to the square of the effective focal ratio.

As an example, let us say that you get a nicely exposed image of a crescent Moon in 1/60 second through your Schmidt–Cassegrain telescope at its principal focus (and hence at f/10) with your DSLR camera set to an ISO rating of 800.

You then decide you would like to treble its size and so you put in an amplifying system to deliver that bigger image. The trouble is that the image is now nine times as faint as it was before because it is now three times its original diameter and so the light is spread out over nine times the area. The image is now way too dim for you to record it well with your camera set to a 1/60 second exposure. In order to record it as well as you did before you now need nine times the exposure! Of the standard range of exposure settings available on your DSLR camera you would probably have to select 1/4 second (though you might just get away with using 1/8 second and accepting a dimmer image).

A longer exposure increases the demands on the mechanical steadiness of the telescope, its mounting and the camera attachment and operating system. In particular, it increases the need for having the telescope to accurately track the celestial bodies . . .

3.7 IS A DRIVE NECESSARY?

As discussed earlier, having a motor drive on your telescope certainly makes life easier for you but is it absolutely essential that your telescope is driven in order to get sharp photographs? In general, the answer is 'no' for single exposures of a small fraction of a second but 'yes' for anything longer or for video sequences of total length longer than a few seconds. Let us examine the situation more closely . . .

Telescopes larger than about 6 inches (152 mm) in aperture could potentially image details down to slightly under an arcsecond in extent. This is about 1.7 km at the Moon's distance and about 2900 km on Jupiter even when the planet is at a favourable opposition. 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 (remember, in this chapter I am just discussing the taking of single frames – the techniques discussed in the next chapter will often deliver sub-arcsecond imaging even on nights of average seeing).

Diurnal motion (the apparent motion of the celestial bodies that results from the Earth's rotation) will smear images of the Sun, Moon and planets by about an arcsecond in $^1/_{15}$ second. Consequently, provided you use an exposure of no more than $^1/_{15}$ second, you could potentially resolve details down to the arcsecond level in your photographs.

The Moon is often the first target for budding astrophotographers. At the Moon's distance an arcsecond spans about 1.7 kilometres. The Moon's diameter is about 2000 times greater than this, so you can see the potential to record impressively fine lunar detail using a simply mounted undriven telescope.

Keeping the exposure time less than $^1/_{15}$ second is usually possible except when setting your digital camera to a low ISO setting and then using it with an f/10 telescope to photograph a thin crescent Moon. A 'fatter' Moon will be adequately recorded with much shorter exposures. Trying to capture the earthshine or surface details during a total lunar eclipse almost certainly will require exposures of several seconds, even with a low effective focal ratio and a fairly high ISO setting. This certainly does necessitate driving the telescope during the exposure.

Jupiter's and Mercury's surface brightnesses (as we see them from Earth) are similar to that of the first quarter or last quarter Moon and so will record as well with the same exposure and ISO settings. Mars's surface appears something like twice as bright, and Venus around ten times as bright, so both need proportionately less exposures. Saturn, though, is much more pallid, needing at least four times the exposure that Jupiter does. Uranus and Neptune are fainter still. The trouble is that the planets all appear so very much smaller than our Moon. By contrast with an impressive field of lunar craters, all one sees of the planets at a low effective focal ratio are their tiny disks.

What about enlarging the primary image? Obviously this will result in a dimmer image and a longer required exposure. Nonetheless, you still ought to be able to obtain images of Mercury, Venus, Mars, Jupiter, the Moon and the safely filtered Sun (remember the warning at the start of this chapter) with a digital camera set to ISO 800 or less with an effective focal ratio of around f/20 and an exposure not exceeding 1/60 second. So you may well be able at least to image these targets – even though you may not get the very best results – if you have a telescope with no drive. If you do not own a driven telescope, why not treat it as a challenge to experiment and find out what is the best result you can achieve with whatever equipment you do have to hand?

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. When using a DSLR I would say that a cable release is mandatory for longer exposures. Fumbling to press a button on the camera while it quivers on the telescope is hardly conducive to getting sharp photographs!

3.8 FINISHING THE JOB

The image you capture with your astrocamera will certainly not satisfy you as it stands. The DSLR camera does carry some onboard electronics that will make your image of the Sun, Moon or planet cosmetically better than the raw image you would get from an astrocamera but still what you get is not the best you could have. With some software – and it doesn't have to be complicated or expensive – you can turn your fuzzy and foggy grey image of a celestial body into something very impressive, showing fine details that you thought were never even present in the first version.

I detail the imaging, photometry and astrometry of asteroids and comets in Chapters 10 and 11. Those subjects and techniques have special requirements. I have more to say about the most successful ways of imaging fine details on the Sun, Moon and planets in the next chapter. For cosmetic enhancements you can choose from a very large number of software programs. Some are free. Some are expensive. Some are easy to learn and some require you to climb a very steep learning curve.

Way back in 1996, I bought a 133 MHz PC with the addition of a *Hauppage* video-capture card. The software suite that came with this card, *Ulead*'s *MediaStudio VE 2.5* included *Image Editor*. This is a delightfully simple and easy-to-use, yet very effective, image-processing program. Modern versions are still available, packaged along with other software, and cut-down versions are available for free download online (please use your favourite search engine to track them down).

I think of *Image Editor* as a simplified version of the other, often expensive, image processing programs you will already know about such as *Adobe Photoshop*, *Paintshop Pro*, *AIP4WIN* and *MaximDL*. The point is that this simple little program has almost all the functions I have ever desired to use in finishing off the processing of Moon and planet, and even deep-sky, images.

Of course, the first piece of software in the chain is that required to operate the camera (in the case of an astrocamera) and download the camera's output to your computer. If that software package contains some basic image-processing functions then that may well be all you need.

Perhaps here I should also mention *Images Plus*, a program especially designed for DSLR users who wish to undertake astronomical imaging.

Other devices can also be used with this software. You will find a review of version 2.75 of this product in the July 2006 issue of *Sky & Telescope* magazine. As the reviewer points out, the program is very complex in its operation and you will need to prepare yourself for a steep learning curve.

One thing I should warn you about is that images saved as JPG files are bereft of much of the depth of data that is necessary for anything but the mildest of image enhancements. If the camera software allows it **do not** convert to a JPG file until you have finished all the processing you intend to do on the image. If you do, you will find that the amount of processing you can do will be very limited. Admittedly, you can get away with doing some image processing on large JPG files, though your enhancements will still be much more limited than if the files were in another format, such as TIFF, FITS, BMP, etc.

If you are using a CCD astrocamera you might well be satisfied with the processing tools that are included in the manufacturer's supplied software package and might not want to get involved with other software suites. If you are a beginner at image processing then I strongly urge you to keep things as simple as possible. Avoid getting bogged down with the intricacies of complicated software until you are familiar with simple routines. That way you will have the maximum amount of fun and some fair images to show for your initial efforts. Master the basics and you will graduate all the more easily and quickly to **successfully** using the more sophisticated techniques and software packages whenever you feel ready and willing to take them on. Happy imaging!

CHAPTER 4

Stacking up the Solar System

If you want to obtain images of the Sun, Moon and planets showing the very finest detail possible with your equipment in any given observing conditions then you have to put in just a little extra effort and go for a more sophisticated approach than taking single frames. The key to success is to find a suitably sensitive camera that is able to take a rapid-fire stream of images, one after the other. In generic terms, of course, this a video camera. It could even be a domestic video camera, though this would not be the best choice. In fact, almost any modern imaging device that takes video sequences known as *AVI*s (the letters stand for *audio video interleave*) can be used to take short video sequences of the Sun, Moon and planets. **Please read and digest Chapter 12 before you even think of trying to image the Sun. The solar radiation collected and concentrated by a telescope is dangerous. There is the potential to blind yourself and/or burn yourself and/or damage property and equipment. You have to know what you are doing and take the greatest care when attempting to image the Sun**.

4.1 THE BENEFITS OF STACKING SELECTED IMAGES

Before the late 1980s, the most successful way for an amateur astronomer to record fine details on the Moon and planets was to critically study the view through the eyepiece and make a drawing. The finest details on that drawing were gleaned from the occasional few flashes of fine detail that occurred during a session of something like 10 to 20 minutes long for drawing the planets, or maybe half an hour for sketching a small part of the Moon. It was almost impossible for the users of photographic film to get such detailed views because atmospheric turbulence usually blurred the image during the exposure. It was necessary to enlarge the image enough to resolve fine details but this dimmed it so much that the insensitive films of the day needed exposures of several seconds to properly capture it. The chance of the image staying sharp and motionless on the film for several seconds was practically zero.

In the late 1980s and 1990s, the use of very sensitive CCD-based cameras spread among the amateur astronomical community. More and more amateurs used these cameras and their computers to capture enlarged images of Solar System objects with very short exposures to deliver sharper images. During each session they would conveniently try and try again while watching the result on the monitor and save just the sharpest of the images that appeared. This contrasts starkly with the situation of not knowing the quality of what you have on film until after it has been chemically processed.

Even better, those using electronic imaging could use computer software to subsequently work on their images and further improve them. So it is hardly surprising that those pioneering practitioners of electronic imaging routinely produced much superior results to those at that time who continued to use photographic film. Further advances came in the first few years of this century. Now amateurs can routinely obtain images of previously undreamed of resolution and quality.

The sensitive CCD and onboard electronics in modern fast-frame-rate (video) cameras are able to record satisfactorily from several to several dozen images of the enlarged Sun, Moon and planets every second. Of course the majority of the individual images captured are smeared by atmospheric turbulence. However, maybe one in a hundred to one in every few hundred individual images, or 'frames', will show details much finer than the others recorded in the same sequence. These frames are the equivalent of the few flashes of fine detail seen during a typical visual observing session. These best frames can be searched out in any recording and stored. If they are then imported into a suitable software suite on a computer they can be improved using standard image-processing techniques.

Unfortunately there is one snag. If you try to process a single grabbed frame you will find that the already slightly grainy-looking image will not stand much enhancement before it looks ghastly; like a picture first printed on coarse sandpaper and then sprinkled with salt and pepper. This happens because the individual images are afflicted with electronic *noise*. Each pixel in the CCD should ideally have an amount of charge liberated in it that is directly proportional to the amount of light falling on it during the exposure. In reality, the array of pixels are afflicted with additional, seemingly randomly allocated, amounts of additional charge.

This noise has a number of root causes. The major one is that the CCD is not cooled, as is mandatory for a proper CCD astrocamera. Another is that the process of reading the image off the CCD and into the camera's electronics also generates noise. Some of the CCD's pixels have no additional charge but most do and some even have enough to fill them to saturation. The effect is only mildly visible in the frames as they come from the camera but most enhancement techniques applied in image processing will cause this noise to spring to the fore.

Fortunately, there is a solution to this – combine a number of frames together so that the random effects of the noise in each individual frame is diluted. In the normal way you watch a video playback, persistence of vision does this combining for you. At any one moment you actually perceive a blend of several frames, rather than each one individually. That is why the quality of the picture seems better – rather smoother – in normal playback of a video than it does when you study its individual frames.

So, it would be great if we could select out all the best images we get from our telescope in any one session and combine just those to form a new image, which will then have much of its random noise averaged out. There would be a further advantage. Even the best individual frames will be affected by some atmosphere-generated blurring and distortions which vary across the image. By combining lots of frames we could average out these afflictions, reinforcing the 'true' fine details in their correct positions and diluting the 'untrue' ones. The composite image would have the effects of atmospheric turbulence minimised as well as having a much better *signal-to-noise ratio*. We could then be much more aggressive with our enhancement tools and so really drag out all the fine detail that it is physically possible for our image to contain.

The good news is that we really can do this. In fact, this is what all the best contemporary Sun, Moon and planet imagers actually do!

4.2 SOME GENERAL PRINCIPLES ABOUT STACKING

How many images of a Solar System object from one AVI sequence **can** you combine? The answer to that depends upon the file size of each image and the available memory space on your computer. With today's computers having hard drives of capacity measured in the hundreds of gigabytes, memory space ought not to be a problem when combining a few dozen images, even if they are the multi-megabyte images produced by digital cameras. With the much smaller image files generated per frame from a typical small CCD fast-frame-rate video camera, we could capture hundreds or even thousands of frames and still have computer memory to spare.

How many images of a Solar System object in one AVI run **should** you combine? The answer to that depends on the quality of each image and the amount of electronic noise it contains. Statistically, the noise content is proportional to the reciprocal of the square root of the number of separate images combined (noise $\propto 1/\sqrt{N}$). In theory, an image blended from four others should have only half the noise content compared to the mean of the four original images. A final image assembled from sixteen separate images ought to have only a quarter of the noise content of the mean of each of the originals.

Aside from your computer's finite memory, there is another factor that may limit the number of images you can combine – the time elapsed between the first and the last of the component images must not be too long. Otherwise a planet will have rotated enough to smear the details on it. This time-span should be no more than a couple of minutes for fast-spinning planets such as Jupiter and Saturn and maybe up to two or three times as long for the others. Details on the Moon stand out in greatest relief along the line that separates night and day because the Sun is there striking the lunar surface at a very low angle. We call this day–night line the *terminator*. When imaging the close-up details on the Moon's terminator the AVI should not be more than a few minutes in duration because the shadows will perceptively alter, though it can be increased somewhat for areas away from the terminator.

How do you go about combining the separate images? You need an image software package that will allow you to stack the images accurately one on top of the other and produce a true average of the combined result. There are automated packages that will let you stack up to several thousand frames if you want to. More about those later. Sometimes you will only want to combine a small number of frames. You could use a simple manual method for that if you so wish, as I describe in the following section.

4.3 MANUALLY STACKING INDIVIDUAL FRAMES

Though this is not quite the best way to record the very finest solar, lunar, or planetary detail, let us say that we have set up an imaging system to give enlarged images along the lines set out in the last chapter and we are using a CCD astrocamera or a DSLR camera to manually take a sequence of multiple images of the object. It might be that you don't wish to get involved with the more complicated techniques of taking and processing video techniques just yet in your observing career. Or maybe you wish to take whole-disk images of the Sun or the Moon, which isn't possible with your telescope and the small CCD on your fast-frame-rate camera.

Whatever the reason, let us say that you have only a small number of individual frames taken and that you wish to combine them to produce the best result you can manage. This technique will prove quite adequate for combining multiple images from digital cameras and astrocameras, as these are relatively noise-free. The same software can even be used for combining manually selected images from webcams and video cameras, either of the domestic or proper astronomical variety. However, the best results from these devices, particularly the 'noisy' webcams, will be obtained from combining large numbers of frames, and this is where the software packages discussed later come into their own.

Major image-processing software packages have manual image-stacking facilities. One such is the highly popular *Adobe Photoshop*. Whatever the package you use, you will have to resort to the supplied instructions to learn how to carry out any of its myriad of processing operations. At least *Adobe Photoshop* has a helpful book, *Photoshop Astronomy*, written by R. Scott Ireland and published by Willman-Bell in 2005, whose target readers are amateur astronomers.

For instance, in *Adobe Photoshop* you would begin the stacking process by pasting one image roughly on top of the next until your stack is complete. The bottom image is known in *Photoshop* jargon as the 'background'. The images on top of the background are described as 'layers'. You can select one layer at a time, leaving the others temporarily 'hidden' (invisible).

Next, painstakingly align each layer in turn with the background (the layers you are not working on all being temporarily hidden), working one at a time through the stack. One way of doing this accurately is to select the 'difference' blending mode and then move that layer's image about until it exactly cancels out the background layer to leave a dark screen.

Non-overlapping details stand out bright against the darkness. If the image is large, say a lunar scene, you can expect a few bright bits on the general field of darkness even on a properly aligned frame. This is because of the image distortions due to atmospheric turbulence, which are effectively frozen in time on each individual frame. Once you are happy with the alignment, switch the blending mode back to 'Normal' and the result you now have is the image in the first layer in tight alignment with the background image. Repeat the whole process until you have the background image and all of the images in each of the layers fully aligned.

An alternative method of alignment is to create your own, initially empty, new layer on top of the upper one containing the image. Next select the background and your new layer. Then 'paint' some markers on your new layer in positions that align with points on the background image that you decide to use as reference. Then you deselect the background and select each in turn of the layers above the background (working on just one at a time) as well as your newly created layer. Making sure that you do not disturb the position of your new layer, adjust just the layer containing the image until your chosen points in it coincide with the markers. Work your way through the stack until you are satisfied you have got all the images precisely aligned. Make use of the ‘zoom’ tool as an aid to precision.

If all the layers are selected (unhidden) in turn, at this stage we would still not see a properly averaged image. We would only see the image in the top layer. We have one more job to do. This is to set the opacity of each layer to such a value that it makes an equal contribution to the final image. I find this operation in *Photoshop* rather counter-intuitive. I would have thought that if I had, say, 10 images to combine I would set each at 10 per cent opacity and the result would be a true equal blend. This is not the case in *Photoshop*. Perhaps a better way of thinking is to imagine each of the images as being printed onto a clear acetate sheet Then further imagine all these images being stacked into a pile. Now consider how it is that you have to look through a particular sheet to see the sheets below. The top sheet would have to have the weakest image, lower sheets progressively stronger images, and the bottom sheet the strongest if each is to make an equal contribution to the final effect.

In the *Photoshop* world, what has to be done is to set the lowest, background, layer to 100 per cent. The next layer is set to 50 per cent. The next is set to 33 per cent and the next to 25 per cent, and so on. The rule is to divide 100 by the number of the layer (starting with the background as 1). The tenth layer’s opacity should be set to 10 per cent.

Of course, you can always deviate from these values if you do want to change the relative contributions of the layers and so favour one or more frames that you judge to be better than the others. However, do be aware that you might then not reduce the noise component to its lowest possible value (this may not be important if the individual frames are fairly noise-free, as they certainly should be from a DSLR or astrocamera with its cooling device switched on).

Using the opacity control gives you a third alternative way of getting the images in the layers all accurately aligned. The procedure would be first to set the background at 100 per cent. Next, select each layer in turn (with all the others deselected) setting that layer’s opacity temporarily to 50 per cent. Then, move that layer about until you get the image combined with the background. As before, using the zoom tool will be a great help in achieving an accurate alignment. Once you have done this, deselect that layer and repeat the process for the next one. Work image by image through the stack until each one is aligned to the background. I must say that I like this method the best.

Figure 4.1 Jupiter imaged by Damian Peach on 2005 April 30^{d} using his 11-inch (280 mm) Celestron Schmidt–Cassegrain telescope, projected to f/42 using a Tele Vue ×3 Barlow lens, and Lumenera LU075M camera with an RGB filter wheel, from his UK back garden. The AVI was subsequently stacked and processed in *RegiStax* and further processed in *Adobe Photoshop* and finally *Paintshop Pro*.

Whatever alignment method you used, afterwards go through the stack setting the opacities so that all images give equal contribution as I described a couple of paragraphs ago. Finally, save the composite image, perhaps in TIFF or bitmap (BMP) format. Then you can either stay in *Photoshop* or export the file to another program, in order to perform your favourite image-enhancement routines.

4.4 THE WEBCAM REVOLUTION

It would have been almost impossible for an amateur astronomer using film photography to obtain the image shown in Figure 4.1. This is the sort of image that, in the old days, a professional astronomer might have obtained during a session with a specially built high-resolution telescope at an exceptional observing site, one example being the 43-inch (1.07 m) reflector at Pic du Midi in France. In fact, this image was taken by Damian Peach with an 11-inch Celestron Schmidt–Cassegrain telescope from his UK back garden! You might care to take a look at Damian's website: *Damian Peach's Views of the Solar System*, which can be found at www.damianpeach.com. I regard Damian's work as the gold standard but it is also true that a dedicated handful of astro-imagers are pretty much up with him in the quality of the results they get.

You can fairly easily take images that will be superior to those of even the best of the film-using photographers of yesteryear. Moreover, you do not need the most expensive imaging devices to do it. A device such as Celestron's NexImage costing a couple of hundred dollars (about £130 in the UK) and a computer of post-1998 vintage, perhaps most conveniently a laptop, fitted with a USB port will be enough for you to potentially get nearly diffraction-limited images from your telescope.

The latest generation of astronomical fast-frame-rate video cameras were developed as a result of a number of pioneering amateur astronomers pressing their humble webcams into use. Several advances came together to make this possible. In particular, the webcam's sensitive detector (a CCD in the best ones) and fast USB download (helped by a little onboard compression) allowed them to capture images with exposures of a tenth of a second or less with good resolution in quite low-light conditions. Another factor was the ever-expanding speed and memory capacities of personal computers and portable laptops. This enabled them to take large numbers of individual frames in any one session and store them all in the computer.

There was one particularly important development that allowed the 'webcam revolution' to happen; software packages that either automatically or semi-automatically could sort the very best images from as many as a few thousand saved ones and then align and stack these best frames. Finish off with some final image processing and voilà! – a picture of a planet or small part of the Moon that would have astounded even the most successful amateur or professional astronomer of the photographic-film era.

4.5 SELECTING YOUR KIT FOR HIGH-RESOLUTION IMAGING

Beginning in 2002, and for a few years following, the most successful and popular webcams for planetary observing were the Philips ToUcam Pro II PCVC 840K and its 2006 successor the Philips ToUcam SPC 900NC. They were very cheap, retailing in the UK at between £50 and £100 (and *circa* $150 in the USA). They had proper CCDs (actually a Sony ICX098BQ) that were highly sensitive and generated less electronic noise than most other low-cost webcams (most of which were fitted with cheap CMOS detectors). The first model was USB1.0 compatible and the second was USB2.0 compatible and capable of faster downloads with less image-file compression (compression throws away information and leads to less detail in the reproduced image – higher speed settings on these cameras resulted in increased compression). The Sony ICX098BQ CCD has an array of 480×640 pixels, each 5.6 μm square and with an overlaid *Bayer matrix*.

A Bayer matrix is a filter-grid that sits over the pixels and allows the device to record images in full colour. I mentioned it briefly in the last chapter in connection with DSLRs and 'one-shot' colour astrocameras. In any square grouping of four pixels, two of them are filtered green and one each is filtered blue and red. This is where the colour information comes from.

It might strike you that the resolution of the colour component of the image (known as *RGB bands* from the filtered colours) must be much poorer than the resolution that could be synthesised from all of the pixels. This is absolutely true. As it happens, though, the human eye and brain are critical of the spatial resolution in a monochrome image but not so critical of the RGB resolution. By means of some artful processing, what the computer does is to construct a full-resolution 'grey-scale image' using all the pixels and overlay it with a lower-resolution coloured version of the image based on the information from the R, G and B channels.

Sad to say, Philips have discontinued these ToUcam webcams and there are no clear successors, though the market is replete with other low-cost models that will produce inferior results. There are a couple of reasons for me having taken the space to describe the ToUcam webcams. One is the obvious possibility that you might pick one up cheaply second-hand. If so, you should also get with it a CD-ROM containing the driver software you will need to install on your computer. This is called *VLounge*. However, many people find this piece of software a bit unstable on their computers and they resort to using *QCFocus*, which can be downloaded free from www.astrosurf.com/astropc. The screens, menus and layouts of *VLounge* and *QCFocus* are well-nigh identical, which is a help if you start with *VLounge* and decide to resort to the other should you find its operation troublesome on your computer.

The other reason I have used precious space to describe the Philips ToUcams is that there is a commercial fast-frame-rate camera system, namely the Celestron NexImage unit I mentioned earlier, that is built around the same CCD and has the old ToUcam's excellent performance. It is designed as an introductory planetary imaging device for amateur astronomers. It currently retails at around £130 in the UK and about $200 in the USA.

Celestron's 'NexImage: Solar System Imager', to give it its full title, is an all-in-one package supplied with a telescope adapter and a CD-ROM of all the operating software and *RegiStax*, which is the most popular of the image-stacking and image-processing programs. *RegiStax* is available to download for free from the Internet but the other items would have to be purchased separately if they were not included in the package.

An infrared-blocking filter is, though, one of the optional accessories, and usually retails at about $55. Other useful optional accessories on offer with this package include a 'reducing lens', costing about $25, which will double the field of view that your telescope can fit onto the tiny (2.7 mm × 3.6 mm) imaging area of the CCD. This is useful for the occasions when you desire to image a larger area of the Sun's or the Moon's surface, or maybe the full spread of Jupiter's brightest moons, in one go. I will shortly have more to say about the accessories you will need to buy for this and any other camera system.

Meade also offer a planetary imaging camera along the same lines, though their detector is a cheaper CMOS chip. CMOS detectors are less sensitive and more noisy than CCDs. I reckon the camera package from Celestron is your best bet if you are new to webcam-style imaging. Please be aware, though, that this is a fast-moving field and there may well have been developments in the time between me writing these words and you reading them. Meade or any other company might by then have produced a similarly priced camera system that is superior to the NexImage. Or perhaps Celestron may themselves have produced an improved model. Manufacturers are marketing new products all the time. Please do at least some research before you go shopping for your own camera system.

There are some accessories you will also need to buy if they are not already included in the package you purchase. In the next few paragraphs I will refer to whatever camera you obtain as a 'webcam', although it is actually most likely to be a NexImage or some other camera intended for astronomers. This is my way of keeping my descriptions simple and clear. Right then, now for some more on those accessories . . .

For use with our telescopes the webcam's lens must be removed. A removable lens is an important requirement in any webcam we intend using for high-resolution astrophotography. Any astronomically dedicated video camera will certainly either have a removeable lens or no lens at all. Please do bear in mind that if you need to disassemble the casing in order to remove the lens from any camera you straight away void the manufacturer's warranty. This is not a problem with many webcams, including the old ToUcams, as the lens simply unscrews from the front.

Next on our shopping list is an adapter that will screw in to the hole left by the now-removed lens and which will be a proper slide-fit into the standard 1¼-inch (31.7mm) telescope drawtube (see Figures 4.2(a) and (b)).

(a)

(b)

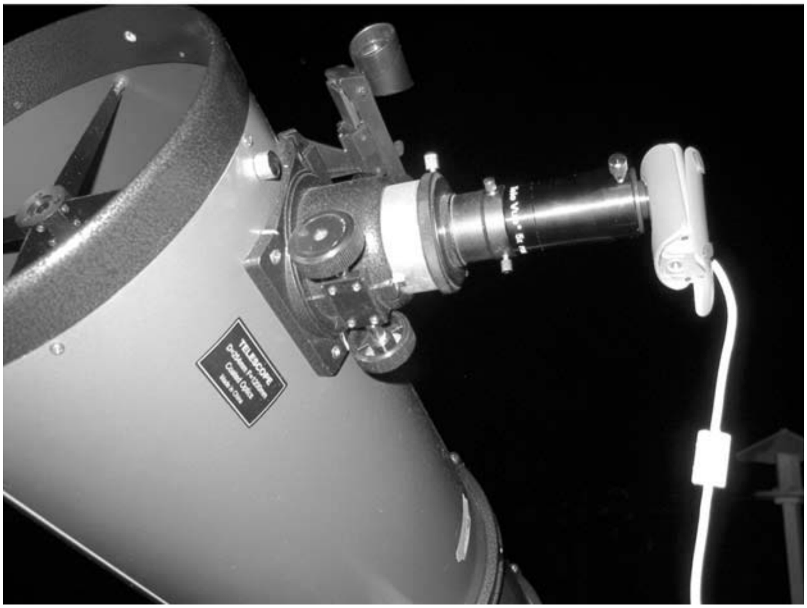


Figure 4.2 (a) Michael Butcher demonstrates his Philips ToUcam webcam with its lens removed and a 1¼-inch (31.7 mm) telescope adapter screwed in its place. An IR/UV blocking filter is screwed in to the open (facing) end of the adapter.
(b) Michael Butcher's webcam plugged in to a ×5 Powermate and the assembly plugged into his 10-inch (254 mm) Newtonian reflector, ready for a night's imaging.

Many astronomy suppliers keep these adapters in stock, particularly so for the most popular models of camera. One important point: **Never leave the CCD exposed to dust and moisture**. Keep the webcam in a sealed clean box, or keep a cap over the hole, or keep the webcam plugged into a Powermate or Barlow lens or other sealed device. If dust does get on the CCD, then use only an aerosol dry-spray cleaner (such as that used by photographers) to remove it.

One more item might be regarded as an optional extra, though I regard it as almost essential – an infrared-blocking filter. Again, this is something your astronomy retailer should have in stock. The wide end of the adapter usually has an internal thread to take this filter (or any other screw-in filter). Figure 4.2(a) shows an infrared-blocking filter screwed into the 1¼–inch adapter. A webcam's lens has an infrared-blocking filter built in. Without it colours are a little washed-out and the colour balance is slightly disturbed. This might be a problem in planet imaging but will probably not bother you for lunar or solar work.

However, there is another problem. If your optical system includes lenses then the focus for the near-infrared wavelengths will not be coincident with that for the other visual wavelengths to which the webcam is sensitive. To get the sharpest pictures you should really have an infrared-blocking filter screwed in. The filter your supplier will provide will likely also block near-ultraviolet wavelengths in order to get a good colour balance in normal use.

Most of the best planetary imagers in the world cut their teeth with the old Philips ToUcam webcam and then progressed to other small-chip (typically 480 × 640 pixels) cameras capable of fast download. In particular, most moved away from 'one-shot' colour imaging devices to cameras with CCDs that don't have an overlaid Bayer filter matrix. To get colour images they take separate video sequences each exposed through coloured filters (usually red, green and blue, though a sometimes-used alternative is magenta, yellow and cyan) and one exposure without any coloured filter (the *luminance*, or *L-band* image) and combine them in the computer after the event. More light gets to the CCD without the Bayer filter and consequently the L-band images have a much better signal-to-noise ratio.

In addition to an improved signal-to-noise ratio, the more advanced cameras offer greater sensitivity. They also allow a much faster download speed without any of the image-degrading compression that afflicts units such as the old ToUcam webcams, particularly at their higher speed settings. The most advanced cameras are much more expensive than the humble webcam, costing maybe of the order of a thousand dollars or even more, though prices vary greatly from camera to camera and supplier to supplier.

If you have the money to spare you might consider going straight for one of these advanced cameras. However, if you are new to imaging then I would strongly advise you first to serve an apprenticeship with a 'one-shot colour' device such as the NexImage or a second-hand ToUcam webcam before considering moving on to more elaborate and expensive cameras. Get some experience and some good results before spending lots of money on a system that is trickier to use and harder to master. After all, get everything right with your telescope and your NexImage camera and your images could be of real scientific use and of a quality at least not too depressingly inferior to those of the world's leading planet imagers who have now graduated to using the most expensive cameras!

Having mentioned expensive cameras, actually a new generation of cheaper ones with impressive specifications are now beginning to appear. One of the first of these was the DMK 21AF04.AS marketed by the company Imaging Source at just $390 in the USA in 2007. This is a monochrome camera with good sensitivity and low noise characteristics and with Firewire downloads of up to 60 frames per second. This company's range of reasonably priced fast-frame-rate cameras has expanded since then. They also do at least one 'one-shot colour' model for those who prefer the simplest arrangement and mode of operation. I strongly recommend looking at the astronomical part of the Imaging Source website at www.astronomycameras.com. There is a link to a page showing a gallery of images obtained by amateurs (some of them very well-known ones) using their cameras. Atik also market a number of cameras of similar price to the Imaging Source models and you might care to start your search for them at www.atik-cameras.com.

Damian Peach and a number of other world-class Solar System object imagers now use fast-frame-rate cameras by Lumenera. Of particular interest, recently Lumenera have developed their SKYnyx range of dedicated Solar System cameras. Retailing at $995 and upwards, though, these cameras are definitely for the dedicated and/or well-off amateur astronomer. Lumenera's main web address is at www.lumenera.com. There is also a link to a page showing the sorts of results these cameras can deliver in the most dedicated hands.

So, there are plenty of expensive cameras if you have deep pockets but there are also some good, reasonably cheap cameras out there. I could say more and spend many pages detailing all the latest cameras on the market. Yet, this list would most definitely be out of date by the time you read it. So the best thing I can do is to urge you to spend some time doing market research on your own.

Seek information from online forums and carefully read all the online reviews you can. Astronomy magazine adverts and reviews are also a good place to start but please be aware that reviews can be biased or maybe even edited by the magazine staff if that magazine gets much advertising income from the advertiser. Additionally, individual reviewers can also have hidden agendas as well as their own peculiar preferences!

Gather as much information about the effectiveness, shortfalls, and difficulties in using any equipment you might consider buying. Just as one example, some users of Celestron's NexImage camera have had difficulties with camera software drivers running in a *Windows 7* environment. Downloading alternative drivers solved the problem. This is the sort of difficulty that can easily stymie a beginner and lead to a newly acquired camera remaining in its box, rather than being plugged into the telescope and producing great results for its owner. Please do your research and know what you are buying before you part with your money.

As far as the computer requirements go for the ToUcam webcam or NexImage cameras, you will need a personal computer later than 1998 vintage (at least 333MHz, Pentium II standard), fitted with a USB1.1 socket or higher, running *Windows 98* or later software. The computer should have at the very least 128 Mb of RAM and multi-gigabytes of free hard-drive space. Also please do not skimp on the screen resolution. Go for at least 1024 × 768 pixels in order to achieve accuracy when focusing.

If you go for one of the 'higher-level' cameras, such as the Lumenera mentioned earlier, then you will need a computer of significantly higher specifications. To get the full benefit from these cameras you will need a system with something like a 2.6 GHz processor and a 7200 rpm hard drive (though some additional software packages, such as *StreamPix* will allow you to synthesise these requirements effectively on a slower machine). If you have a mid-price computer made in the last few years its speed and memory should be sufficient for good performance from even the top range of fast-frame-rate astronomical cameras.

Most amateur Moon and planet webcam users prefer to use laptop computers. Although these devices are more expensive than desktop PCs with the same specifications, and have a rather shorter average working life, their portability is a great advantage. Most people prefer to be close by the telescope in order to make fine adjustments. However, if the telescope is on a fully driven mounting equipped with remote slow-motions and an electric focuser then this is not strictly necessary.

The cable supplied with the webcam is usually only about 1.5 m long, which is another reason for wanting your computer close to the telescope. Alternatively, you will have to use USB extension/repeater cables but in practice this might lead to a loss of stability in the link-up. Check with your computer dealer to see what will work well with your machine and webcam/fast-frame-rate camera (hubs, powered cables, etc.). Let me also recommend that if you buy a laptop, you spend a bit more and get one with the highest quality display possible.

4.6 A MOONLIT FIRST NIGHT

Having purchased your camera and installed its controlling software (supplied with it), please take a little time to experiment with it before your first intended night of Solar System imaging. A little familiarity will make things go so very much better on that first night. First, try out the camera-control software suite. Find the control box that switches the camera from 'auto' to 'manual' and play with all the controls. If you have purchased a conventional webcam, such as a second-hand ToUcam, you can try it out first by keeping its lens in place and use it in a dimly lit room. If you have purchased an astronomical version of the unit, such as a Celestron NexImage that isn't supplied with a conventional webcam lens, then plug it into a telescope which is set to look at some distant scenery (you will not be able to rack the focuser far enough out in order to focus on a nearby object). You will probably also have to fashion a cardboard diaphragm to reduce the light entering the telescope.

Practise using your camera to obtain and store AVIs in its supplied software suite. Once you are reasonably familiar with the camera and how to control it, then it is time to think about using it to obtain your first Solar System images. I strongly urge you to select the Moon as the first celestial subject for your newly purchased camera. It is big and bright and very easy to locate and to keep in view. It is also packed with detail. Get some practice and enjoy some initial success with lunar imaging before trying for the more difficult targets.

An imaging run with a Philips ToUcam

I wanted to put at least some step-by-step practical instruction of camera use into this book but the trouble is that the details of the camera controls and software vary from camera to camera. You must familiarise yourself with whatever software suite supports your newly purchased camera. Perhaps the following notes might be of some use to you, though they are based on using a Philips ToUcam. My hope is that you will be able to adapt what I have to say when working with your own camera-control software suite.

I am going to assume that you have taken my advice and have chosen the Moon as your target on this first night with your newly acquired camera. For this first go I would urge you to image at the telescope's principal focus. By that I mean do not put in any additional optics to further enlarge the image. Just plug the camera in where the eyepiece would normally go. With most telescopes you will still only be able to image a portion of the lunar disk even without further enlargement. You will see plenty of lunar detail if you manage to get everything right, without further complicating your first practice session by having to deal with additional optics.

First, set up your telescope with its sidereal drive switched on and an eyepiece plugged into it. Make sure that you have your PC/laptop safely connected to the mains, or that your laptop's batteries are fully charged. Also, check that your webcam is plugged into the USB port **before** powering up the computer.

Select 'Video Properties' and set the webcam's resolution to maximum (in most cameras this will be 640×480 pixels). In the Philips software this is in a box called 'Output Size', to be found in a menu that goes under the heading of 'Stream Format'. Calling up the various camera-control and image windows, make sure that the camera control is set to 'Manual' and adjust the gain setting to somewhere between half and full. Make sure the 'Audio' box is un-ticked in the 'Audio Control' menu which you will also find under 'Properties'. Leaving it on may cause problems later – don't worry about this, just make sure 'Audio' is turned off. Of course, you will not have to worry about any audio settings if your camera is one intended for astronomy rather than a webcam.

In the 'Image Controls' menu, set the 'Brightness', 'Gamma' (this is image contrast), and 'Saturation' (this is how strong the colours are) all to their mid settings. Next select the 'Frame Rate'. In Phillips software for the old ToUcams you have a choice of 5, 10, 15, 20 and a few higher speed settings. Choose 10 frames per second. Set the 'Exposure 'setting to $1/25$ second.

If necessary, click off the various control-setting menus until you can see the camera-image display screen. Next, aim the telescope at the centre of the sunlit portion of the Moon (I recommend that you first set your telescope using an eyepiece, then replace the eyepiece with the webcam). You will see the camera image display screen awash with white light. If the screen is virtually brilliant white, call up the 'Image Controls' window and adjust the 'Gain' until the screen looks light grey. Leave the 'Brightness' control alone at this stage – control the screen brightness by means of the 'Gain' setting. It is always an advantage to turn down the gain because this reduces the electronic noise the camera generates.

Now have a go at trying to focus. At some point you should see the lunar vista come into focus on the camera display screen. You might need to adjust the 'Gain' setting once more, and then further adjust the focus. Keep going until you are satisfied. Then you might like to call up the 'Image Controls' menu again and adjust the 'Gamma' setting, and maybe just tweak the 'Brightness' setting, until you are pleased with the image. A final check of the focus and all should be ready.

Finally, call up the 'Capture' menu and set the duration and frame rate of the AVI, (choose 10 frames per second, 1/25 second exposures, and 30 seconds duration for your first go with a ToUcam but shorter exposures for a more sensitive monochrome camera) and a filename ('Moon#1' – not very original but it will do!). When you press 'Return' off it will go – image files will be created from the camera's output and will be rapidly filling up your computer's hard drive.

4.7 STACKING THE IMAGES USING *REGISTAX*

After your session at the telescope you will have one or more AVI files of images to process. You will normally want to do this in comfort indoors – and this brings me to an important warning: **NEVER power up computer equipment, or any mains-driven equipment, that has been recently brought from a cold environment into a warmer one**. Condensation could breach the electrical insulation on any mains-powered equipment causing danger to you. Also, delicate electronics (even if low voltage) and disk drives can be wrecked, I repeat **wrecked**, if operated when damp. An observing session in sub-zero temperatures certainly demands that you leave all your equipment until the next day before powering anything up. This might not be such a bad idea even for occasions when the temperature difference between inside and outside is not so extreme.

Now we come to the stacking, alignment and processing software. The most popular package is the wonderful *RegiStax*, by Cor Berrevoets. This is free to download from: www.astronomie.be/registax/download.html. This product can stack and align up to 5000 frames (or up to a 2 Gigabyte limit) which is plenty. It also includes some powerful processing software to use on the stacked image.

Other programs, some of which can also control the webcam for making and saving the AVIs, include: *AviStack*, *IRIS*, *K3CCDTools*, *AVIedit*, *AstroVideo*, *AstroStack* and *Astro-Snap*. *AviStack*, created by Michael Theusner, has not been around for very long but it has become a rival for *RegiStax*. Use your favourite search engine to find any of these online. *AviStack* is especially good for stacking and processing lunar and solar images as it uses *multi-point alignment*. Large image areas can suffer frame by frame distortions due to seeing-induced undulations. Part of what *AviStack* does is to monitor chosen points across the image and finally warp each image so the points all come into alignment. *AviStack* can be downloaded for free from: www.avistack.de. I must add that the later versions of *RegiStax* also carry the facility to do multi-point alignment but some users who have compared one software with the other say that *AviStack* produces a better finished result on large solar and lunar images. On the other hand, Cor Berrevoets is continually developing and improving his software and publishing new versions. Most users say that *RegiStax* has always delivered the best processed planetary images of the two programs compared. Certainly, premier planetary imager Damian Peach is a high-profile user of *RegiStax*.

All the foregoing programs come with descriptions, Help files, and/or tutorials and I recommend you study these well. However, do prepare yourself for a steep learning curve. In particular, you will find that there are a number of different choices to make at each stage of the process. There are different ways of doing things and a wide array of settings you can alter to your preferred values.

Perhaps it would be some help if I present here a very much simplified procedure for getting some good results from your very first attempts at using *RegiStax*. This does seem to be the most used and most popular of the available programs, so I shall use this one as a working example. Lack of space prevents me going into much more detail about *RegiStax*, let alone describing all the other software packages.

Stick to using the simplest possible procedure for the first few nights of your imaging and glory in the images you will get. Then, if you so desire, you can begin to experiment with the software package in tandem with re-reading the software author's advice (who, after all, is the expert!) in order to improve your results.

I should also warm you that each successive version of *RegiStax* differs somewhat from the last. You may very well find the layout and operations rather different to how I describe them in the following notes, when you come to download the latest version to your own computer. Please allow for that possibility and adopt a flexible attitude of mind. At the time I am writing these words *RegiStax 5* is the latest but I do know that the release of *RegiStax 6* is imminent. The astronomical community owes a huge debt of gratitude to Cor Berrevoets and his dedicated gang of developers for creating and continuing to develop this immensely useful software that anyone can download for free.

As I intended for the previous notes involving the camera-control software, I hope that the following will be of some use in pointing the way to quickly and easily getting good results on your first night of trying. They are based on the simplest way possible of getting acceptable results from *RegiStax 5*. So, to make a start, let us say that you have *RegiStax* downloaded onto your computer and you start it running. Then:

1. Click 'Select' and load the AVI file from wherever you have it stored on your computer. You should see the first frame of your AVI now appearing

in the image window (which fills up a large part of the screen). As you work through the program please leave all the various control buttons and boxes at their default settings for the first few times you use it (except where I indicate otherwise in the following steps). The default settings can potentially give you great results but you can so easily make it impossible to get good results if you meddle while still inexperienced. Get some consistently good results **before** you start experimenting!

Please do not be intimidated by the complex-looking first page of *RegiStax* that appears in front of you. Remember, you need only interact with one or two of the many tabs and buttons in order to get good results when starting out. However, I would first get you to check one thing. Near the top of your screen you will see a tab labelled 'Use Extended Mode' with buttons to select various options. Please ensure the button labelled 'Always' is ticked (when I say 'ticked', actually it appears orange with a black dot inside it – 'unticked' ones appear just a plane grey). If it isn't ticked then please click on this button to set it.

2. At the bottom-left of the screen you will find a small tab labelled 'Goto Frame'. Click on one of the two little buttons to advance frame by frame through the AVI. The buttons each have an arrow on them indicated moving forwards or backwards. You will see that the tab shows you the number of each frame as you click through them. What you need to do is work frame-by-frame through the AVI until you find a single frame that is clearer and sharper than the average. Write down the number of that frame and then keep searching through the AVI to see if you can find an even better one. Make a note of the number of any good ones you see and when you have had enough of clicking forward through the frames (maybe after a couple of minutes, maybe more, depending on your patience!) go back to what you think is the best frame of those you have found. This frame is going to be the 'reference frame' against which *RegiStax* is going to measure the quality of all the others in your AVI. Simply leave this frame visible while you move on to the next stage.

3. Your next task is to select what is called an 'Alignment Box'. You will find this on the menu that appears down the left-hand side of your screen. As you will see from this menu, you can choose the size of this box. If you click on the buttons one after the other you will see what size of alignment box is created. If it is the Moon you are imaging then select a size of box that will surround a particular lunar feature such as a large crater. When you come to image a planet you should choose a box of size that surrounds the entire planet and ideally leaves just a little blank sky surrounding it. I would guess that you might find an alignment box

size of 64 or 128 pixels about right in order to surround a suitable large lunar crater. Alternatively, choose an area with lots of very well-defined features and choose a larger box size to suit. Once you have the box selected you can then drag it (by holding down the left-hand mouse button as you would when dragging anything else about on your computer screen) over the particularly well-defined lunar crater you have selected. At the centre of the alignment box you will see a little cross. I recommend fine-adjusting the position of the alignment box until the cross is nicely aligned on some particularly well-defined piece of fine lunar detail. In the case of imaging a planet you might simply position the cross onto the centre of the disk of the planet. Left-click your mouse and you will see the alignment box become solid white and fixed on the image.

4. A nice feature in *RegiStax 5* is that it prompts you onto the next stage by, for instance, putting a green underline at the next tab or button that it wants you to click onto or at least to deal with the menu options visible below it. You should now see the 'Align' button underlined in green (this happened when you fixed the alignment box in position), so click on this button. Then sit back for a short period while the software goes through every one of the individual images in your AVI and pulls each one into exact alignment with all the others (normal seeing conditions and any irregularities in your telescope's drive system will cause image shifts and so the image details will appear slightly displaced going from frame to frame).

5. When this alignment process has finished you will next see a button near the top of your screen labelled 'Limit' underlined in green. This is intended to allow you to tinker with the reference frame and make it serve its purpose a little better. You do need to click on this button to move things on – but otherwise please do nothing more than that on your first few goes with *RegiStax*. When you have gained some experience you can get involved with this part of the procedure but you can be assured that you will get acceptable results without bothering about limits at all.

So, having just clicked the 'Limit' button, please next find the button labelled 'Optimize and Stack' that should have appeared near the top-left of your screen (it did so when you clicked on the 'Limit' button). Click on it and you will see a preview window open. On the left, you will see your reference image and on the right you will see your AVI running.

The program is now busily going through all the individual images in your AVI, discarding those it decides are too poor in quality. You will see some information about that running in the bar at the bottom of your screen. Then it will begin to stack the saved best images (you will see the 'Stack' button underlined in green but this process should start running without you having to click on this button – sorry to state the obvious but if it doesn't then please do click on it!). All this can take a while, depending upon the speed of your computer. A few minutes is typical but stacking a few thousand frames on an elderly slow computer can take hours!

6. When the stacking process has finished the screen will change and you will see a button labelled 'Do All' near the upper-right underlined in green. **Do not** click on this just yet. Down the left-hand side of the screen you will see a column of buttons and slider-controls under a heading of 'Wavelet settings'. This stage is for dragging out the finest detail from your stacked image. *Wavelets* allows certain ranges of spatial frequencies, in other words details on different scales, to be enhanced.

Given this is intended to be the simplest possible guide to getting started, I am here going to get you to ignore everything on the left-hand side of the screen but the six slider-controls (labelled 1:1 to 6:1). For the same reason I am going to get you to ignore most of the controls on the right-hand side of your screen.

There is one thing I must mention now. While you are experimenting with the slider-controls you will see that only part of the image is being altered. The rest of it remains the same at this stage. The part that changes is contained within a box. The box's sides are not indicated by any drawn line but they will become apparent when you start work with the slider-controls. You can click-and-hold on this box and drag the box about over the image to suit the area you want to monitor. Don't worry – eventually the entirety of your image will be treated – the box is there just as a preview area that is much quicker for the program to work on, so you can very quickly get to see the changes caused by your adjustments.

Experiment with the six slider-controls just one at a time. Starting with the top one, slowly drag it to the right and notice the effect on the image. You will also notice the number on the slider's indicator (in a small box on the right of the slider-control) increasing from its initial '1' setting. Then take the slider back to the '1' setting and next try the same thing with the next slider down. Try each slider in turn. The top one enhances the finest details (the details with the highest spatial frequency), including any unwanted electronic noise. Each of the sliders in turn enhances larger- and larger-scale features (lower and lower spatial frequencies).

Your aim is to balance the application of the slider-controls in order to achieve a combination of settings which best exploits the spatial frequency information in the image. Those actual best settings will depend on what is in your image. My experience is that a good start is to begin with all the sliders set to '1'. Then move the third slider until the image looks as good as it can without looking artificial due to pushing things too far. Beware white fringes appearing around detail boundaries and even false details beginning to appear. Next, start moving the fourth slider but only keep going as long as you see any improvement in the image. Then do the same for the second slider. Then turn your attention to the fifth slider. You might then try the first slider. Then do the same for the sixth slider.

Other people work differently. For instance, many work through the sliders starting with number one and then progress in order, through to number 6. However you work to get to a first version of the improved image, you can carry on tweaking the sliders to see if you can improve the appearance of the image any further. You might, for example, try backing off the setting on the third slider and see if that allows you to put a little more on the second and/or fourth ones, etc.

6(a) Optional RGB align. If you see significant colour-fringing in your image you can correct this by clicking on the 'RGB Align' button you will find on the right-hand side of the screen under the 'Functions' heading. A drop-down menu will appear at the bottom of which you will see a button labelled 'Estimate'. If you click on that, this will deal with the colour-fringing automatically. While you are still in your learning phase please ignore the other controls, which will allow you to do the correction manually or perhaps to refine it further. I can assure you that just clicking 'Estimate' is sufficient to do a good job of diminishing the colour-fringing caused by the Earth's atmosphere that sometimes might spoil your images. If your target object is riding at least fairly high above the horizon then you should have no need for bothering with the 'RGB Align' function at all.

7. We are nearly finished with our enhancements. Over on the right-hand side of the screen you will see a couple of sliders under the heading 'Contrast' and 'Brightness'. See if moving those produces any improvement in your image but please stop before it starts to look unnatural. When you are done you can now click on the green underline button labelled 'Do All'. After a moment or two of on-screen activity you will see your image now fully corrected over its entire area.

8. Look for the tab labelled 'Final' near the top middle of the screen. This time there is no green underline to prompt you. Click this tab and you will see the screen change. The screen layout is this time quite simple and the controls that appear are very obvious. These allow you to tweak the hue, saturation and brightness of the image, as well as rotate it and crop it if desired.
Then save this image. The button for this is near the bottom left of the screen. Choose to save it as a JPG only if you are sure that you will not want to do anything more to it. I recommend a BMP format if you wish to export it to another program. In fact, I think it is well worth you doing so, as you may well be able to improve the image sharpness a little, especially if you have not quite managed to get your *Wavelets* sliders set to their optimum values for your image. Also, you can adjust the tonal values with rather more flexibility in many other software suites ('Curves' is good for this in *Adobe Photoshop*, for instance).

Figure 4.3(b) shows the same image as in Figure 4.3(a) but after *Wavelets* processing has been applied, and the image has been finished

Figure 4.3 Rimae Triesnecker imaged by Martin Mobberley. (a) The best 150 frames from an AVI of 2000 frames selected and stacked using *RegiStax* software.

(b)

Figure 4.3 (*cont.*) (b) The image in (a) has now been processed using *Wavelets* while still in *RegiStax* software suite. To finish the job, the accompanying caption has subsequently been created and stitched on. Please see this caption for further details.

off by being converted to greyscale and a caption has been created and stitched on to the bottom of it.

4.8 TARGETING AN ENLARGED PLANETARY IMAGE ON A SMALL CCD

A principal-focus image of the Moon or the Sun is relatively easy to acquire and keep on the small CCD of a typical fast-frame-rate camera. The tiny disk of a planet presents a less easy target. Add optics to enlarge the principle focus image and you are then dealing with a very small patch of sky on the CCD. Getting the planetary disk in that small patch of sky to appear on the imaging area of the CCD is then very much more tricky. Even with the telescope pointed quite close to the planet you could stir the telescope about for a very long while and yet have practically zero chance of getting the planet to appear on the CCD. You could easily waste most of an evening just trying to acquire your target, never mind actually imaging it!

So, whenever you try to get a small planetary disk onto the chip of a small-format camera it will prove easiest, and quickest in the long run, to proceed in several stages. First, centre the planet visually using a wide-field eyepiece plugged into the telescope, then do so in a high-powered eyepiece. Then carefully, trying not to disturb the pointing of the telescope, replace the eyepiece with the camera without the amplifying lens system (Barlow lens, Powermate, eyepiece projection assembly, etc.) and centre the image (OK, actually the out-of-focus blob of light!) on the laptop/PC screen. You probably will need at least to crudely focus the image to allow you to do this. Next, once again taking great care not to disturb the pointing of the telescope, remove the camera and attach the amplifying lens system to it. Then, carefully insert the complete system into the telescope (as shown in Figure 4.2(b)).

Hopefully at this stage you will see a big out-of-focus blob of light somewhere on your screen. If so, roughly focus and centre the image. If you do not see the planet you could try very slightly nudging the pointing of the telescope about to see if its image enters the field. If it doesn't then don't persist doing this for more than a minute. Instead go back to the camera without the amplifying-lens system and try again. Once you have succeeded in getting the image centred and roughly focused you can prepare the camera-control software and further refine the focus ready to begin your imaging run. I will have more to say about imaging specific planets in the relevant sections later in this book.

4.9 STRIVING FOR THE BEST RESULTS

Is your telescope accurately collimated? If in doubt please refer to Appendix 1, near the back of this book, for details on how to check this and the procedure for making any necessary corrections. Poor collimation is a real killer of a telescope's optical performance. The world's best lunar and planetary imagers are all obsessive about precise collimation – and with good reason!

Is your telescope sited in the best place? Looking over rooftops, long spans of concrete, warm buildings, etc., will all cause bad seeing. Do whatever you can to give yourself the best chance of obtaining quality images. Taking a warm telescope out into the cold night air and trying to image straight away is usually pointless. Try to minimise the temperature difference between the telescope and the night air. Take the portable telescope outside, or open up the observatory, as long as possible before you begin.

If your telescope has a cooling fan (very useful on larger reflecting telescopes) then switch it on as early as possible before you begin. If you have a choice of what equipment to use then a small, high-quality telescope may well be better than a large, mediocre-quality one. It might also turn out that thermal characteristics of the smaller telescope would allow you to obtain images superior to those you could get from the larger one even if both were optically perfect.

When taking the AVIs make sure that you and any heat-generating equipment, such as your laptop, are well away from the front end of the telescope. If at all possible position yourself and your equipment downwind of the front of your telescope.

Take the time to focus the image as precisely as possible. The normal state of the Earth's atmosphere will make this a trying exercise. The image will shift in and out of focus as well as gyrating and distorting all on its own, even without you touching the focus adjuster. It can be quite difficult judging where the true focus point really is. A good-quality electric focuser is a real boon. If you have to touch the telescope to focus it you will likely throw the image into jitters, making the task of achieving a good focus even more difficult.

I discussed using additional optics to enlarge the primary image enough to satisfy the Nyquist theorem in the last chapter. Of course in practice the ambient seeing conditions and the size of telescope have a big bearing on how much image enlargement is profitable. The bigger the telescope, the less often will it be able to resolve anywhere near its theoretical limit. Once you have mastered the basics, experiment to see how far you can push the enlargement factor with your equipment in given seeing conditions before that enlargement becomes unprofitable.

Experiment with the length of AVIs. Do more frames get you a better final result? Generally the optimal number of frames increases with image enlargement. This is because the image dims with enlargement and noise becomes more important with dimmer images. Find out what works best for you.

Finally, get to know the camera-control software and the stacking and processing software and experiment with a view to improving the results you get. Make use of any Help files, About notes, and tutorials the software authors provide. Also find out what other people are doing.

There are a couple of books: *The Lunar and Planetary Webcam User's Guide*, by Martin Mobberley (Springer-Verlag, 2006) and *Introduction to Webcam Astrophotography*, by Robert Reeves (Willmann-Bell, 2006), which have my highest recommendation. In addition there are plenty of helpful materials online and even a few practical demonstrations of equipment and techniques on *YouTube*. Above all else, though, I hope very much that you will derive great pleasure and satisfaction in obtaining your own photographs of some of the great sights in our wonderful Solar System.

CHAPTER 5

Our Moon

Our nearest neighbour in space is the celestial body that most people first look at with their newly acquired telescope or binoculars. It provides real spectacle when seen through even the lowliest of equipment and the sight of the lunar surface through a half-way decent telescope is nothing short of stunning. Add a little insight into the Moon's real nature and evolution and the spectacle becomes augmented by a level of intellectual fascination that can, believe me, persist for a lifetime.

The Moon is a rocky body with an equatorial diameter of 3476 km, over a quarter of that of the Earth. Its mass is 7.4×10^{22} kg, the Earth's mass being 81 times greater. Dividing its mass by its volume gives it a mean density of 3340 kg/m^3, roughly three-fifths that of the Earth.

The brilliant light of the Moon in the night sky is almost entirely due to reflected light from the Sun, with a small amount added due to indirect sunlight reflecting off the Earth's surface. There is also a very small contribution caused by fluorescence – the re-radiation at visible wavelengths of previously invisible solar short-wave radiations by some of the Moon's surface minerals.

The component of the light illuminating the Moon due to sunlight reflecting off the Earth is called *earthshine*. It allows details to be faintly seen on the night side of the Moon. It is easiest to see when the Moon's crescent is thin because there is not so much glare from the sunlit portion. Also, 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. The brightness of the earthshine also depends on the overall amount of reflective cloud cover in the Earth's atmosphere at the time. Of course, 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.

When the Moon is close to full, its surface seems dazzlingly bright and covered in bright streaks and spots and it can be 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, only 7 per cent of the light falling on it.

5.1 ORBIT, PHASES AND ECLIPSES

The Moon orbits the Earth at a mean distance of 385 000 km taking 27.3 days to go once round. Technically, we say that the *sidereal period* of the Moon is 27.3 days. As the Moon moves around its orbit we see varying parts of it lit by sunlight, so generating the familiar *phases* over a 29.5-day cycle, as illustrated in Figure 5.1. That sequence is properly called a *lunation* and the 29.5-day length of it is the *synodic period* of the Moon.

The fact that the Earth–Moon system is also in orbit around the Sun means that the direction of the sunlight changes while the Moon is moving around the Earth. This is why the synodic period is a little longer than the sidereal period. The Moon has to go just a little further than one complete orbit of the Earth to go from one full Moon to the next.

Occasionally the Moon can stray in front of the Sun, as seen from the Earth. This can only happen at the time of a new Moon and the result we call a *solar eclipse*. For more on solar eclipses see Chapter 12. Sometimes, at the time of a full Moon, the Moon's orb can wander into the shadow that the Earth casts into space, producing a *lunar eclipse* (see Figure 5.2(a)).

The Moon's orbit about the Earth is inclined by 5° to the plane of the Earth's orbit about the Sun, so most new Moons occur with the Moon appearing to pass either north or south of the Sun in the sky. Similarly most full Moons occur with the Moon a little north or south of the Sun, as it appears from Earth. Consequently eclipses only rarely happen, rather than at every full Moon and new Moon, as might be implied by Figures 5.1 and 5.2(a).

Actually, the situation shown in Figure 5.2(a) – 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 (see (b)–(e) in Figure 5.2).

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. Then all the direct sunlight will be cut off. The only light then reaching the surface of the Moon is that refracted and scattered by the Earth's atmosphere. At those times the Moon can look very strange, bathed in a copper-coloured glow.

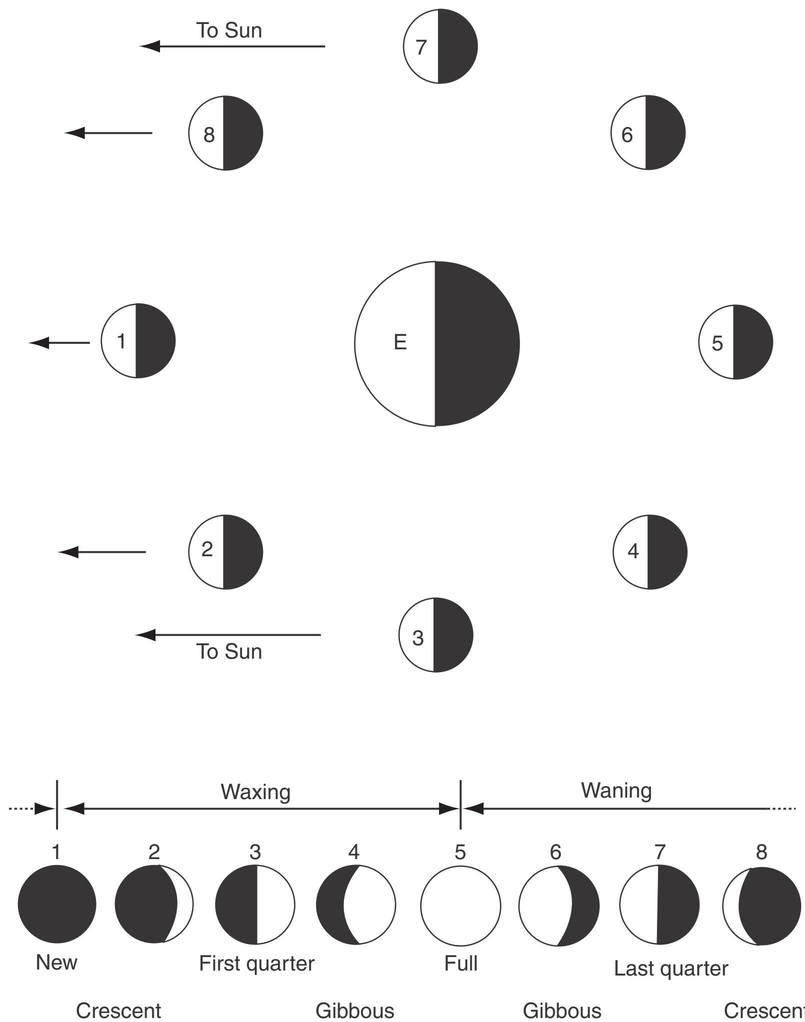


Figure 5.1 The phases of the Moon. The upper section of the diagram illustrates the Moon in a sequence of positions in its orbit, while the corresponding phases that we see from the surface of the Earth are shown in the lower part of the diagram.

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 particular colourations seen, vary from eclipse to eclipse (and often 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 Earth's limb as seen from the Moon at the time of each of the eclipses.

It might be that for a particular eclipse the Moon only partially enters 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*,

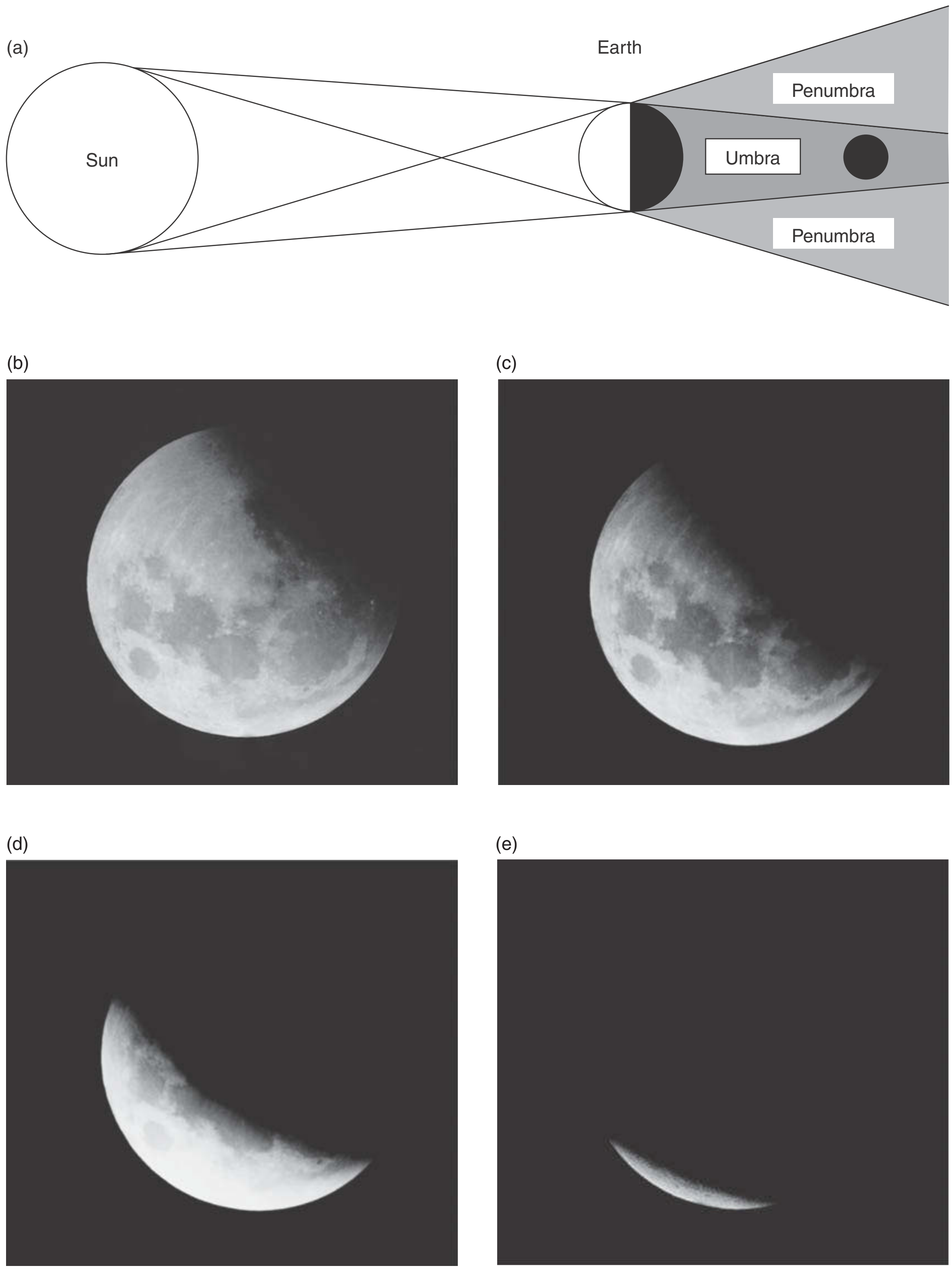

(a)
Earth
Sun
Penumbra
Umbra
Penumbra
(b)
(c)
(d)
(e)

Figure 5.2 Lunar eclipses. (a) 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. (b)–(e) Four photographs of a whole series taken by the author showing the progression of the umbral shadow onto the Moon during the lunar eclipse of 2007 March 3^d. These photographs were taken at the f/7.74 Newtonian focus of the author's 8½-inch (216 mm) reflecting telescope, using an old film-based camera. The film used was Fuji XTRA (800 ISO).
(b) 1/500 second exposure at $21^h\ 40^m$ UT;
(c) 1/500 second exposure at $21^h\ 52^m$ UT;
(d) 1/60 second exposure at $22^h\ 15^m$ UT;
(e) 1/60 second exposure at $22^h\ 38^m$ UT.

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 lighter, though the umbra still looks coppery red and its edge is often coloured bright yellow. A Danjon 4 eclipse is the lightest, with the Moon looking bright orange or yellow even at mid-totality.

5.2 LUNAR OCCULTATIONS

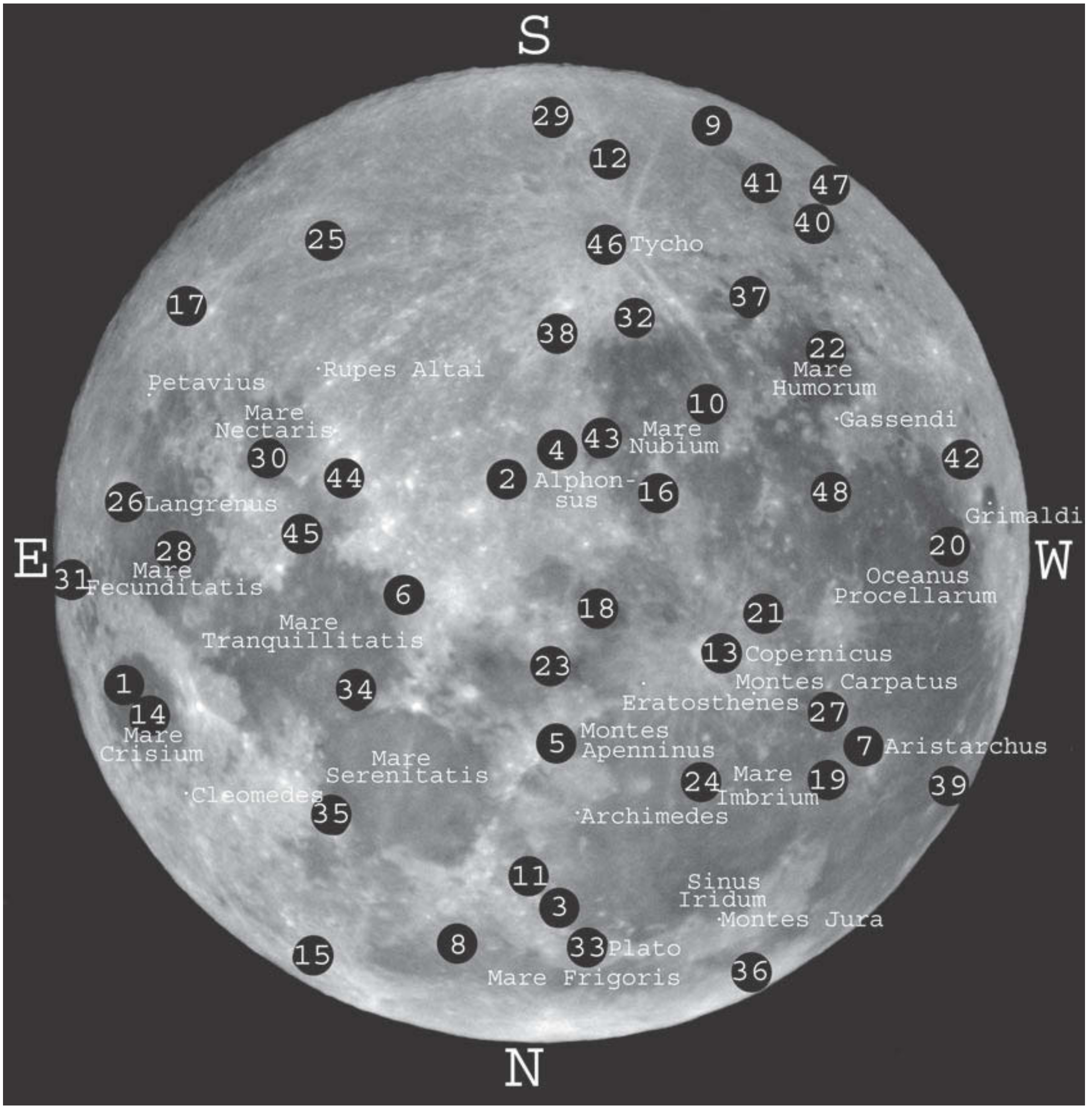
For many years, the precise timings of *occultations*, the passages of the Moon's disk across the background stars, have been the dedicated work of a very small band of amateur and professional astronomers. The data have generated particularly valuable information about the topography of the Moon's limb regions and the motions of the Moon in its orbit, as well as being used for a host of spin-off studies. Now many of these lines of research are better served by other professional methods, though a very small number of amateur astronomers continue to make timings of the immersion and egress of stars behind the Moon.

Given the space limitations in this book, I will simply refer those who might be interested in occultation timings to the lunar observing section of their national astronomical society. These sections have links with the professional organisations involved with occultations of the Moon, planets, and asteroids, for example the International Occultation Timing Association (IOTA). I do describe the timing of occultations of stars by asteroids in Chapter 10 (see Section 10.15). Suffice it to say here that the same basic procedures can be used for timing occultations of stars by the Moon.

5.3 THE MOON THROUGH BINOCULARS AND TELESCOPES

I extensively discussed telescopes for visual observation, together with eyepiece types and image magnification, in Chapter 2. Binoculars can also show a lot of lunar detail provided they are image-stabilised, or are at least firmly mounted.

Figure 5.3 shows a photograph of the full Moon on which the locations and names of some of the major formations are indicated. 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. They are given names such as Mare Imbrium (Sea of Showers – also see Figure 5.4),



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

Figure 5.3 Key map of the Moon. Michael Butcher took the original photograph and subsequently labelled it to accord with a hand-drawn Moon map created by the author. Michael took the photograph on 2003 April 16^{d} 22^{h} 57^{m} UT by hand-holding his Canon Powershot digital camera, set to maximum zoom, up to the 40 mm Plössl eyepiece plugged into his 4.9-inch (125 mm) Meade ETX Maksutov telescope. The camera was set to automatic exposure and focus and a speed of 100 ISO.

Mare Serenitatis (Sea of Serenity) and Mare Tranquillitatis (Sea of Tranquillity). 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). You will find these indicated on Figure 5.3.

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 (Lake of Death). These are the smaller of the mare-type dark plains, though they are still visible through a steadily held pair of 10 × 50 binoculars.

The lunar equivalent of the Earthly 'cape' is the *promontorium*. An example is the Promontorium Agarum (Cape Agarum) on the south-eastern border of the Mare Crisium (its position being indicated as feature number 1 on Figure 5.3).

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 viewing. 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. 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 (again see Figure 5.4). *Dorsa* are ridges occurring elsewhere than on the lunar maria.

The lunar seas are the easiest features to see with the minimum of optical aid. The saucer-shaped depressions known as craters are the next-most-dominant surface feature on the Moon. They range in size from those too small to resolve in telescopes to some that are several hundred kilometres in diameter. The smaller craters vastly outnumber the larger ones. Craters are given the names of deceased famous personalities, most usually astronomers and scientists. The only personalities still alive that have their names assigned to features on the Moon are the *Apollo* astronauts thanks to special exceptions made by the International Astronomical Union (the ruling authority for astronomical nomenclature).

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 – much more like saucers rather than bowls or cups – 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 5.5) but there is an obvious paucity of large 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.

Often the floors of large craters are peppered with smaller craters. The 225 km diameter Clavius (shown in Figure 5.6, also identified as feature number 12 on Figure 5.3) is an obvious example. There are also many examples of craters breaking into others. In almost all the cases it is the smaller crater which breaks into the larger. Gassendi (labelled near feature 22 on Figure 5.3) and Posidonius (feature 35 on Figure 5.3) are examples of these. Each is of the order of 100 km across and intruded by a crater of about 30 km. You might be able to spot a number of other examples in Figure 5.5.

Craters differ in more than their sizes. Some, such as Copernicus (diameter 93 km) and Eratosthenes (diameter 58 km), have elaborately terraced walls. These two are also examples of the many craters to have centrally positioned mountain masses. See both craters pictured together in Figure 5.7. Copernicus is located as feature 13 on Figure 5.3.

Other craters, such as the 101 km diameter Plato (see Figure 5.4 again; feature 33 on Figure 5.3), have their floors flooded with mare material. Some craters have their walls broken down and are almost totally immersed in mare material.

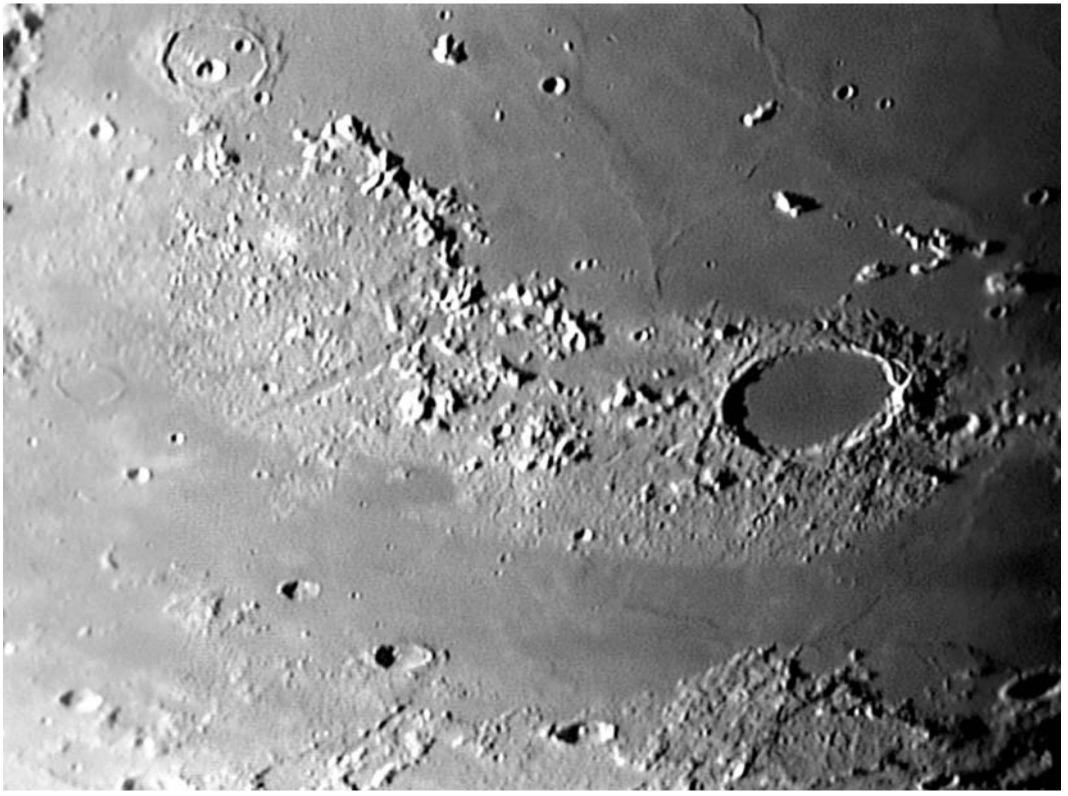
Some craters have bright interiors, an obvious example being the 85 km diameter Tycho (see Figure 5.5 again; feature 46 on Figure 5.3). This is also one of the best examples of craters which are the source of bright streaks of material splashed across the lunar surface, termed *rays*, appearing to extend radially from the source crater.

In most cases these rays are very hard to see when the Sun is at a low angle over the feature. Such is the case for the rays of Tycho. A high Sun angle (near full Moon in the case of Tycho) generally shows a crater's ray system to the best advantage. 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. Its rays are also obvious through binoculars and are also clearly shown in Figure 5.3. Yet they are not visible in Figure 5.5. Most other craters have relatively dark interiors and no associated ray systems.

Mountains (generic name *mons*), along with mountain ranges and groups of peaks (*montes*) abound. They have been named after their earthly counterparts, so on the Moon one can find the Apennine Mountains (Montes Apenninus – feature 5 on Figure 5.3) and the Alps (Montes Alpes – visible just below the crater Plato shown in Figure 5.4). The lunar highlands are very rough and hummocky, whereas the maria are much smoother.

Mountain ranges usually border a mare. Isolated peaks also exist, sometimes actually on a mare. Examples of this type are Mons Piton and

Figure 5.4 The lava-flooded Plato is the largest crater shown in this view imaged by John Gionis, Mike Butcher and the author on 2005 May 17^{d} 20^{h} 45^{m} UT. They used a Philips ToUcam Pro webcam on the Breckland Astronomical Society's 19½-inch (0.5 m) f/4.8 Newtonian reflector, stopped off-axis to 8 inches (0.2 m) aperture. The frames comprising the AVI (10 frames per second for 12 seconds) were aligned and stacked in *Registax 3* and processed using *Wavelets* in *Registax 3*. The resulting image was further processed in *Image Editor* by the author. Plato is set into the lunar Alps (Montes Alpes). The narrow 'gash' cutting through the Alps to the left of centre is Vallis Alpes. The strip of mare to the north of (below) the Alps is the Mare Frigoris. The expanse of 'lunar sea' occupying the upper part of the image is the northernmost part of the Mare Imbrium. The distinctive crater at the upper-left of the frame is Cassini.



Mons Pico (again close to the crater Plato and shown on Figure 5.4), 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 15 km diameter crater Hortensius (about 200 km west-south-west of the crater Copernicus). They are hard to detect except when the sunlight over them is at a particularly low angle. In other words, they are easiest to see on the lunar surface when the lunar terminator is nearby.

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 is *rupes*, an example being the Rupes Altai on the Moon's south-eastern quadrant (and indicated by name on Figure 5.3). Actually a portrait of Rupes Altai is displayed as Figure 3.4 in Chapter 3. It is the curved raised 'ridge' that partially encircles the prominent craters

Catharina, Cyrillus and Theophilus (which have diameters of 97, 93 and 100 km respectively). Theophilus is indicated as feature 44 on Figure 5.3.

There are gorge-like valleys, called *valles*, such as the huge Vallis Rheita near the 190 km diameter ruined crater Janssen (feature 25 on Figure 5.3) at one extreme of the size range. A smaller version, the Vallis Alpes, also appears on Figure 5.4 and is indicated as feature 3 on Figure 5.3.

Much finer (though often longer) sinuous channels, known as *rilles*, also cross the lunar surface. As far as naming them goes, *rima* is used for single examples and *rimae* for networks or groups of rilles. Hence, Rima Hadley and Rima Hyginus (pictured in Figures 5.8(a) and (b)) and Rimae Triesnecker (see Chapter 4, Figure 4.3). All the rilles and most of the lunar escarpments and valleys are named after the closest appropriate major feature, with the sole exceptions of Rupes Altai, Rupes Recta, Vallis Bouvard and Vallis Schröteri.

5.4 LIBRATION

The Moon takes the same time to turn on its rotation axis as it does to go once round the Earth. Consequently the Moon keeps the same hemisphere facing the Earth. Or at least it almost does. In fact, the Moon appears to slightly nod up and down and rock to and fro over a lunar cycle. This effect is termed *libration*. Over a long period of time one can actually map as much as 59% of the lunar surface from the Earth, though the foreshortening at the limb always makes study of these regions very difficult.

There are three separate causes of libration. The rotation rate of the Moon on its axis is constant but the rate at which it travels around its elliptical orbit is not. This causes *libration in longitude*. An apparent 7° east–west oscillation is produced over one lunar cycle (see Figure 5.9(a)).

Libration in latitude is due to a combination of the 5° inclination of the Moon's orbit to the ecliptic and the 1½° tilt of the Moon's rotation axis to the line perpendicular to the plane of its orbit. As the Moon moves around the Earth so it is possible to see alternately up to a maximum of 6½° beyond one pole then the other (see Figure 5.9(b)).

Diurnal libration is a minor effect and is caused solely by the rotation of the Earth. This causes the observer's viewpoint to change with respect to the Moon. At moonrise the observer can see a little way beyond the mean eastern limb of the Moon, while at moonset the observer can see a little way beyond the mean western limb (see Figure 5.9(c)). The direction and extent of diurnal libration also varies with the latitude of the observer's location on the Earth.

All three librations combine. Added to this there are progressive slow variations in the Earth's and the Moon's orbits – effects called *precession* and *nutation* – further complicating the situation. Consequently, the

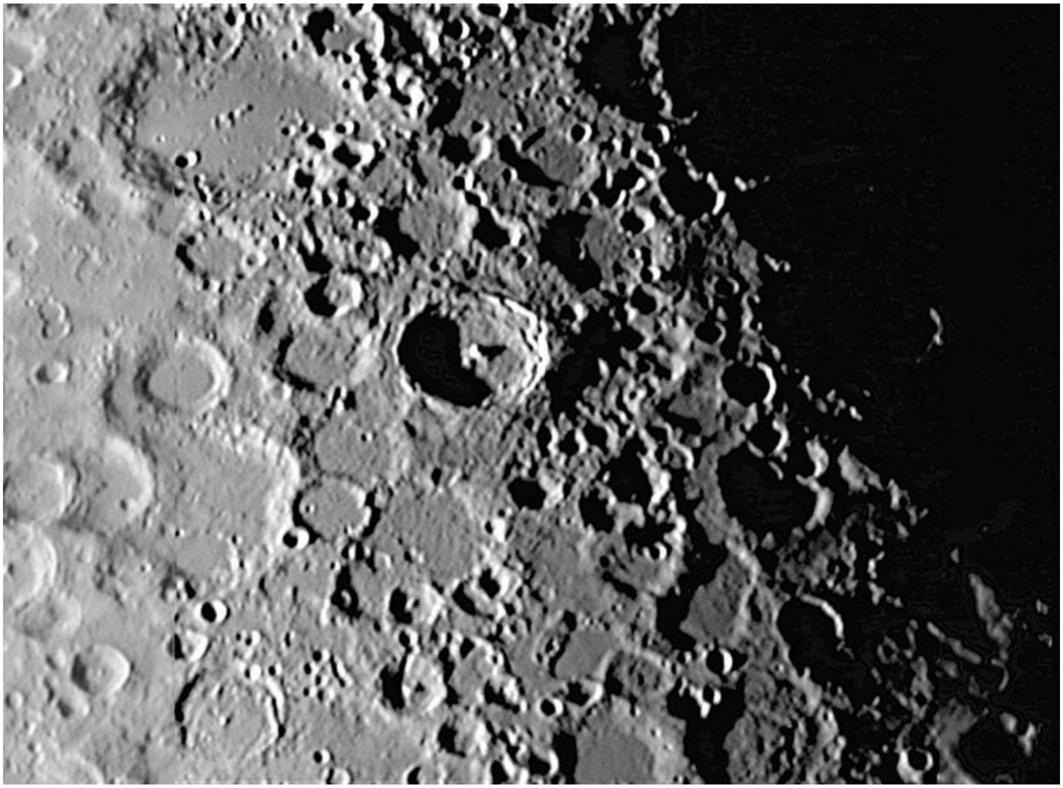


Figure 5.5 Tycho is the prominent crater shown just left of centre in this image by John Gionis, Mike Butcher and the author on 2005 May 17^{d} 20^{h} 32^{m} UT. The other details are the same as for Figure 5.4.

pattern and extent of libration varies from one lunation to the next. Lunar ephemerides include predictions of libration.

5.5 LUNAR CO-ORDINATES AND IMAGE ORIENTATIONS

Latitudes are defined on the lunar surface in the same way that they are on the Earth. The lunar equator has a latitude of 0°, with positive latitudes going north until the north pole which is at +90°. Southerly latitudes are negative with the south pole at −90°. When you observe the Moon through a telescope with the sidereal drive switched off you will see the Moon moving through the field of view. The **leading** edge of the Moon is then its **eastern** limb, as defined by the International Astronomical Union in the 1970s. Look on older maps, though, and you will find east and west marked the other way round.

If disorientated when you are at the eyepiece it might be useful to think of two easily identifiable formations. **Clavius** is far **south** on the lunar disk and **Mare Crisium** lies towards the **eastern** section of the limb of the Moon – okay, nearer the east-north-east but this is still good enough for us to easily sort out east from west. If you prefer, you could

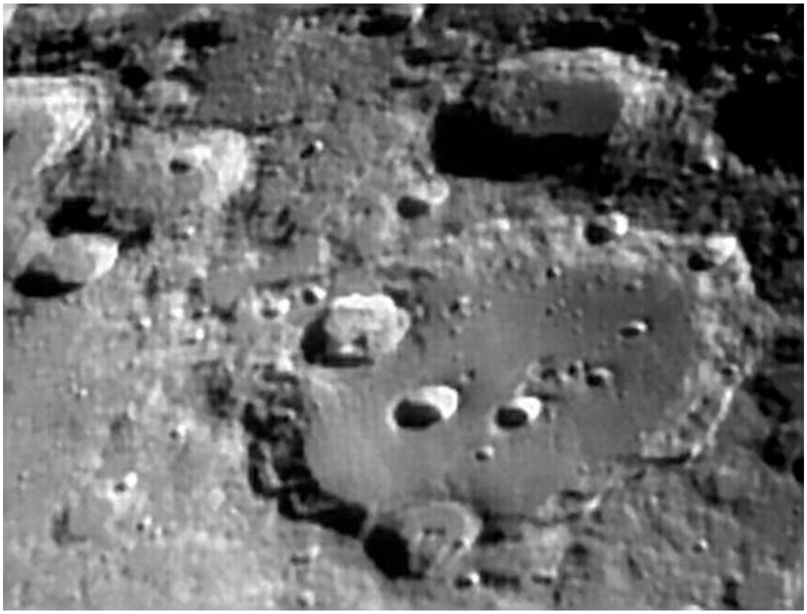


Figure 5.6 The lunar crater Clavius, imaged by the author on 2004 March 01^{d} 18^{h} 20^{m} UT. He used an SBIG STV camera in wide-field mode fitted into a ×2 Barlow lens, plugged into the 19½-inch (0.5 m) f/4.8 Newtonian reflector of the Breckland Astronomical Society, stopped to 8 inches (0.2 m) off-axis because the seeing was a rough ANT. IV at the time. The image was subsequently processed using *CCDOPPS5* and *Image Editor* software.

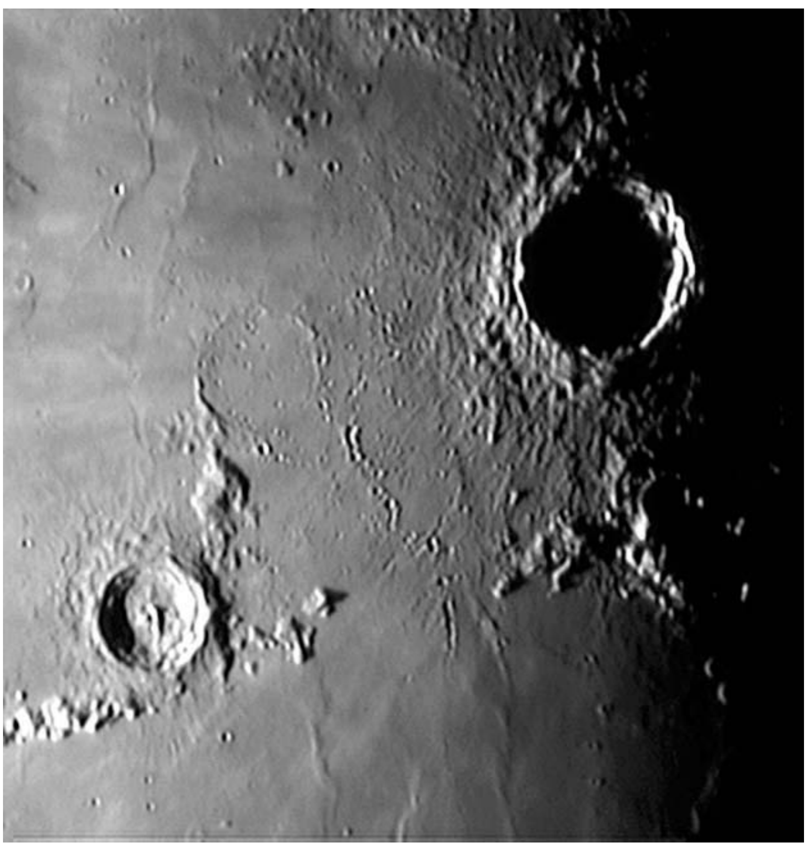


Figure 5.7 Sunrise over Copernicus (the right-hand crater). The crater in the lower left of the frame is Eratosthenes. Webcam image by John Gionis, Mike Butcher and the author on 2005 May 17^{d} 19^{h} 08^{m} UT. The other details are the same as for Figures 5.4 and 5.5.

choose Tycho as a 'southern marker' though it is a crater which rapidly loses its prominence at times away from full Moon.

True, these formations are sometimes invisible but they are so easy to mentally place relative to the rest of the visible Moon's topography that they should still help you with the image orientation even when they are hidden on the dark side of the terminator. The modern placements of north, south, east and west are shown on Figure 5.3.

The zero point of lunar longitudes is defined as the centre of the visible disk and it increases going eastwards. Thus the east limb of the Moon is at a longitude of 90°. It further increases going around the back of the Moon until it is 270° at the western limb. It then further increases on the Earth-facing side to 360° (equivalent to 0°) at the centre once more.

Having explained the general idea I must now refine my statements. Firstly, co-ordinates on the surface of the Moon are known as *selenographic*. For example the *selenographic latitude* of the Moon's south pole is −90°. Secondly, selenographic co-ordinates are actually defined with respect to the **mean** visible positions on the Moon's disk. To explain this, the position of zero points of latitude and longitude on the Moon's rocky surface will only be at the exact centre of the Moon's visible disk when the libration is truly zero – a situation practically never achieved. Hence the need to use the mean visible position when defining selenographic co-ordinates.

In many lunar ephemerides you will find a column of numbers headed by the term *selenographic colongitude*. This is simply the selenographic longitude of the morning terminator. Thus, the selenographic colongitude when the Moon is at first quarter is 0°. That at full Moon is 90° because the morning terminator has now reached the eastern limb. At last quarter Moon the morning terminator now lies on the far side of the Moon and the selenographic colongitude is 180°. At new Moon the sunrise terminator now coincides with the western limb and so the selenographic colongitude is 270°.

The figure for the selenographic colongitude at the time of the observation is often considered useful because it gives an idea of where the terminator lies relative to any feature one happens to be interested in. However, I should warn you that the figures for seleno-graphic colongitude usually published in ephemerides take no account of libration. Consequently, when you go to your telescope you might well find a particular lunar feature you wish to see has been librated further away from the terminator than you expect, or maybe even carried over the terminator into darkness!

Having got co-ordinates sorted out, there is another complication, namely the orientation of the image you see through your telescope.

(a)

(b)

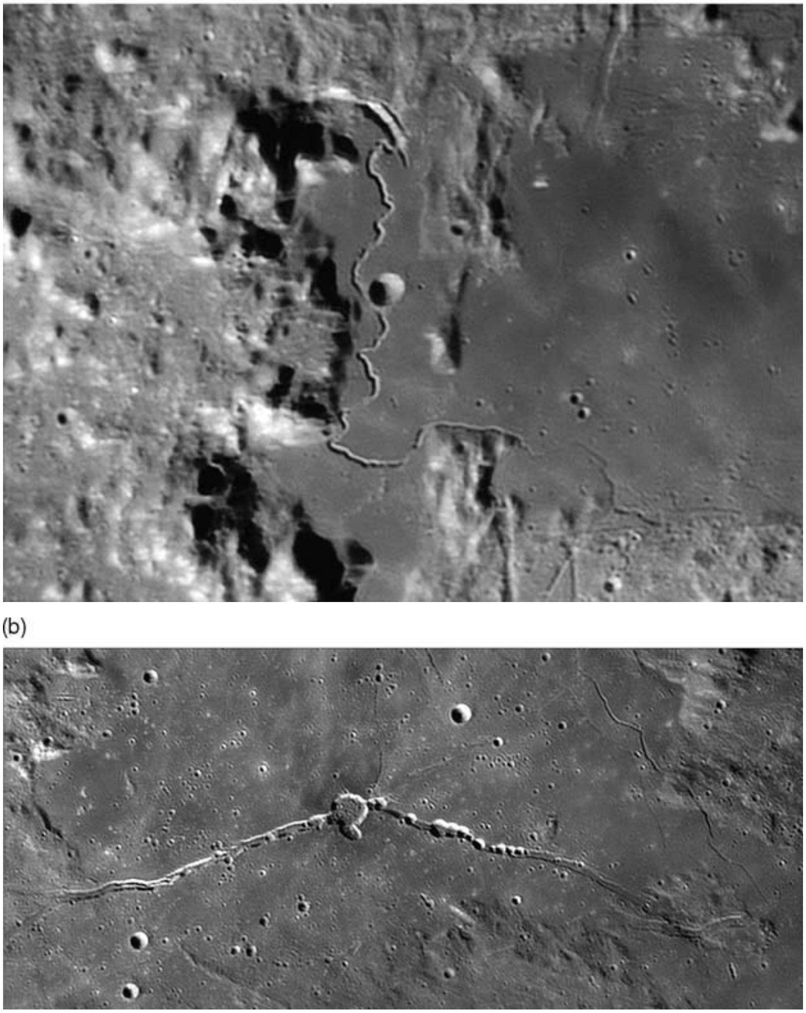


Figure 5.8 Lunar rilles imaged by Damian Peach using his 14-inch (356 mm) Celestron Schmidt–Cassegrain telescope, projected to f/42 using a $\times 2$ Powermate, and SKYnyx 2.0M camera with an RGB filter wheel. Each image was stacked and processed in *RegiStax* and further processed in *Adobe Photoshop* and finally *Paintshop Pro*. The images are orientated with south to the upper-left in both cases.
(a) Rima Hadley, imaged on 2007 May 26^{d}. The Apollo 15 astronauts landed close to the rille.
(b) Rima Hyginus, imaged on 2007 May 26^{d}. The crater Hyginus (the largest crater visible near the centre of this frame) seems to form part of the rille, though in fact is deeper than the rille that passes through it.

Refracting telescopes, Cassegrain, Schmidt–Cassegrain, and Maksutov–Cassegrain telescopes used 'straight through' (no star diagonal plugged in) and any other reflecting telescopes that have an even number of mirrors in the light path produce images that are, to use an old-fashioned term, *astronomically normal*. In the case of the Moon, this orientation is just as shown in Figure 5.3 – south up and lunar east to the left. It is true that the image may appear rotated through an angle depending on the position of the Moon (or other object) in the sky and the orientation of the tube of the Newtonian reflector, etc., but basically the image will still be astronomically normal.

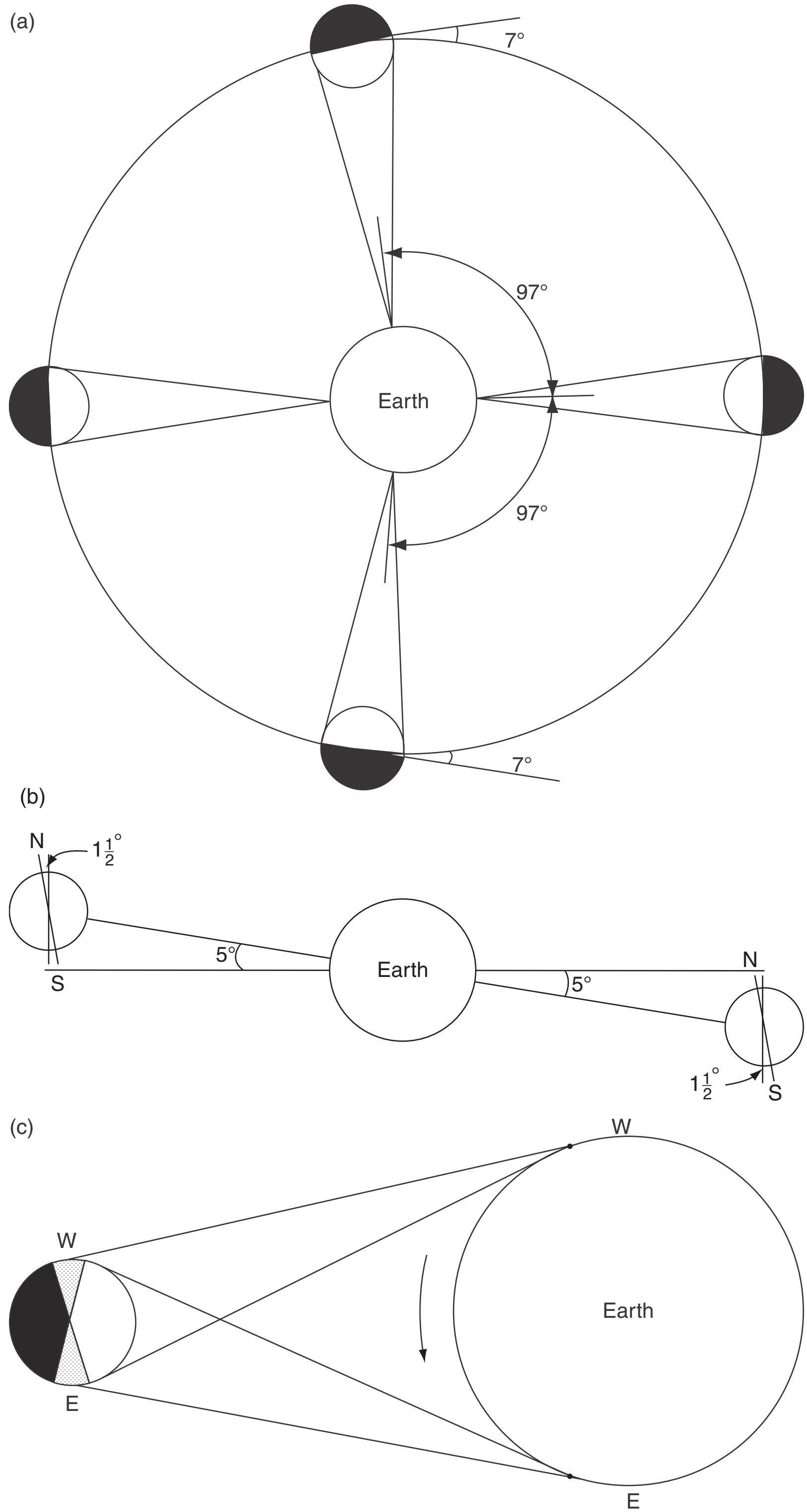


Figure 5.9 Libration.
(a) Libration in longitude;
(b) Libration in latitude;
(c) Diurnal libration.
See text for details.

The reason that this term is now little used is that the once-despised star diagonals have now become standard fare with supplied telescopes. They are, though, almost never used with Newtonian reflectors. Two things result from their use. One is that the image now has north at least approximately uppermost (again allowing for a partial rotation of the image, depending on the orientation of the device in the back of the telescope in addition to the position of the object on the sky). The other change is more fundamental – the image is mirror-reversed. An upside-down image can always be matched to a map simply by turning the map upside down. A mirror-reversed image can never be made to match that same map however the map is turned.

This brings me to an important decision affecting the illustrations in this book. Until relatively recently, all books and magazines aimed at amateur astronomers showed images orientated astronomically normal. Now it is normal practice to display them as if they were seen with the naked eye. In other words, the images are displayed with north uppermost and, in the case of the Moon, lunar east to the left.

Having agonised over this, I have decided to buck the modern trend and display images of the Moon and planets in this book with astronomically normal orientation. If you use a Newtonian reflector (the type of telescope I recommend for visual observation), or one of the other common telescopes without a star diagonal, then the images in this book will have the same orientation as the view through your telescope (provided you observe from the Earth's northern hemisphere). I think this is the best course of action to take in any book intended for the practical observer.

Remember, turning this book upside down will then give the 'north-uppermost naked-eye equivalent' views now standard in magazines – **but if you use a star diagonal then your view can never match a naked-eye orientated photo, nor any normal map, however you rotate the image or the map**.

5.6 PRINTED LUNAR ATLASES

A particularly good Moon atlas is *Atlas of the Moon* by Antonin Rükl. The latest edition (2004) is published by Sky Publishing Corporation (accessed through SkyandTelescope.com). The bulk of its 224 pages is given over to a map of the Moon's near side in 76 sections. These are airbrushed surface-relief drawings of excellent quality. On the facing pages of each section are lists of feature names, along with their sizes, etc. One thing to beware of: the maps are presented north uppermost.

A photographic atlas originally created by Commander Henry Hatfield RN in the 1960s has been re-issued in a slightly modified form.

Now it is called *The Hatfield Photographic Lunar Atlas*, edited by Jeremy Cook and published by Springer-Verlag in 1998. The atlas covers the Moon's nearside in 16 overlapping sections to the scale of 64 cm to the Moon's full diameter. Each opens with a detailed hand-drawn map which is extensively labelled, facing a photograph of the same area. The following pages show the same area under differing lighting conditions. In some cases the selection also includes close-ups of specific lunar areas/features at the scale of about 90 cm to the Moon's full diameter. In total, there are 88 photographic plates making up this atlas. It ends with an extensive index of all the named features, with the plates on which they appear, their selenographic co-ordinates and their sizes. The plates are Commander Hatfield's originals taken in the 1960s and the resolution is not as high as someone might now obtain using a webcam used with even a fairly small telescope. However, the scale and size of the individual sections and the whole arrangement of the atlas – including having south uppermost – makes it especially useful in the field. I am always referring to my copy.

To be really useful at the telescope in the Earth's northern hemisphere a Moon atlas should either show the inverted view one gets through a normal telescope – south at top and lunar east to the left (Tycho at the top and Mare Crisium to the lower-left), or it should show the view one gets using a normal telescope used with a star diagonal – most times north at the top but with lunar east to the left (Tycho at the bottom and Mare Crisium to the upper-left).

Jeremy Cook prepared another version of the Hatfield Atlas that was intended for observers using telescopes with star diagonals that give mirror-reversed images. *The Hatfield SCT Atlas* was published by Springer-Verlag in 2005, just after Jeremy suddenly and unexpectedly died. Commander Hatfield has also recently (April 2010) passed away. Both were friends and colleagues of mine in the British Astronomical Association. There are plenty of other printed Moon maps, charts and atlases one can use but the ones cited here have my particular recommendation.

5.7 *CONSOLIDATED LUNAR ATLAS* AND SPACE-BORNE PHOTOGRAPHS ONLINE

Despite centuries of previous telescopic observation, most of our concrete scientific understanding about the nature and evolution of the Moon came as a result of the *Apollo* manned landings of 1969–1972, with contributions from a small number of unmanned landings and the many orbiting space probes before and since. Here is not the place to go into the long and complex story of the space missions but I ought to explain how you can access some of the mission-derived material for yourself. I will begin with a superb photographic lunar atlas, prepared in the 1960s as part of the preparations for the Moon missions, which now exists online.

A good start would be to visit the website of the Lunar and Planetary Laboratory at www.lpi.usra.edu/resources/cla. This webpage opens with links to enable you to navigate through the *Consolidated Lunar Atlas*, providing you with a number of options of the ways you can view the material.

To give it its full title, the original *Consolidated Lunar Atlas, Supplement Number 3 and 4 to the USAF Photographic Lunar Atlas* was created by Gerard Kuiper, Robert Strom, Ewen Whitaker, John Fountain and Stephen Larson and published by the Lunar and Planetary Laboratory, of the University of Arizona in 1967. It consists of the best 227 photographs (out of over 8000 actually taken) of the Moon made using two 1.5 m telescopes. The online digital version was created by Eric Douglas in 2000. By clicking on a link on the page you can even order a copy of this atlas on CD-ROM.

At the bottom of the same webpage are further links which will take you to the opening pages of *The Digital Orbiter Photographic Atlas of the Moon* (including a link you can click on to order a copy of it on DVD−R), the *Apollo Image Atlas* and the *Ranger Photographs of the Moon*. Each of these pages has links to click on for the purposes of navigation around the sites. Another useful web address is NASA's home page (www.nasa.gov). There is also the National Space Data Center (NSSDC) at nssdc.gsfc.nasa.gov.

Particular highlights, post-Apollo, have been the *Clementine* mission of 1994 and the *Lunar Prospector* mission of 1998. Since those we have had Europe's 2004 *SMART-1*, the Japanese 2007 *Kaguya* mission, China's 2007 *Chang'e 1* and India's 2008 *Chandrayaan-1*, and, more recently, *Lunar Reconnaissance Orbiter* (*LRO*) and the *Lunar Crater Observation and Sensing Satellite*. The *LRO Camera* archive was published online in March 2010. This consists of more than a hundred thousand truly incredible high-resolution images. To access these log on to wms.lroc.asu.edu/lroc#damoon.

There is also an immensely useful online lunar photomosaic that has been created from *LRO* images taken by its 'Wide Angle Camera'. It is presented in a zoomable browser. Zoomed out you can see the whole of the lunar disk. After you zoom in a little you can drag any chosen area to the centre of the frame. When you fully zoom in to your chosen target area you will see a resolution many times finer than you could possibly hope to see with your telescope even under the best conditions. You can get to this resource directly at: wms.lroc.asu.edu/lroc_browse/view/wac_nearside.

There are other mosaics you can access that have been created from *LRO* data but I will stop here. Space is pressing, so I will leave you to surf the Internet yourself to find more of the huge amounts of data, photos and results that now exist online.

5.8 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 Internet has innumerable sites where this information can be found (though it is always 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 *LunarPhase Pro* (reviewed in the June 2003 issue of *Sky & Telescope*) 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, and ever increasing amounts of freeware are appearing on the Internet, so I must leave you to search out for yourself the up-to-date advertisements and reviews and obtain the product that best suits your own needs. However, one I feel I must make special mention of is *Virtual Moon Atlas* (*VMA*). This is an excellent piece of freeware you will find at www.astrosurf.com/avl/UK_download.html.

Created by Christian Legrand and Patrick Chavalley, you only need a very basic computer package to download and run this program. You get a fairly detailed representation of the Moon created from the US Geological Survey maps. The image is correct for lunar phase, and libration. What you see on the screen can be for the current date and time but you can also date-zoom forwards and backwards in time and watch things change. You can change the orientation of the image or even mirror-reverse it to suit the equipment you are using.

A side panel shows lots of relevant data. For instance, it can display a list of all the lunar features very close to the terminator at any given time. You can look of the whole Moon or zoom in to specific areas. You can place the cursor over a given feature and read off lots of information about that feature. There is even the option of adding your own notes about that feature. You can even use the cursor to measure distances on the lunar surface.

There is more I could say about the Virtual Moon Atlas. Instead I will simply urge you to download a copy of it for yourself. As an aside I hope that it, along with any other websites I recommend in this book, are still active by the time you read these words! A lot can happen in the interval between an author finishing the writing of a book and its final publication.

5.9 THE NATURE AND EVOLUTION OF THE MOON

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 of elements such as aluminium, calcium and magnesium.

In contrast to earthly rocks, there is nearly a complete absence of water in chemical combination in any of the samples brought to Earth by the *Apollo* missions. At least that is the case in all the rocks that have been examined so far. Only very recently have the most sophisticated tests been able to detect traces of water in the parts per million range. Recent space probes have detected the signature of some traces of water mixed into the top couple of millimetres of lunar soil. In addition, much hoopla has been made of the water vapour detected in the ejecta from the deliberate crashing of the *LCROSS* (*Lunar Crater Observation and Sensing Satellite*) probe into a permanently shadowed region of the lunar south pole crater Cabeus. However, in most practical senses the Moon is a very arid world.

Nor have we ever found 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. Further, most of this material, along with the water-ice so far discovered, undoubtedly originated from outside the Moon and was delivered onto it by meteorite and comet impacts.

The highland rocks and mare rocks are very different from each other. The lunar maria are composed of iron- and titanium-rich volcanic rock types known as *basalts*. They have a diversity of compositions within the main type, as is also the case for the highland rocks. Temperatures on the lunar surface vary greatly, because of the absence of a blanketing atmosphere. The equatorial 'noon' temperature reaches 100°C, whilst at night it falls to −150°C.

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 is picturesquely called *gardening*.

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

Thanks to *moonquake* detectors left by the *Apollo* lunarnauts and precise gravimetric measurements made from orbiting probes we have been able to gain clues about the Moon's internal structure. Below the crust is the *mantle*, thought to be rich in certain minerals such as olivine and pyroxene. The mantle becomes less rigid with depth.

Gravity data, especially those 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 900 km if it is composed mostly of iron sulphide. It is possibly molten, perhaps at a temperature of about 1700°C if it is pure iron. If the core is not pure iron it could be molten at a lower temperature, maybe around 1000°C if mostly iron sulphide (nickel is another likely ingredient). Overall, the Moon's globe is very iron-depleted compared to the Earth. Recent magnetic examination of an Apollo rock sample has produced results which suggest that the Moon did once have a global magnetic field that was about 2 per cent the current strength of the Earth's field. A global magnetic field implies the dynamo effect in action – the same mechanism that is the source of the Earth's magnetosphere – and that requires a molten lunar core. Despite the current absence of a global magnetic field, suggesting it has solidified, the jury is still out over the question of the current state of the Moon's core.

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 was first to reveal that there is 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.

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, leaving the lightest elements to float 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. In addition, recent computer models of the formation of the Solar System suggest that the early migrations inwards of Jupiter and outwards of the other gas-giant worlds may have really 'stirred up' the asteroids. During these early times, about four billion years ago, massive lumps of material were smashing into the Moon and the other planets. This is known as the *Late Heavy Bombardment*.

Great basins and smaller craters were created by the huge, 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 this battering abated until it was largely 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.

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

The creations of the biggest basins were real Moon-rocking events, leaving a heavily fractured crust. Some of the fissures extended down to the still-molten mantle. Radioactive decay caused temperatures within the Moon to climb in the first billion or so years of its existence. Lava eventually erupted through the fissures. The chemical compositions of these lavas caused them to have viscosities very much less than that of Earthly lavas. These runny lavas flooded the basins, solidifying to form the maria we see today.

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.

After the upward surge in temperatures caused by the initial high (but from then on dwindling) rate of radioactive decay, the interior of the Moon then began to cool. Consequently, the main lava-flooding activity dwindled and eventually ceased about 3200 million years ago.

5.10 LUNAR CHRONOLOGY – AND HOW TO INTERPRET WHAT YOU SEE THROUGH THE TELESCOPE

We have divided the 4.6 billion year history of the Moon 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 events as primary benchmarks.

The first of these benchmark events was the formation of the Nectaris Basin – which later lava-flooded to form the Mare Nectaris. This occurred some 3.92 billion years ago, according to modern determinations. The first lunar era is thus the time from the formation of the Moon to the event which created Nectaris Basin. So, what we call the *Pre-Nectarian Period* spans from 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 just about 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 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 Orientale Basin (almost entirely hidden beyond the Moon's western limb) 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. The period between the formation of the Imbrium Basin and Eratosthenes (3.85 to 3.2 billion years ago) 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. It is during the Imbrium Period that most of the basaltic lava-flooding of the basins occurred, most of it occurring early in the period.

The formation of the crater Copernicus, 0.81 billion years ago, provides the last of the key chronological markers. The *Eratosthenian Period* spanned 3.2 to 0.81 billion years ago. The Moon in that period was very much less troubled with volcanism or large meteorite impacts than before.

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 (if any at all) have disturbed the Moon's quietude in the last billion years.

All of the Moon's history from the Nectarian Period onwards is laid out for your inspection on its surface. If you feel so inclined you can have a go yourself at gauging the order of events that has shaped any part of the lunar surface you care to study. You might even care to deduce the likely dates of formation of selected features.

To take one easy example, have a look at the 56 km diameter crater Cassini that appears on the top-left of Figure 5.4. You will see that its interior is flooded with mare lava and that it has two small craters within it. Cassini is sited near the edge of the Mare Imbrium. How could it have survived the impact that created the mare basin? The answer is it couldn't. Therefore, we know that Cassini was formed after that event 3.85 billion years ago. However, it has been flooded by mare lavas so the crater must have existed before the lavas stopped flowing about 3.2 billion years ago. Hence we have pinned down the creation of Cassini as happening between 3.2 and 3.85 billion years ago. What can you say about the ages of the two small craters within Cassini?

You can also ponder how the various types of formations you choose to scutinise were formed. For instance, what about the rilles? There are two distinct types. *Sinuous rilles* appear as thin, winding, channels. They give the impression of being formed by running lava and this is probably correct. *Linear rilles* (sometimes known as *arcuate rilles*) are straighter in appearance. Where they change direction, they do so suddenly, rather than bending slowly. It seems this type of rille is actually what geologists call a *graben*. In this case the ground to either side of the fault is pulled apart and the soil along the line slumps downwards into the gap. What do you think are the natures of the rilles shown in Figure 5.8(a) and (b)?

I will stop there – but you have the whole of the Moon's Earth-facing hemisphere to study and interpret through your telescope if you feel so inclined. I go into all things lunar in far more detail than I can here in my book *Observing the Moon: the Modern Astronomer's Guide* (Second Edition, Cambridge University Press, 2007).

5.11 DRAWING AND PHOTOGRAPHING THE MOON

Until the mid-twentieth century there was real scientific value in making carefully executed drawings of small areas of the Moon. Now, our detailed knowledge of the Moon's topography far exceeds the fineness of details resolvable by any amateur's telescope. Nonetheless, there remains a small number of amateurs who like to draw the Moon. Certainly, drawing what you see through the eyepiece is a very effective way of really getting to know your chosen areas of the Moon. Doing so will also create a link between you and the lunar cartographers of yesteryear who **had** to draw the Moon because there was then no more sensitive way of doing it.

Perhaps this is an activity you might like to try for yourself? Your drawing could be a simple line diagram. At the other extreme it could be a high-quality work of art showing all the half-tones. What is possible depends on your abilities. This will, of course, improve with practice. Even though your work will not be used for pioneering research, astronomy **is** still a science, so your drawing must be accurate.

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. There are now even a number of hand-held electronic devices that can be used, such as many PDAs (personal digital assistants) currently on the market. Each will demand its own techniques. Moreover, you will undoubtedly find various ways of working that suit you best. Consequently, all I will do here is to offer a few guidelines for making drawings the traditional way.

An illuminated drawing board to use at the telescope will prove invaluable for making your initial drawing and making notes. You can easily construct one of these for yourself as I indicated in Chapter 1 (Section 1.4).

Having decided on your chosen target, spend a while scrutinising it with different magnifications before committing anything to paper. The area you cover in your drawing should 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 5.10(a), which shows the first stage of a drawing of the crater Mairan by my friend 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 5.10(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. Having a range of pencils of varying grades of hardness will prove invaluable for this. You might make an outline by tracing over a suitable photograph. This technique

Figure 5.10 (a)–(e) Showing stages in the drawing of the lunar crater Mairan by Andrew Johnson. See text for details.

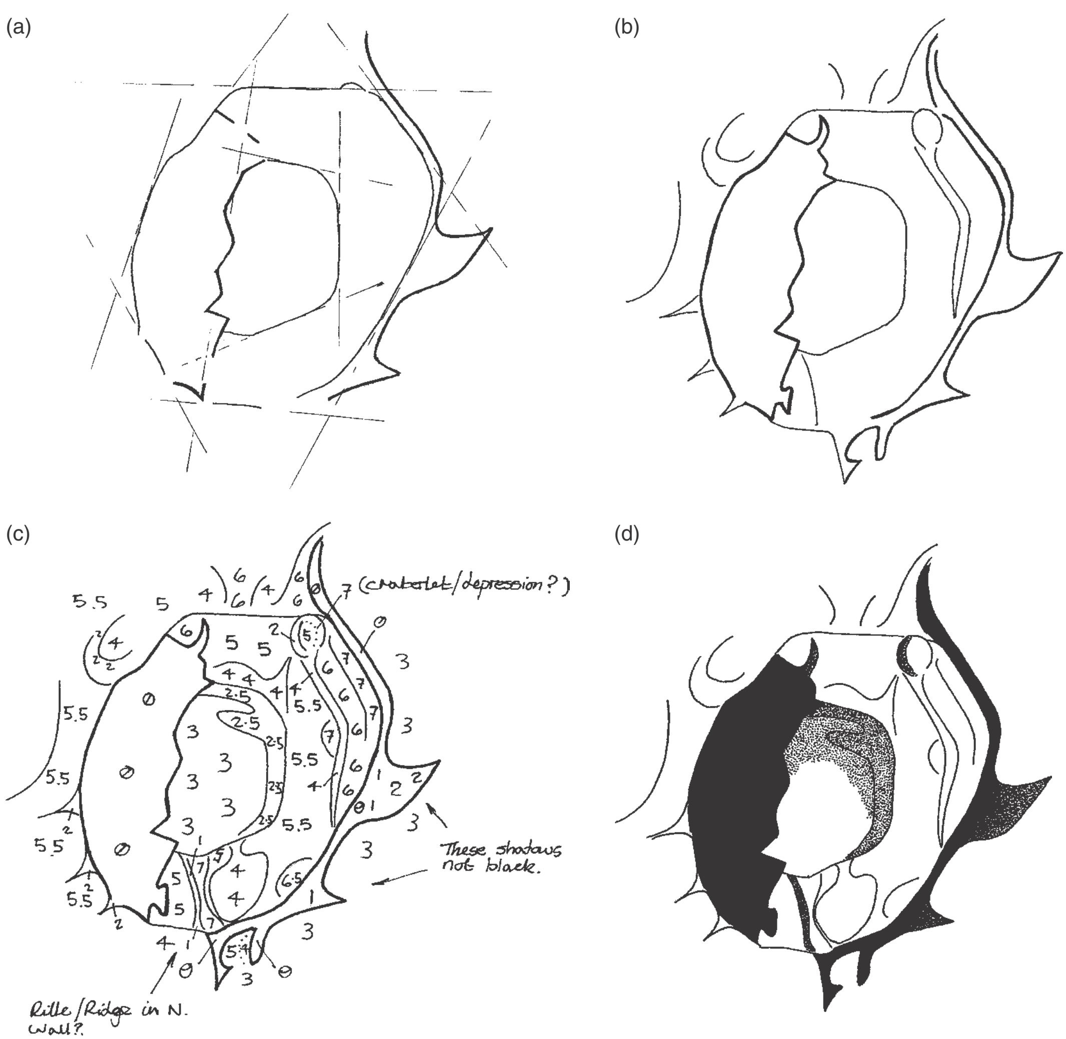
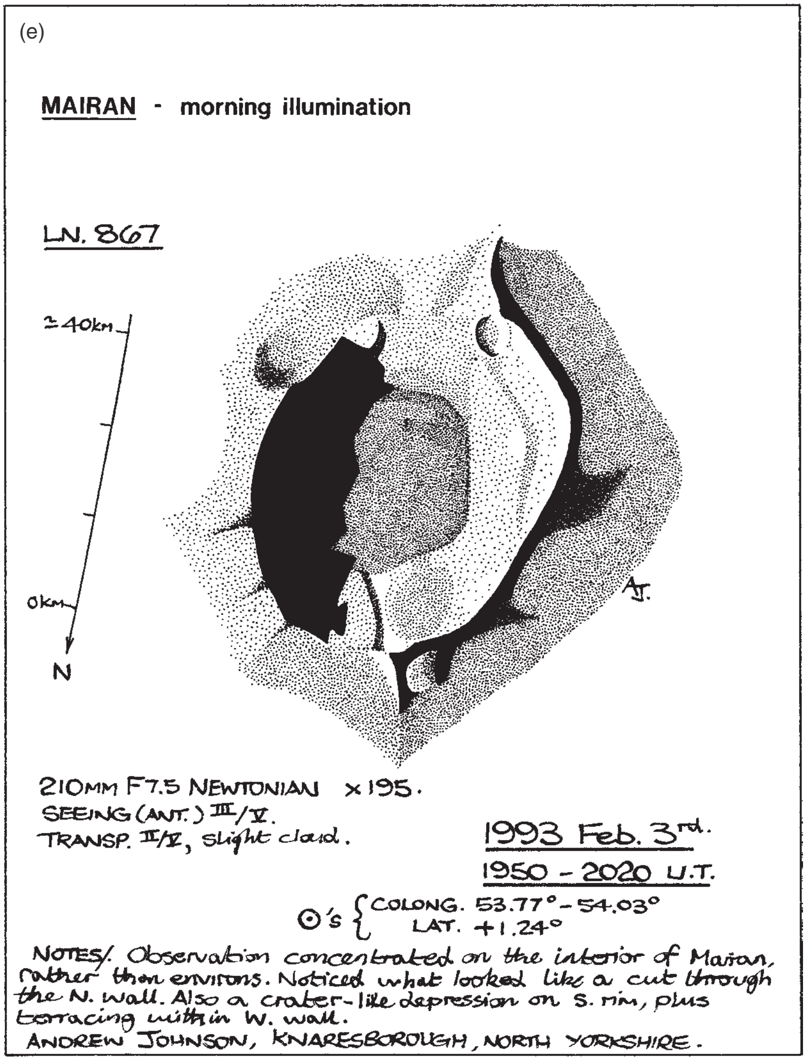


Figure 5.10 (*cont.*)



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 also subtle colourations that you might see if your eyes are sufficiently colour-sensitive, though most people see the Moon only in monochrome). There are a number of ways you can represent these shadings on your drawing. One is to add numbers to the areas, representing brightness gradations. Figure 5.10(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. I describe note-taking, along with drawing planets, and the assessment of seeing conditions in much more detail in the next chapter (see Sections 6.5 and 6.6).

You might prefer to make your final version at the telescope, complete with all shades of grey and the black shadows filled in. 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 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 beforehand. 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, I repeat, the ways you can do it are almost unlimited. Today's lunar artists frequently use stippling as a way of representing half-tone shadings in their finished drawings. With great patience the shadings are built up, dot by dot. A desk-mounted magnifying glass with good illumination will ease eye strain. The greater the density of the dots, the darker the shading when the drawing is viewed from the normal distance. Andrew typically takes around two hours to produce the finished version of one of his drawings. Figure 5.10(d) shows the process underway for his Mairan observation and Figure 5.10(e) shows the final result.

There is no denying that even the most skillfully executed drawing will show less genuine fine detail than would a properly executed and processed video image made with the same equipment at the same time and location. I cover Moon and planet photography in Chapters 3 and 4. Chapter 4 is specifically concerned with video imaging. Also, I give details of how the photographs displayed in Figures 5.2, 5.4, 5.5, 5.6, 5.7 and 5.8 were obtained in the accompanying captions.

5.12 TRANSIENT LUNAR PHENOMENA

Going right back to the earliest days of telescopic observation of the Moon, many observers have reported occasional odd appearances affecting small areas of the lunar surface. These are known as *transient lunar phenomena* (*TLP*) in Europe and *lunar transient phenomena* (*LTP*) in America. Thanks to a number of extremely vocal cranks and crackpots who have claimed to see frequent weird and wonderful effects on the Moon this field of study is now widely derided. However, there is now a solid core of evidence that a very small number of reported TLP are genuine. Some of the apparent TLPs occasionally reported by rational and skilled observers are explainable by effects that are real but do not have their origin in anything physical happening on the lunar surface. My view is that the majority of the so-called TLP reports are the result of errors and misinterpretations on the part of either inexperienced or over-enthusiastic observers. Additionally, no doubt even some very experienced observers have also made mistakes.

It is the very controversial nature of TLP that makes an observing programme to study it scientifically worthwhile. To start with, let me list the most frequent anomalies noted and offer some possible mechanisms that might explain them. In each case the area of the lunar surface affected is usually only a few kilometres square, at most.

Short-term brightness 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 most times for rather less than an 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.

Many materials fluoresce in nature when bombarded either by short-wave electromagnetic radiation or by electrified particles. The Sun emits both copiously and it is not unreasonable to attribute lunar surface fluorescence to particularly strong blasts of solar wind (which are also the source of Earthly aurorae) striking outcrops of certain minerals on the Moon's airless surface.

A number of instances have actually been observed by professional astronomers. In the 1960s, a group of lunar specialists headed by Zdeněk Kopal photographed and measured a number of instances of sporadic brightenings of the lunar surface in particular lunar features that were already known TLP 'hot spots', such as the craters Plato and Aristarchus. In some cases the increases in brilliance were as much as 80 per cent of that under the ambient sunlight.

To take another creditable instance, members of the Tokyo Astronomical Observatory were conducting a long-term study of the photometry (brightness measures in selected wavebands) and polarimetry (the way the reflected light is modified by the surface reflecting it) of the Moon when they recorded an anomalous brightening of the crater Aristarchus on 1970 March 26[d]. Not only did the crater brighten by over 30 per cent, it became significantly bluer and the polarisation of the light changed. Meanwhile, the surroundings remained normal. The author of the report, Naosuke Sekiguchi, suggests that a solar flare observed 29 hours before the observed lunar brightening may well be responsible for the fluorescence. My own researches lead me to believe that the majority (of the very few that are genuine) TLP reported are due to fluorescence of the surface rocks caused by extra-strong gusts of solar wind reaching the Moon.

Obscurations of surface details

There are some reported cases where 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 – suggestive of a cloud of vapour thinning out.

Could certain areas of the Moon very occasionally vent gases? Again, this is not unreasonable. In fact, instruments aboard the orbiting *Apollo 15* and *Apollo 16* command modules detected the signature of alpha-particle energies that correspond to the decay of radon gas. Later studies of the *Apollo* results showed that the Moon emits radon gas in particular areas. Further, the sites of strongest emission coincided with established TLP ‘hot spots’, with Aristarchus registering the highest gas emission.

Maybe if any gas release was particularly ‘violent’ (though still extremely feeble by terrestrial standards) some of the very finest dust particles could be swept up from the lunar surface to produce a temporary hazy 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 brownish or 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.

Coloured effects

Sometimes coloured effects are seen as an accompaniment to brightness changes, or to surface obscurations; sometimes they are seen on their own. Most of the anomalies reported by experienced observers 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. To me, that is suggestive of surface fluorescence being the true cause.

Colour featured in the famous observation of a TLP by Nikolai Kozyrev in 1958. 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. On 3 November 1958, 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. 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.

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 that was 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.

I speculate that solar wind particles might have caused the gas to fluoresce by colliding with the gas atoms/molecules, so causing electrons in the atoms to be temporarily excited to higher energy levels. When they naturally de-excite, the electrons hop down the energy level rungs in the atoms, so producing a characteristic spectrum. Radon gas has a strong emission line in the blue-violet part of the spectrum. Any other gases brought up with the radon would also produce spectra.

Maybe Kozyrev observed a gas release, which raised some dust causing the initial reddish colouration. As the particles cleared perhaps the gas was exposed to an arriving gust of solar wind, causing the bright fluorescence he saw and registered spectrographically?

Flashes of light

These appear as bright (sometimes very bright) flashes of light or brief twinkles of light against the Moon's surface. Occasionally flashes are seen along with other types of TLP in progress.

As to their cause, it strikes me that ionised gas atoms/molecules in motion while venting from a lunar surface fissure could lead to charge separation and a resultant build-up of electrical potential difference. This is especially the case for atoms and molecules interacting with any solid particles swept up. I think that the eventual discharge through the tenuous gas (a form of sheet lightning) might well account for the rarely observed bright flashes and sparkles.

Actually, there is one other incontrovertible cause of lunar flashes: meteor impacts. These were first established as fact during the night of 1999 November 17/18 during the annual Leonid meteor shower. J. Kelly Beatty gives an account of the events of that night in the June 2000 issue of *Sky & Telescope* magazine. There were at least six yellowish flashes witnessed and confirmed by at least two or more observers in the USA and recorded on videotape. They occurred on the unlit western side of the 10-day-old Moon. The brightest flashes were estimated at magnitude 3 and certainly lasted less than 0.03 second as they showed up on only one video frame each. The brightest flashes must have resulted from rocky meteors about 8 inches (20 cm) across. So much for meteor strikes. What about the flashes that seem to be associated with other transient phenomena, or multiple flashes from the same location? In these cases one must look for another cause, perhaps the one I have previously muted.

5.13 BOGUS TLP

I am sure that the vast majority of observed anomalies have nothing whatever 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. 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. The Earth's atmosphere acts rather like a glass triangular prism turned upside down (in other words, with its base uppermost). As well as astronomical objects appearing slightly elevated – making sunrise happen slightly early and sunset happen slightly late – the light rays from them are slightly *dispersed* (split into their component colours) as a result. Obviously, for each light–dark boundary in the lunar 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 part of the full 'rainbow' is obvious. 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.

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. If you are interested in monitoring for TLP I would urge you to get to know what coloured effects are usual for a given feature.

Image turbulence, or more properly *scintillation*, is also a real nuisance. Sometimes the image is soft but fairly steady. At other times it undulates 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. 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 assumes the lateral form. Observations made with refractors could be suspect because of this but often it is the telescope's eyepiece which produces the worst effect. So, you might well experience the greatest trouble if using a reflector of low focal ratio with a cheap eyepiece.

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 slightly move the telescope in order 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 a high-quality Barlow-type lens or 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. Also, a good photographic atlas is always a help, whatever your level of experience.

5.14 TLP OBSERVING PROGRAMME

If you are a novice observer, it is essential that you first observe through a number of 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.

When I go to the telescope to carry out lunar monitoring, 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 medium–low magnification, say about $\times 140$, and 'raster-scan' the whole of the lunar surface, both the sunlit and the darkened hemispheres. This might take about 15 minutes. By raster-scan 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. Actually, I switch off the telescope drive and let diurnal motion provide the east–west motion for me. 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 up to whatever the seeing allows, spending some time to re-scrutinise my selected features.

I recommend joining a society with a TLP observing group. Then, if your suspicions are aroused, you can telephone a central co-ordinator – 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 Chapters 3 and 4) is an obvious extension of purely visual work. You could include the use of coloured filters with all the imaging methods. Photometry is possible (especially with 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 purchase a spectrograph (SBIG and Adirondack Video Astronomy each market a spectrograph for the amateur market) you could follow in the steps of Kozyrev. However, please be aware that you might have to wait for a very long time, probably even years, before you see anything likely to be genuine TLP. Despite all the rubbish produced by the 'enthusiasts', there is enough good evidence to convince me that TLPs really happen – but they also **rarely** happen!

5.15 LUNAR RESEARCH UTILISING ONLINE DATA

This is a book intended to be of use to prospective serious telescope users, not a book about Internet resources. However, I must give at least a brief mention of the fact that a growing number of enthusiasts are carrying out research, some of it very advanced and bearing genuinely useful results, using the plethora of lunar imagery and data that now exist online. Charles Wood hosts a website at the-moon.wikispaces.com which makes a very good starting point for access to a large range of resources and introduction to current lines of research. The MOON ZOO project is one I could mention, suited to those of a diligent and careful frame of mind but not requiring great knowledge or experience. The Directors of the BAA and ALPO lunar sections will also guide you towards currently active online and telescope-based projects. I will say no more about them here, as I have much more telescope-based practical astronomy I would wish to describe than I have room for in this book, without even beginning to digress into Internet-based projects!

CHAPTER 6

Mercury and Venus

Mercury and Venus are known as *inferior planets* because they orbit closer to the Sun than the Earth does. As a consequence of this they never appear very far from the brilliant solar orb in our skies. Innermost Mercury is particularly Sun-hugging. So, a bit before sunrise or a little after sunset is the only time we have any chance of seeing these planets against a dark sky. Adding to the problems, the ecliptic plane – and the planets stay close to the ecliptic plane – can sometimes intersect the horizon at a rather shallow angle. At those times the best we can do is to catch a glimpse of the planet as it appears low over the horizon, twinkling through the greatest thickness of the Earth's unsteady atmosphere. So, these worlds are not the easiest targets for our telescopes.

6.1 STELLAR AND PLANETARY BRIGHTNESSES

The *apparent visual magnitude* of any celestial body is a measure of how bright it **appears** to be in our sky. The magnitude scale can cause confusion to the uninitiated because the larger positive number actually corresponds to the dimmer object.

The steely blue coloured Vega (the brightest star in the constellation of Lyra) is defined to have an apparent visual magnitude of $0^{m}.0$. There are four stars which appear brighter than Vega and so they are given negative apparent magnitudes. The brightest of these is the brilliant 'Dog Star', Sirius, which has a magnitude of $-1^{m}.5$.

The magnitude scale is not linear (equal steps for equal brightness changes) but is instead based on ratios, with each magnitude difference corresponding to a brightness difference of 2.5 times. The reason behind this is the fact that the eye appreciates brightness differences in terms of ratios and the empirical magnitude figures that were originated by the astronomers of yore happened to correspond to brightness ratios of about 2.5.

A difference of 5 magnitudes corresponds to a brightness difference of $2.5 \times 2.5 \times 2.5 \times 2.5 \times 2.5$ times, which is very nearly one hundred times. Mathematicians define such a scale, where equal steps on the scale represent a change by a constant multiplication factor, to be a *logarithmic scale*. Looking at this from a mathematician's point of view, if we say that a number N is equivalent to another number of the form a^x (for instance $100 = 10^2$), then we can write a relationship between these numbers in terms of a logarithm. The relationship is $\log_a N = x$. (For example $\log_{10}100 = 2$). Logarithms may be an artificial construct but they do lend themselves to conveniently representing and manipulating numbers. Let me restate the relationship, known as the *log identity*, that defines a logarithm:

$$\text{If } N = a^x, \text{ then } log_a\, N = x.$$

The figure a is known as the *base* of the logarithm. For the magnitude scale we are only interested in logarithms of base 10 ($a = 10$) and in this special case we do not need to bother to write $\log_{10}$ each time. Instead we can simply write Log (note the capital L).

Here, then, is the basis of the stellar magnitude scale:

$$m = -2.5 \mathrm{Log}\, I$$

where I is the apparent luminosity of the celestial body, in relative units, and m is its resulting apparent magnitude. The difference in apparent visual magnitude, Δm, between one body, for example a star, and another is then given by:

$$\Delta m = 2.5 \mathrm{Log}\,(I/I')$$

where I and I' are the relative brightnesses of the stars, I being the intensity of the brighter star (which, remember, also has the **lower**, or **more negative**, magnitude number). Set the apparent intensity of the star Vega to be 1 and you have the basis for the magnitude numbers assigned to other celestial objects.

On the very best nights, if you have very keen eyesight and are sited well away from any sources of 'light pollution', you can expect to see stars down to magnitude $6^{m}.5$. Of course an observer with exceptionally acute vision and access to a superior site might do better – a few observers have claimed to see stars as faint as eighth magnitude from some mountaintop locations using nothing but their unaided eyes. This is good enough to easily see the planet Uranus and maybe even to catch a glimpse of Neptune. The rest of us will need optical aid to see these planets. Fortunately, the other major planets are bright enough to allow us normally sighted people to pick them out easily on a starry night and manually set our telescopes on them. That is the case even under fairly light polluted skies.

6.2 THE ORBIT AND PHASES OF MERCURY

The 4878 km diameter orb of the innermost planet, Mercury, orbits the Sun at a distance of 58 million km, with a sidereal period of 88 days. However, its orbit is highly eccentric and while its perihelic distance is 47 million km, its aphelic distance is 69 million km.

This results in the maximum angular distance between Mercury and the Sun varying from 18° to 27° at *elongations*. As the months go past, it appears first to the west of the Sun and then to its east. When Mercury is at its greatest distance to the west of the Sun it is said to be at *western elongation*, and the planet can then be viewed in a twilight sky in the morning where it rises a little before the Sun. At *eastern elongation* Mercury is at its furthest distance to the east of the Sun. It then follows the Sun down in a twilight sky after sunset.

As I mentioned earlier, the varying angle the ecliptic plane makes with the horizon at sunrise and sunset combines with the variations in distance from the Sun to make elongations unequally favourable. From the northern hemisphere, western elongations that occur in the autumn and eastern elongations that occur in the spring have the most favourable ecliptic angles. In each case the most unfavourable ecliptic angles occur six months later.

Since Mercury orbits closer to the Sun than the Earth, we see phases similar to those of the Moon. However, the situation differs from that of the Moon in that Mercury changes its apparent size along with its phases. Venus does the same and the principle applying to both planets can be explained with the aid of Figure 6.1.

At positions labelled 1 and 3 on Figure 6.1 the planet is at its greatest western and eastern elongations, respectively, and then shows a half-phase, or *dichotomy*. Its apparent separation from the Sun is then at its greatest. Mercury then appears to the naked eye as a star-like object of magnitude about $-0^{m}.3$ while its orb actually subtends an apparent diameter of about 9 arcseconds.

Staying with Mercury, at position 4 this planet is, to all intents and purposes, between the Earth and the Sun. It then presents its unilluminated hemisphere to the Earth. It is also at its closest to us and its 4900 km diameter globe then appears at its largest, subtending an apparent diameter averaging 13 arcseconds. At position 2, Mercury is on the far side of the Sun as we see it from the Earth, and then appears fully illuminated though at its smallest apparent

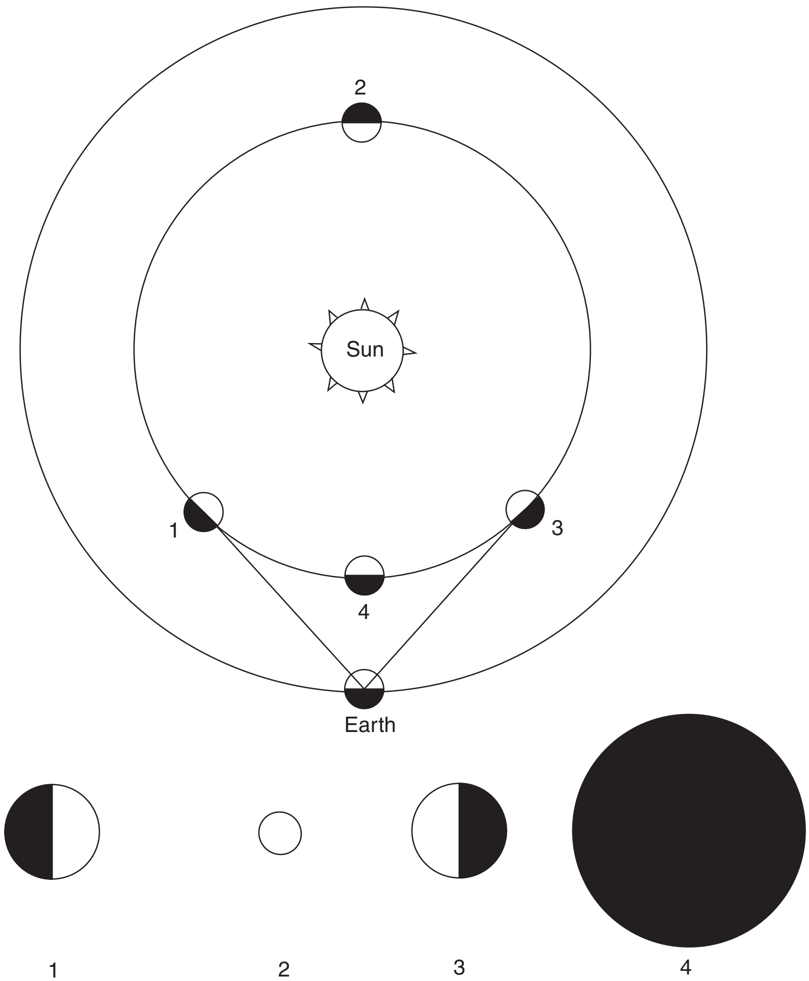


Figure 6.1 The diagram shows how the variations in phase and apparent size of Mercury and Venus occur. The positions of these inferior planets are shown in the upper part of the diagram, with their corresponding appearances as seen from Earth illustrated in the lower part.

diameter of about 4½ arcseconds. Positions 4 and 2 are those of *inferior conjunction* and *superior conjunction*, respectively.

The synodic period of Mercury – the period between successive conjunctions – is 116 Earth-days. Figure 6.1 might give the impression that Mercury should be seen as a black spot against the Sun at every inferior conjunction of the planet. In fact, owing to the inclinations of the orbits of Mercury and the Earth, such *transits* are rare. Venus also very occasionally undergoes transits of the Sun. You can monitor both when they occur and I have more to say about transits in Section 6.12.

As the phase of Mercury decreases, so its apparent diameter grows. This causes the apparent brightness to vary in a complicated way. At its brightest, the planet reaches an apparent magnitude of $-1^{m}.9$, a little less than half of the illuminated hemisphere then being presented to us.

6.3 SEEING MERCURY THROUGH THE TELESCOPE

Serious observers of Mercury often observe it in broad daylight in order to have the planet as high as possible in the sky. Of course, finding a planet in daylight is not easy and its proximity to the Sun poses a real danger. In my opinion, your telescope's mount must be fitted with a drive and accurate setting circles, or it must be on an accurately set and reliable GOTO mounting, before you attempt to find any planet near the Sun in a daytime sky.

Even then, getting a fix on something to calibrate the telescope's computer control or the right ascension (RA) setting circle is problematic. One way is to point the **capped** telescope at the Sun. The finderscope should also be capped, for fear of burning the crosswires, unless its aperture is less than about 30 mm – **but do not look through it, no matter how small its aperture**. You should be able to point your telescope at the Sun to an accuracy of a degree, maybe better, by watching the profile of the shadow your telescope casts as you move it. Your aim is to minimise this profile.

You might then briefly uncap the **finder** telescope and momentarily hold a card 10 cm or so behind its eyepiece in order to 'catch' the projected image. This should enable you to refine the pointing of the telescope to a fraction of a degree. Then input the solar co-ordinates to the computer, or use the Sun's RA at that time to set the RA setting circle. Now you can proceed to set the telescope on the ephemeris co-ordinates of Mercury. Wait until you think the telescope is looking at Mercury before uncapping it.

Never put your eye to the freshly set telescope's eyepiece when the Sun is about without first checking by momentarily putting a hand or a card close to it. You must be absolutely certain that there is no direct sunlight passing through your telescope.

If you have to do any manual searching within a patch of sky anywhere near the Sun then never, **never**, **NEVER** randomly sweep the telescope about with your eye to the eyepiece. If you really do have to manually sweep (please avoid this if at all possible) then make absolutely sure that you only ever move the telescope in a direction that points it further away from the Sun during all the periods that you are looking through the eyepiece.

When the sky is clear and deep blue the planet Mercury can be studied but **PLEASE BE CAREFUL!** A moment's glimpse of the Sun through your telescope and your sight through that eye will probably be ruined for the rest of your life. Even if you are not instantly blinded, there can be latent eye damage, which might slowly degrade or destroy your sight over a period of years after even the most fleeting exposure to concentrated solar radiation. **Unless you can be absolutely sure that your attempt to find and observe Mercury in the daytime creates zero chance of you exposing your eye to a dose of sunlight through your telescope, do not do it. This responsibility is yours, no-one else's. You have been warned!**

If you observe from inside a dome then sometimes the dome slit can be positioned to reveal the planet but cut off the direct sunlight falling on the telescope. To achieve the same ends, a portable telescope might be positioned close to a building or other large obstacle to cut off the view of the Sun and yet still show the planet. This can help a lot but do be aware that if the planet is west of the Sun, then the shadow will retreat and direct sunlight will begin to reach the telescope after a few minutes and the dome, or portable telescope, will need to be moved again.

The difficulties in observing Mercury are compounded by its small apparent size. A magnifying power of approximately $\times 200$ is needed around the time of maximum elongations to make its image appear the same size as the Moon seen with the naked eye. A high-quality 4-inch (102 mm) aperture telescope is enough to reveal faint dark patches on Mercury's disk to the eye of the observer when the conditions are especially favourable. While a bigger telescope might reveal a little more under the very best seeing conditions, it will not show as much as you might think it should.

Probably the best map of the surface of the planet before the Space Age was that produced by E. M. Antoniadi in 1933. He used the 33-inch (0.83 m) refractor of the Meudon Observatory in France. He had also used this telescope to produce a reasonable map of Mars and he was a very experienced observer. However, we now know that Antoniadi's Mercury map only vaguely matches the planet's real variations of albedo. Details on Mercury are very difficult to observe visually from the Earth with any degree of reliability. In fact, the wrong rotation rate was very confidently ascribed to Mercury until as recently as 1965!

To me, the overall colour of Mercury sometimes seems to be tinted a very slight pinkish-brown when seen against a fairly dark twilight sky. This is more like an off-white than any genuinely strong colour. Mind you, its low altitude at these times undoubtedly adds to the pinkness. Contrast with a brighter blue sky background can also add to the impression of a stronger pink tinge to the planet. Space probe results indicate the planet to be a grey orb very lacking in colour.

A common illusion is that the southern cusp of the crescent Mercury appears blunted, in fact slightly foreshortened, compared to the sharply pointed northern cusp. The cause is simply a question of albedo variation. The planet just happens to be slightly dimmer at its south pole and when illuminated by a low-angle Sun (as it is by definition at the terminator) this causes the image to apparently fade into the sky background more readily than at the brighter northern cusp.

6.4 THE REAL PLANET MERCURY

From observations of the dark markings, astronomers had long concluded that the rotation period of the planet was the same as its sidereal period, namely 88 days. It was the fact that the vaguely seen dark markings on the disk of Mercury often looked similar when the planet was in the same position relative to the Sun – near elongations – in the sky that fooled the early observers. Had the markings been better seen, particularly at times other than near elongations, then this mistake would not have occurred. Thus it was that Mercury was considered to have a captured rotation, rather like the Moon, and would keep one face of the planet constantly facing the Sun. The opposite face would then be permanently exposed to the intense cold of night.

Astronomers measured the radio flux from Mercury in 1962 and were surprised to find that the average flux from the unlit hemisphere was much larger than had been predicted, indicating that it was far warmer than expected. Theorists had predicted that the sunward hemisphere would be at a temperature of over 400°C, while the unlit hemisphere was expected to be no warmer than −250°C.

The temperature of the sunlit hemisphere was confirmed, but the hemisphere experiencing night seemed to be not much colder than 0°C. Actually, the temperatures measured by the radio techniques were of sub-surface soil, and we now know that the daytime surface temperature at the equator reaches 430°C, with a minimum night value of −170°C. The puzzle was solved in 1965 when the 305 m radio telescope at Arecibo was used to measure the rotation period of Mercury by a radar technique.

A radio pulse was fired at Mercury. Since the planet is rotating, one side of the planet approaches us, while the other recedes. The radio waves arriving on the approaching side of the planet will be slightly compressed as they are reflected back to the Earth. On the other side the waves are slightly stretched. Thus the waves arriving back at the Earth will consist of a spread of wavelengths, with the amount of spreading depending on the rotation rate. In this way, Mercury was found to turn on its axis at a rate of once every 58.65 days, exactly two-thirds of the planet's sidereal period. This means that the year on Mercury is only 1½ Mercurian days long!

Rather than Mercury turning on its axis once in the same time that it takes to go once round the Sun, three rotations of the planet occur while the planet goes twice round the Sun. This *spin–orbit coupling* is not coincidental. Mercury is not perfectly round but is slightly egg-shaped. In other words, Mercury is slightly larger along one diameter than another. Further, at perihelion, when the planet is closest to the Sun, the longest axis of Mercury is aligned to the Sun. At this time the gravitational influence of the Sun on Mercury is at its maximum.

In this way the Sun is responsible for keeping the longest axis of Mercury pointing towards it when the planet is at perihelion. Only certain values of rotation rate are possible if this condition is to be met, and the 3:2 ratio is one of them. The same mechanism operates between the Moon and the Earth, the ratio in that case being 1:1.

The radar results also showed that Mercury's spin axis is pretty much perpendicular to its orbital plane and so the northern and southern hemispheres of the planet do not experience seasons, unlike other planets of our Solar System.

In April 1974, *Mariner 10* encountered Mercury in the first of three flybys, at long last ending centuries of ignorance about the planet. Many instruments were carried by the probe, including a camera that could take and transmit high-quality photographs.

The photographs revealed a surface that is strikingly similar to the Moon. Mercury is heavily cratered and has maria (flood plains of solidified lava), though these are much less darkly contrasted than the lunar maria. The lack of surface corrosion indicates that Mercury can never have had an extensive atmosphere, just like the Moon. However, there are various differences, notably in the interior construction of the two worlds, and it is instructive to compare them.

Mercury and the Moon are each heavily cratered, with many bright-rayed craters being visible. As already mentioned, extensive lava flooding also appears to have occurred on Mercury, given that the planet shows several large plains relatively devoid of large craters. The lava flood plains of Mercury cover roughly 40 per cent of the planet's surface. By contrast the lunar flood plains (the maria) occupy only about 20 per cent of the lunar surface (If you think that I am mistaken about the '20 per cent' figure do remember that almost all of the lunar maria are on the Earth-facing hemisphere). Mercury is asymmetrically developed, one side of the planet bulging outwards more than the rest. The same is true of the Moon.

The Moon displays the obvious evidence of major impacts occurring at the time of the Late Heavy Bombardment, around four billion years ago. We see these as the great basins which were later flooded with lavas to form the lunar maria. On Mercury we also see some basins. One in particular dominates: the Caloris Basin. This huge circular depression was only partially seen by *Mariner 10*. We now know it to be 1550 km in diameter. It is bordered by high mountain chains and has large interior concentric rings and a vast array of complicated topography. It is thought that this feature was produced by a massive meteorite impact roughly 3800 million years ago.

There are indications that a wave of global volcanic activity started after the Caloris impactor had struck. On the opposite side of the globe of the planet there is much evidence of turmoil caused by the shock waves focused from the site of the impact.

Of particular significance was the discovery of a magnetic field surrounding Mercury. You will see various figures quoted in the literature for planetary magnetic fields. You will soon notice that these figures differ. The main reason for this is that different authorities are quoting differing quantities such as the equivalent magnetic dipole moment (don't worry about what this means if you haven't heard of it before) or the field strength, which itself differs at different locations over the planet and varies with height above the planet's surface. I will keep things simple in this book. At the surface of Mercury the average magnetic-field strength is slightly less than 1 per cent of the average strength of the Earth's field at its surface.

Together with measurements made by the spacecraft of Mercury's gravitational field, the magnetic-field measurements indicate that Mercury has a metal core, probably composed of iron, and at least some of which is molten. The first results and analysis suggested that this core occupied four-fifths of the diameter of the planet but the most recent results and analysis suggest it is slightly smaller – still, though, a whopping three quarters of the diameter of the planet!

By contrast, the Moon has no overall magnetic field and only a small metallic (or maybe just partially metallic) core. The average density of Mercury is 5420 kg/m^3, similar to the density of the Earth and rather higher than that of the Moon.

The craters on Mercury tend to be smaller than those on the Moon. Also, the crater ejecta and secondary-impact craters are much more closely clustered around the primary craters than their lunar counterparts. This effect is due to the Mercurian gravitational field strength at the surface of the planet being about twice as strong as the Moon's field at its surface.

The Mercurian craters are structured differently from those on the Moon. Most Mercurian craters larger than about 14 km in diameter possess terraced interior walls, but interior terracing is only common in lunar craters of diameter greater than about 50 km. Several of the large, flat-floored Mercurian craters show a complex pattern of ridges on their floors, while the lava-flooded lunar craters have relatively smooth floors.

The surface of Mercury is scarred by huge cliffs, termed *lobate scarps*, which run for hundreds of kilometres. Typically, they reach heights of around 3 km above the surface and they cut across craters and inter-crater areas. It has been suggested that they were caused by compressional stresses in the crust as the huge core cooled after its formation.

Photometric (brightness) and *colorimetric* (brightness in particular wavelengths) measurements indicate that the surface is mainly composed of silicates, with much less iron and titanium than on the Moon. These elements are responsible for the relative darkness of the lunar maria, as compared with the lunar highland areas. Their scarcity on Mercury explains the absence of strong contrasts between the Mercurian highlands and the inter-crater plains. Nonetheless, the average albedo of Mercury is very similar to that of the Moon, at 0.06. It is perhaps surprising that Mercury should have so much iron in its interior but so little in the way of iron-based minerals on its surface.

Until recently, no other probes had visited Mercury since *Mariner 10*. Then, in January 2008, after a 3½-year flight, the space probe *Messenger* made the first of several sweeps past the planet. Looping through the inner Solar System, the probe made a second flyby in September 2008. In September 2009, it made another brief flyby, then another in March 2011. On this fourth encounter *Messenger* was captured by Mercury's gravity and entered orbit around it. It then commenced globally mapping the planet – this has just started at the time I am about to send the manuscript for this book to the publisher.

Even from the first flybys we already have images of much superior resolution to those from *Mariner 10* covering a much larger area of the planet, along with many detailed physical measures. For instance, traces of an atmosphere – in fact, so thin it is properly termed an *exosphere* – have been found. Vapours of magnesium, calcium, sodium and hydrogen have been detected in this exosphere but the fact that the spatial distributions of these components differ from each other gives clues as to the compositions and distributions of the surface materials from which they are derived.

Mercury's magnetic field has been found to be particularly symmetrical, including well-defined north and south poles, this result being a useful constraint in modelling the planet's interior. Also, the fine details of the evolution of the Mercurian topology are only now beginning to be understood. Undoubtedly great things are still to come and new results may emerge while this book is going through production. You can find plenty of space probe information and images on the Internet. Let me offer one website – that of NASA – which is a great place to start: www.nasa.gov/mission_pages/messenger/main/index.html. At the time of writing there is also a main site for *Messenger* images and data that is likely to remain active for at least as long as the mission is underway: messenger.jhuapl.edu/mer_flyby1.html.

Meanwhile, let us return to the main theme of this book and address what can be done by the average amateur astronomer ...

6.5 VISUALLY OBSERVING AND DRAWING MERCURY (AND OTHER PLANETS)

Whether you observe Mercury high up in a daytime sky or low over the horizon at dusk, image contrast and freedom from scattered light are crucial. This demands high-quality optics. It also demands clean optics. Any and all reflective films in the light path must also be in good condition. Telescope mirror coatings tend to develop pinholes even before the coating as a whole goes obviously milky. The light scattered from a reflective film in this condition will cause a slight luminous fog to envelop the already low-contrast image. Such faint details that may appear on a bright planetary disk will then be even harder to discern.

For a full discussion of telescopes that are most suitable for visual observation of the planets see Chapter 2. My own personal preference is for a Newtonian reflector of about 10–14-inch (254–356 mm) aperture. As well as being of first-class optical and mechanical quality it should have a focal ratio of at least f/6 if you are to use it with low- to mid-priced eyepieces. Expensive planetary eyepieces such as Tele Vue's Radians will deliver quality images when used with lower focal ratios, as will lower-cost eyepieces if used in combination with a high-quality apochromatic Barlow lens.

Higher focal ratios in Newtonian reflectors do allow the use of secondary mirrors, which are a smaller percentage of the aperture of the telescope, and this helps with image contrast. My preferred planetary telescope would also have a well-ventilated solid tube, preferably with fan cooling of the primary mirror, itself held in a well-ventilated cell.

Never compromise on quality for the sake of size. On nights of average-to-poor seeing a sizeable telescope will show little or no advantage over a smaller one. This is especially the case when trying to observe

Mercury and Venus as these planets are seldom seen in good atmospheric conditions. Please note I am here just discussing visual observations of the planets. Instrumental requirements can be very different for other observational tasks.

Even in the absence of thermal problems – and remember, large telescopes can behave like storage heaters – the seeing conditions sometimes cause the image produced by a large aperture to be blurred and confused when a smaller one would show a sharper (albeit gyrating and distorting) image.

So, sometimes smaller can actually be better. For that reason an off-axis mask applied to anything bigger than a 15-inch (381 mm) telescope can occasionally improve the sharpness and contrast of the images it delivers. This is even more the case if the optical quality of that telescope happens to be poor. Maybe something that at least approximates to an apodising screen, homemade from layers of meshwork as described in Chapter 2 (Section 2.7), can also help with image sharpness and contrast for the same reasons as the off-axis stop does.

To proceed, let us say that you have successfully found the planet and now have it in the field of view of your telescope (as described in Section 6.3 – being particularly careful to observe the safety precautions!). You will need more than a quick glance through your telescope if you are to see any Mercurian details. Take your time and allow your observing eye to acclimatise to the scene.

Try a range of magnifications. I can still remember my joy at seeing each of the planets for the first time through my childhood 3-inch (76 mm) reflector. I also remember this joy being tempered by my surprise at just how tiny the planets appeared even using the most powerful eyepiece my telescope was supplied with (which delivered a magnification of $\times 117$). My youthful eyes adapted easily to the scene and I had no trouble in seeing all the planetary details which that size of telescope would be expected to show but it did, nonetheless, take me quite a while to get used to just how small planetary images appear.

Therein lies the main skill required for visually observing the planets – seeing details on a small disk that may appear blurred and will almost certainly be rippling and gyrating. Apply more magnification and the faint planetary markings may well 'wash out' into nothingness, even if the image itself is plenty bright enough. Use too low a magnification and, while the details will usually appear better defined and with more contrast, accurately assessing their shapes, proportions and positions will then prove very difficult.

Experience always helps, of course, but even seasoned visual observers take their time in assessing a planetary image while applying a range of magnifications to tease out whatever details may be present. In particular, the average seeing conditions that most of us have to endure usually result in us getting only sporadic glimpses of fine details in any one observing session. The rest of the time in that session the planet's disk will appear blurred and devoid of all but coarse detail. You have to do your best in gleaning what details you can in these brief glimpses.

A really good way of visually studying any planet is to draw the details you see on a pre-prepared outline. Details can be slowly built up on the drawing as they appear to you. In this way the finished drawing will show more than you could see at any one moment during the observing session. The process of scrutinising the planet and drawing details will also train your eye to search out any details that may be present. You will find that you see more and more planetary detail with less effort as your experience grows.

Drawing the planets used to be the main activity of most serious amateur Solar System observers. Thanks to atmospheric turbulence, even the best of the film-based photographs of yesteryear failed to show as much detail as could be recorded on a drawing by a skillful amateur astronomer using the same telescope under the same conditions. Now, though, the situation is very different. Images obtained using fast-frame-rate cameras (at the cheap end of the market this can even include some webcams) can be fairly easily processed to show a level of detail well beyond that seen by eye using the same equipment and conditions.

Nonetheless, there remains some value in making drawings. For one thing, a record of how a planet appears to the eye does allow for an assessment that can keep the reigns on the results of any astrophotographer's image processing. Image processing can easily be taken too far and keeping a handle on what a planet really looks like at any given time is vital. There is also the question of continuity. In one sense the modern images and the old drawings can be mutually calibrated by means of modern drawings. Certainly the directors or co-ordinators of the various planet observing sections of the national astronomical societies are still welcoming good-quality planet drawings at the time I am writing these words. I expect they will continue to do so for some years to come.

Even if you have no wish to contribute your own observations to your national astronomical society (though I very much hope you will), making notes and a drawing of a planet is personally rewarding. You will be creating a long-lasting record of how that planet appeared to you each time you observed it. A series of drawings that spans the observing season of a planet is interesting to look over at any later date. Yes, you can certainly use imaging equipment to record the planet more accurately and in greater detail but the drawings you create by exercising your telescope, eye, brain, pencil and paper is **your** record of what **you** personally observed on an alien world across millions of kilometres of space – and not just what the imaging device and computer recorded, with you then little more than a bystander.

Figure 6.2 An observation filled out on a BAA standard-issue observation form. Note the intensity estimates given on the drawing.

I discussed fashioning an illuminated drawing board in Chapter 1 (see Section 1.4). You will find one of these invaluable for making your drawings and taking notes at the telescope. As is the case for drawing the Moon (see Section 5.11), you can use a variety of media and materials, including PDAs and other modern hand-held electronic drawing devices, for drawing the planets. However, pencil drawings made on plane white paper are probably best. The planet observing section director/co-ordinator will undoubtedly supply you with 'blanks' for making the drawings and recording brief notes (see Figure 6.2).

Alternatively, a compass-drawn circle of 50 mm diameter on a sheet of paper will serve very well. You could draw a square around the circle, the area outside the circle and enclosed by the square representing the sky background. The sky background can be left blank, or it can be blacked in (usually with felt pen, ink or paint) either before or after the observation. Some observers prefer to fill in the sky background with a shade appropriate to that of the sky actually seen on occasions when the planet is observed in daylight or in twilight.

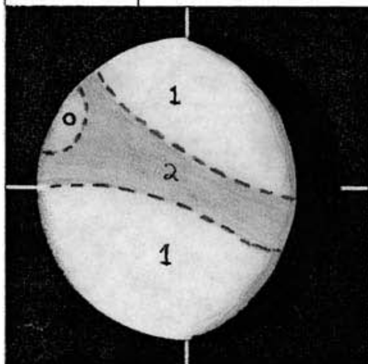
After spending some time just looking you can begin sketching in the details. The first thing to indicate is the terminator. Normally you can leave filling the night-side area to approximately the same shade as the sky background until after the session.

You should look for any shading along the terminator and then any shaded areas and other details on the planet. Smudging and smoothing penciled areas with a finger can help with your representations. Having to hand a range of pencils of differing hardness will make it much easier for you to deal with representing different types of detail. An eraser can also be of use in shaping your rendition of the dark areas. Do your best to make your drawing match the appearance of the planet. I should add here that seeing any genuine details on Mercury is extremely difficult. If you are new to observing you will be doing very well to record just the visible phase that Mercury shows with any degree of accuracy. Most of the time even highly experienced observers using good equipment set up in their backyards will see nothing more.

The notes that must accompany your drawing are as important as the drawing itself. You should record the date, the beginning and end times of the observation, and the time of completion of your drawing. You should also record the equipment details (size and type of telescope – preferably with its focal ratio), types of eyepiece and any other

BAA **Venus**

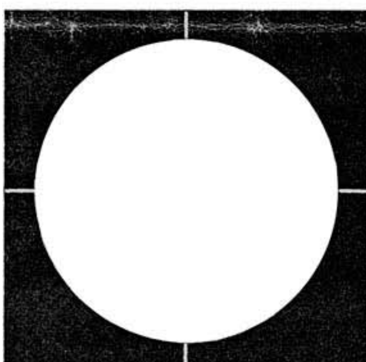
Observer	GERALD NORTH	Location	ROYAL GREENWICH OBSERVATORY (HERSTMONCEUX, EAST SUSSEX)



date & time (U.T)	1989 JULY 15d 16h 31m – 16h 42m UT
e/p. & mag.	7/8-INCH RAMSDEN (×160 approx)
telescope aperture	10-INCH, f/13.7, REFRACTOR
filter	NONE USED
obs. phase ±	90% approximately.
seeing & transp.	ANT V. Transparency fair.

Computer Analysis:	Definitely present	Possibly present	Definitely absent
N. cusp cap	☐	☐	☑
N. cusp cap collar	☐	☐	☑
S. cusp cap	☐	☐	☑
S. cusp cap collar	☐	☐	☑
Term. shading	☑	☐	☐
Term. irregularity	☐	☐	☑
Limb brightening	☑	☐	☐
Cusp extensions	☐	☐	☑
Cusp shortenings	☐	☐	☑
Ashen Light	☐	☐	☑
Night-side darker	☐	☐	☑

Comment: Seeing v. bad. Position and extent of the markings only approximate. Daylight observation. Notice that Venus appears strongly yellow against the light blue sky background.



date & time (U.T)	
e/p. & mag.	
telescope aperture	
filter	
obs. phase ±	
seeing & transp.	

Computer Analysis:	Definitely present	Possibly present	Definitely absent
N. cusp cap	☐	☐	☐
N. cusp cap collar	☐	☐	☐
S. cusp cap	☐	☐	☐
S. cusp cap collar	☐	☐	☐
Term. shading	☐	☐	☐
Term. irregularity	☐	☐	☐
Limb brightening	☐	☐	☐
Cusp extensions	☐	☐	☐
Cusp shortenings	☐	☐	☐
Ashen Light	☐	☐	☐
Night-side darker	☐	☐	☐

Comment:

Computer analysis: Please tick the appropriate box. – Intensity estimates: 0 = brightest to 5 = darkest. – Please use a separate form for each day of observation.

accessories used. Add to the list the magnification(s) used – and that used when making the drawing if different. Anyone else reading your account should be able to deduce what equipment you used and how you used it.

The seeing conditions, both atmospheric transparency and atmospheric turbulence, at the time are also pertinent information that must be included. That is a subject which I cover in more detail in the next section.

Finally, include any details about the planet which can supplement your drawing. For instance, if your drawing is in monochrome, as it normally will be, you could add details about any colours seen. Make a note of the effect of any coloured filters you might use.

Don't be afraid to include a note of any shortcomings of your drawing. For instance, are the shadings exaggerated for clarity? Should a dark feature really be shown a little larger or displaced a little in a particular direction? Nobody is going deride you for pointing out your own artistic shortcomings. On the contrary, adding such notes will actually boost the usefulness of your observation.

On the subject of filters, these can be of great use to the planet observer. Many observers use them habitually. I tend to the other extreme and only use them occasionally. Certainly in the case of Mercury their advantage is restricted to darkening a light sky background. A polarising filter could be tried, the filter being rotated until it darkens the sky background to the greatest extent. Otherwise an orange or red filter may produce the same effect.

Your observations will have the greatest value if the coloured filters you use are standard types of known spectral transmission. Kodak's Wratten series of filters, developed in the days of film-based photography, have long been adopted as a preferred standard in amateur astronomy. Each coloured Wratten filter comes with its own designation. For instance, W25 is red, while W21 is orange and W15 is deep yellow.

Lumicon is just one company that markets a set of filters ready mounted in threaded mounts for screwing into standard 1¼-inch (31.7 mm) and 2-inch (50.8 mm) eyepiece barrels. They are equivalents of the Wratten series and are identified by a hash symbol followed by the same number as the equivalent Wratten filter. For instance the Lumicon red filter is #25 and the deep yellow is #15. As well as filters, Lumicon sell many other useful accessories. The company's main webpage can be found at www.lumicon.com.

6.6 ASSESSING THE ATMOSPHERIC CONDITIONS

Some observers obsessively record all the local meteorological conditions, including barometric pressure, temperature and humidity along with other data, for each observation. I do not. I always record the image characteristics that the seeing conditions impose on the image but I only make a note of any other factors if they directly and obviously affect the quality of the observation. Windshake, interruptions due to passing clouds, mist or fog, or dewing of the eyepieces are obvious examples of what should be noted.

If there are any specific difficulties that arise with your equipment that affect the quality of your observation then these, too, should be noted.

The main factors to record are the state of the atmospheric transparency, including any haze, along with an estimate of the extent of the atmospheric turbulence. One should also make a note of any spurious colour seen (colour-fringing due to dispersion in the Earth's atmosphere).

Taking atmospheric transparency first, I use the classifications 'very good', 'good', 'fair', 'poor' and 'very poor' and add a qualifying note only if I feel one is needed. Most other observers do the same.

Assessing atmospheric turbulence, or 'seeing', is more tricky. Various scales of seeing have been devised and used by some over the years. Of the more popular ones, there is a ten-point numerical scale, originated by Pickering and modified by others, running from '1/10' for the worst seeing to '10/10' for the best. Many observers do like to use Pickering's seeing scale but the differing characteristics that go to make up the deleterious effect on the image blend in different proportions for different sizes (and to a certain extent different types) of telescope. Indeed, the seeing varies from night to night and even hour to hour. I feel this complicated picture makes the ten-point precision somewhat spurious. I prefer a simpler scale.

Most observers prefer to use the scale of seeing devised by E. M. Antoniadi. The official wording of Antoniadi's scale runs as follows:

ANT. I	Perfect seeing, without a quiver.
ANT. II	Slight undulations, with moments of calm lasting for several seconds.
ANT. III	Moderate seeing, with moderate air tremors.
ANT. IV	Poor seeing, with constant troublesome undulations.
ANT. V	Very bad seeing, scarcely allowing the making of a rough sketch.

The difficulty here is that near-perfect seeing for a small telescope may be rather poor for a large one. I use the Antoniadi scale but modify it to suit an aperture of 10 inches (254mm) or more. If you can forgive my temerity in tampering with a hallowed scale devised by a deservedly esteemed observer of the early twentieth century, here is my version of it:

ANT. I	Can consistently see detail as fine as 0.5 arcsecond (or a steady and nearly perfect image in a telescope of 254 mm aperture).
ANT. II	Can, for much of the time, see details finer than 0.7 arcsecond.
ANT. III	Can, for some of the time, see details finer than 1 arcsecond.
ANT. IV	Can, at least in glimpses, see details finer than 1.5 arcsecond.
ANT. V	Cannot see any detail finer than 1.5 arcsecond in extent.

Of course, any estimate of the seeing conditions can only be rough. My own estimate of the finest detail that can be discerned in given atmospheric conditions has been calibrated from years of observing craters of known sizes on the Moon. Long experience allows me to interpret atmospheric turbulence on this scale even when observing non-lunar subjects. I find that on most nights I record the seeing as ANT. IV, with ANT III being the next most common rating. ANT. V nights happen fairly often at my observing site but ANT. II nights are depressingly rare. I have only recorded ANT. I seeing a handful of times during my observing career.

Seeing can sometimes vary enough during the course of an observing session to take its assessed Antoniadi value into the next category. You should note all such changes together with the corresponding times.

6.7 THE ORBIT AND PHASES OF VENUS

Venus can sometimes be seen shining in the pre-dawn or evening twilight sky with a silvery brilliance that sets it apart from all other celestial bodies. It moves in a nearly perfectly circular orbit of radius 108 million km. We see phases that vary with the apparent size of Venus for the same reason that we do for Mercury. At superior conjunction, the distance of Venus from the Earth is at its maximum and the disk of the planet subtends an apparent angular diameter of only 9½ arcseconds. At this time the illuminated hemisphere is turned towards us but the planet is swamped in the glare of the Sun.

As the phase shrinks, so the apparent diameter of the planet increases to reach 65 arcseconds when at inferior conjunction – but again too close to the Sun for easy observation. The planet is then only 40 million km from the Earth, the closest that any major planet approaches. At dichotomy, Venus subtends an angular diameter of 25 arcseconds. When at its greatest brilliance, Venus reaches an apparent magnitude of $-4^{m}.4$, much brighter than any object in the sky, apart from the Sun and the Moon. Its angular diameter is then 35 arcseconds.

Venus takes 224.7 Earth-days to go once round the Sun (the sidereal period) and the time that elapses between successive superior or inferior conjunctions (the synodic period) is 584 Earth-days.

6.8 SEEING VENUS THROUGH THE TELESCOPE

At its most favourable elongations, Venus can set six hours after the Sun or rise six hours before it. At other times, serious observers often study the planet in broad daylight. The same techniques as I describe in Section 6.3 for locating Mercury in the daytime can be used for locating Venus – **and the same warnings I proffered there still very much apply**. At least the angular separation from the Sun is most of the time greater than is the case for Mercury and it can be as much as 47°.

Venus's image is very much brighter than Mercury's and this makes it easier to see against a daytime sky. Venus also appears larger than Mercury in the telescope. For instance, around the times of maximum elongations a magnification of ×80 is enough to make Venus appear about the same size as the Moon does to the unaided eye.

6.9 VISUALLY OBSERVING AND DRAWING VENUS

The impressiveness of the naked-eye view of the planet tends to generate great expectations of its appearance through a telescope, but the first-time viewer never fails to be disappointed by what is little more than a brilliant white disk or crescent, showing only the phase with any clarity. The reason is that Venus is completely swathed in opaque clouds, which block any direct view of the surface of the planet.

The cloud tops of Venus have an albedo of 0.69. That is, they reflect away fully 69% of the sunlight falling upon them. It is because of this that the planet appears so brilliant as seen from Earth. The experienced visual observer equipped with a 150 mm or larger telescope can sometimes make out a few shady markings and occasional bright spots in this cloudy mantle. I find that Venus looks distinctly yellow when seen against a daytime sky but, of course, this is at least partly due to colour-contrast.

As always when studying a planet through a telescope, try a range of magnifications. In the most favourable conditions Venus may present a reasonably sharp image with a power as high as ×300 but more often ×200 or less is the limit. How does the appearance of any markings change with different magnifications?

If you are observing Venus against a dark sky background you will find it bright enough to generate illusions – for instance a square-shouldered look to the planet's outline or possibly apparent dark shadings where there are actually none. Changing magnification and

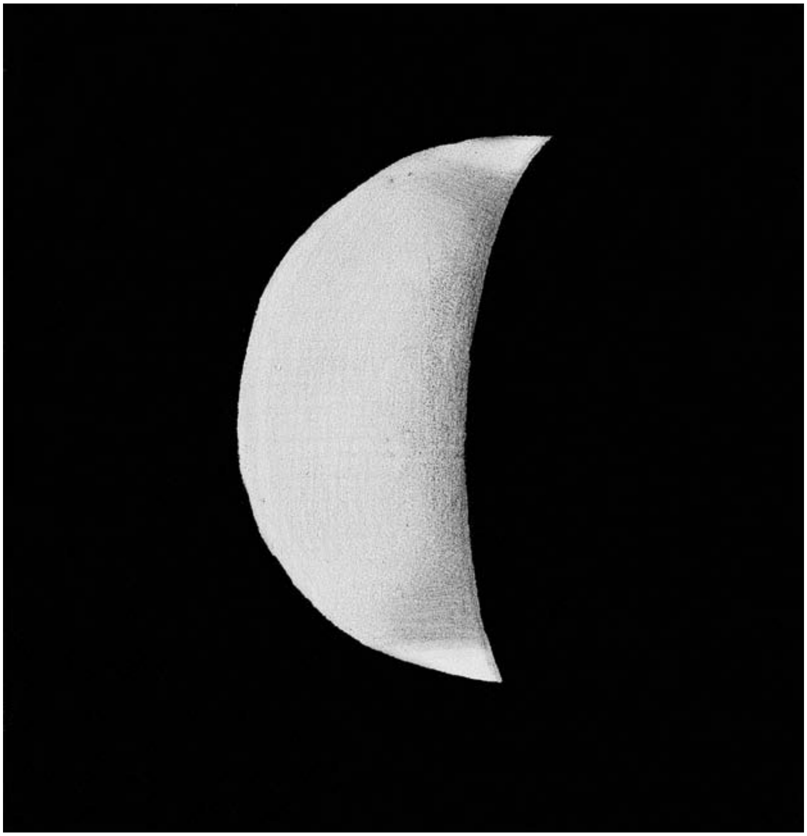


Figure 6.3 Pencil-shaded drawing of Venus, from an observation by the author on 1988 April 23^{d} 19^{h} 19^{m} UT, made using the 36-inch (0.9 m) Cassegrain reflector of the Royal Greenwhich Observatory, at their former site in Herstmonceux, in southern England. Magnification ×312 (this was the lowest magnification available). Seeing ANT. IV.

scrutinising the result of doing so should help sort out the real from the illusory. You could also try a neutral-density (grey) filter or a polarising filter to see if that helps.

On the subject of illusions, the crescent Venus is occasionally reported as enclosing an area that appears darker than the sky background. Actually, when Venus appears as a very thin crescent it is then close enough to the Sun for it genuinely to be seen silhouetted against the solar corona. The solar corona is the Sun's extended atmosphere, which appears as a pearly white glow during total solar eclipses (see Chapter 12 for more detail about all things solar). However, the brightness of the sunlight scattered by our atmosphere would certainly overwhelm any true Venusian silhouette, so this is regarded as yet another illusion.

Sometimes the planet will be seen to have bright *cusp-caps*. Each cusp-cap is often bordered by a dark collar. Figure 6.3 shows the effect well. These tend to be of somewhat variable visibility and they do not always lie exactly at the cusps. Bright patches can be visible in other positions. The whole of the limb of the planet often has a particularly brilliant appearance, though any real brightening is usually very much exaggerated by contrast with the darker sky background.

Faint grey streaks and shadings are often seen crossing the disk and these tend to be most prominent near the terminator. Take particular care to note the general terminator shading and any additional regions of darkening along the terminator. Also watch out for any terminator irregularities – sometimes the smooth curve is disturbed by one or more corrugations.

Sometimes the cusps of the planet may be extended well beyond the normal north and south limbs of the disk during the crescent phase. At other times they may appear blunted short. It is always important to go to the telescope with an open mind. It is inevitable that visual observation will involve a degree of subjectivity but you should at least be aware that it is very easy to deceive oneself into seeing (or not seeing) something merely because of a prior expectation.

Coloured filters can be useful. A W47 (violet) filter tends to enhance any real shadings in Venus's atmosphere, whereas any terminator irregularities are most easily seen using a W25 (red) filter. As with Mercury, a red or orange filter will apparently darken a twilight or daytime sky background.

You will also find slight variations in the phase of Venus when using different coloured filters. Usually a red filter makes the phase of Venus look slightly 'thicker' but you should establish the reality or otherwise of this effect for yourself afresh every time you observe the planet. As always, make sure you include full details of any filters used in your report.

Drawing Venus

Begin with a pre-drawn outline of diameter 50 mm, as you would for drawing Mercury. Remember also to take time to look at the planet and allow your eye to become accustomed to the scene before committing anything to paper.

Begin your drawing by marking the position of the terminator but do not bother filling in the dark portion at this point. Any genuine shadings on Venus are usually very difficult to see. The following number scale is usually used to denote the intensities of any shadings:

0 = brilliant white;
1 = the overall tint of the planet's disk;
2 = very faint shadings, hardly discernible;

3 = definite, though still faint, shadings;
4 = somewhat darker shadings;
5 = still darker shadings (only very rarely seen).

A visual observer's estimate can only ever be subjective. Much depends upon the seeing conditions and the quality of the telescope, not forgetting the quality of the observer's eyesight.

One way of representing any shadings present is by means of dotted lines, the intensity numbers then being used to label specific areas of the drawing (see again Figure 6.2). Alternatively, one can make a more artistic rendition (as in Figure 6.3) using pencil shadings suitably smudged by finger. Figure 6.4 shows another technique, where density of stippling has been used to represent various levels of shading. As always, the most important factor is accuracy. If you adopt the second or third methods you will have to draw in the shadings rather darker than you saw them for the benefit of others analysing your observation. You should clearly state this in your report. Actually, it is a good idea always to include numerical intensity estimates either in the accompanying notes or on a separate drawing. Finally, do not forget to include all the pertinent details of seeing, magnifications, equipment, etc. in your accompanying report.

Schröter's effect

An anomaly between the observed and theoretical phases of Venus has been known for about two centuries and is commonly referred to as *Schröter's effect*. The observed phase always appears a little less than the theoretical, so dichotomy occurs a few days early when the phase is waning and a few days late when it is waxing.

The effect is no longer the mystery it once was. It is caused by the refraction and scattering of sunlight in Venus's atmosphere, which intensifies the darkening along the terminator. Predictive computer modelling produces a close match with the observed effect. However, phase estimates are still of interest. To pick an instance at random from my observing log, on 1989 November 6^{d}, I observed the waning crescent using my 6¼-inch (158 mm) Newtonian reflector at ×200 and estimated the phase to be 49 per cent. The very slight concavity of the terminator was obvious. Yet theoretical dichotomy was still about two days away.

The ashen light

One phenomenon involving Venus that still awaits a definite explanation is a rarely seen glow that seems to faintly illuminate the unlit hemisphere. Sometimes the glow is reported as having a brownish or

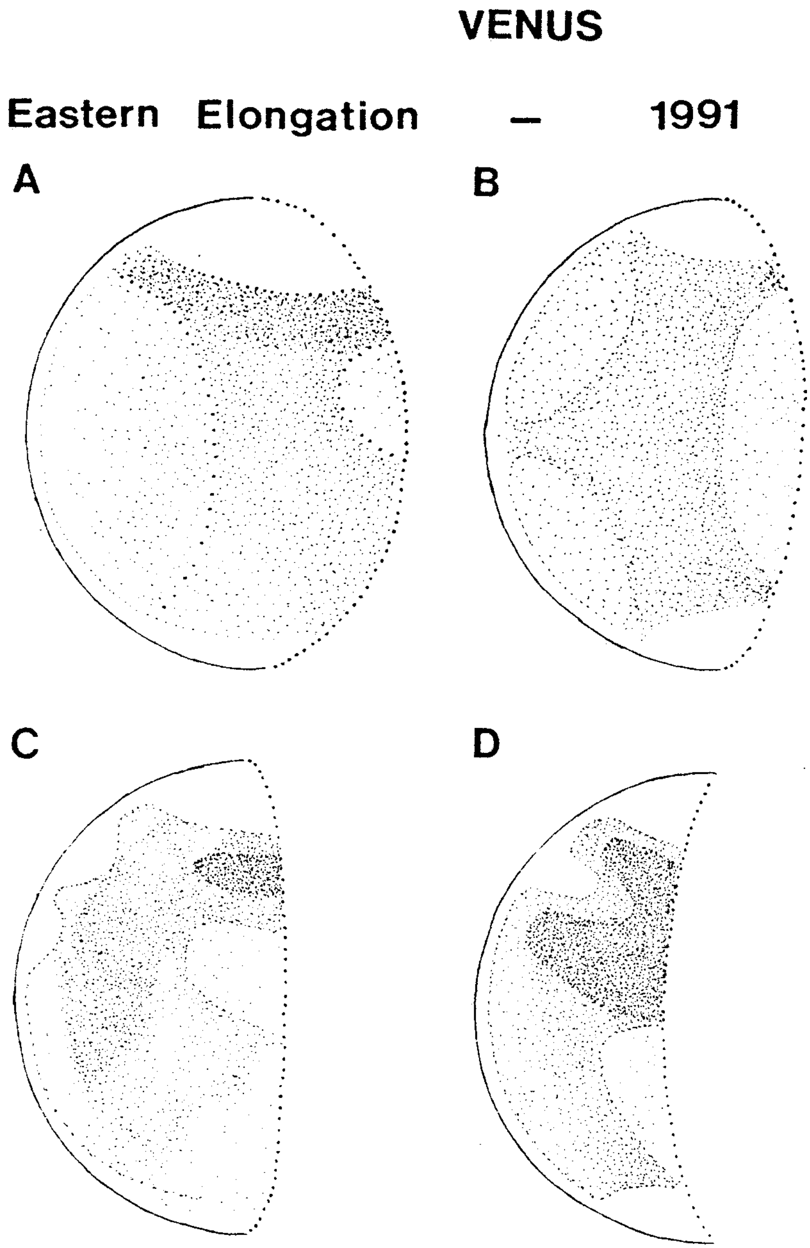


Figure 6.4 Drawings of the planet Venus during its 1991 eastern elongation, made by Andrew Johnson using his 8.3-inch (210 mm) Newtonian reflector at ×195 and using a Wratten 15 (yellow) filter. **A** – March 21; **B** – April 27; **C** – May 22; **D** – June 27.

violet colouration. Whether or not the effect is real has always been a matter of contention. However, an extensive study was conducted by Dr John Phillips of the Los Alamos National Laboratory and Dr Christopher Russell of the University of California. They organised a world-wide campaign for the highly favourable 1988 elongations of the planet.

A summary of their report is published in the January 1990 issue of *Sky & Telescope* magazine, suffice it to say here that they concluded that the ashen light is a real phenomenon.

I took part myself and had one definite sighting and a couple of suspect ones. During my positive sighting, the dim glow of the night-time hemisphere reminded me of a rather faint version of earthshine on the Moon. At the time, I was using three telescopes at the Royal Greenwich Observatory: the 36-inch (0.91 m) Cassegrain reflector, the 7-inch (178 mm) f/24 guiding refractor on the Cassegrain telescope, and the 30-inch (0.76 m) coudé reflector with its associated high-dispersion spectrograph. The ashen light was visible through all three telescopes. I saw the glow as grey while a friend present saw it as blue-grey.

I knew that there would be no chance of recording a spectrum using the spectrograph if the weak glow consisted of a broad-band or continuum emission (especially given the spectrograph's high dispersion and not aided by the detector being an old-fashioned photographic plate) but I thought there might be a slim chance if it was a line-emission. I made a 29-minute exposure with the spectrograph slit placed to span the bright crescent and the ashen-light region. I got the expected over-exposed spectrum from the bright hemisphere of Venus but nothing at all from the ashen-light region. The wavelength range covered by the equipment was 350 nm to 510 nm (near-ultraviolet to green light).

In their report, Phillips and Russell say that the presence of the ashen light was corroborated by six or more independent observers on 1988 April 6^{d}, 13^{d}, 23^{d}, 24^{d}, and May 10^{d}, 11^{d}, and 21^{d}. My own positive observation was made on April 23^{d}. My suspected sightings occurred when I was using my 18¼-inch (0.46 m) reflector on April 10^{d} and May 21^{d}. On the vast majority of evenings that I observed Venus in 1988, I recorded the ashen light as definitely not visible.

As to the cause, well, it has recently been reported that space probe observations have revealed that Venus's surface rocks are hot enough to glow even at night (there is practically no difference in Venus's daytime and night-time surface temperatures) and, further, this glow does shine through Venus's cloudy mantle. Many doubt that the glow is bright enough to be seen from the Earth, so whether this is the real cause is far from settled. I must say I am highly skeptical of this explanation because I cannot see how rocks at 470°C could possibly produce a glow bright enough through Venus's clouds to be seen visually from Earth. I think that the surface would have to be at least a couple of hundred degrees hotter for this explanation to be viable. Having said that, is it completely beyond the realms of possibility that there can at times be some partial thinning of the cloud layers which does let enough of the glow through? Also, the thermal glow **has** been recorded through near-infrared filters and sensitive cameras even by amateur astronomers. Figure 6.7, presented later on in this chapter, shows a good example. Another idea stems from calculations that show that lightning in Venus's clouds might provide a more plausible explanation.

Many remain skeptical about the existence of the ashen light. Actually, a faint airglow of Venus's night-side atmosphere has been detected by a recent space probe. What appears to be happening is that some carbon dioxide (CO_2) is broken up into carbon monoxide (CO) molecules and monatomic oxygen (O) atoms in the upper atmosphere on the daytime side. Atmospheric currents carry these to the night-side and there the extremely reactive monatomic oxygen atoms combine with each other to form normal oxygen atoms (O_2). The process releases energy in the form of the glow seen. At the time I write these words, the glow has always been too faint to produce an ashen-light effect bright enough to be visible from the Earth (and the chief emission line is actually in the near-infrared, invisible to earthly eyes). I can't help wondering whether or not continued monitoring will show this process to be variable. If it is then maybe this airglow can at times be bright enough to explain those rare instances where the ashen light seems to be definitely something more than just an illusion or the wishful thinking on the part of over-enthusiastic observers?

If you think you see the ashen light, please do your utmost to rule out scattered light before you contemplate reporting your sighting. Of course it is necessary to observe the planet against a dark sky but this usually means an unfavourable altitude with its attendant poor seeing and spurious colour effects. Try blocking out the bright portion of the planet by moving the telescope so that the bright portion is beyond the edge of the field of view. Is the effect still visible – if so, is it more or less easily seen?

In particular, beware of the diffraction bars which extend from the bright portion of the planet, caused by the secondary-mirror support vanes present in most reflecting telescopes. These bars will overlap in the same position as the dark part of the planet and may create the illusion that the dark hemisphere is glowing. If you see these bars (there will be four visible if the telescope has a four-vaned spider and six if it has a three-vaned spider), try using an off-axis stop. Is the ashen light still visible? Try the effect of using coloured filters, even in the knowledge that any faint glow is most likely to be rendered invisible by attenuation.

6.10 VENUS UNVEILED

Despite centuries of telescopic observation we remained in ignorance about the true nature of the surface of Venus and the conditions there until just a few decades ago. Indeed, until the radar measures of the 1960s, even the rate of rotation of the planet was unknown. It was then found to turn on its axis, in the wrong direction compared to other planets, once every 243 Earth-days, making Venus's day longer than its year!

Venus is a rocky world only slightly smaller than the Earth. Its diameter is 12 100 km. Venus has a mass about 81% that of the Earth and a density of 5250 kg/m^3, slightly less than that of the Earth. It is thought to have a core of roughly similar size and composition to that of the Earth. Venus used to be called 'Earth's sister planet' because of the similarity of the physical dimensions of the two worlds but this term has had little use since we learned more about the conditions on Venus's surface.

A giant leap forward was made in 1962 when the American space probe *Mariner 2* flew past the planet at close range. Infrared instruments carried by the spacecraft indicated that the temperature at its surface is something in excess of 300°C. This result shocked the scientific world and was viewed with scepticism by many. *Mariner 2* also indicated that the planet had no measurable magnetic field.

Mariner 2 was followed in 1965 by *Mariner 5*. This probe confirmed the earlier findings and provided more reliable information. In the same year, the Russians managed to soft-land a craft, followed by two more in 1969, but little useful information was obtained from these early Russian probes as they failed either during descent or on touchdown. The situation improved in 1970 when the Soviet *Venus 7* parachuted to a soft landing and measured the atmospheric pressure as 91 times that at the surface of the Earth. The temperature turned out to be even higher than the *Mariner* probes had indicated – a staggering 450 to 500 °C! *Venus 7* functioned under the harsh conditions for only 23 minutes.

The next major step came in 1974 when *Mariner 10* bypassed the planet on its Mercury–Venus mission. This probe took thousands of high-quality photographs of Venus's cloudy mantle in ultraviolet light. These showed the structure and motions of the clouds, revealing an underlying global current that rises at the equator, heads north and south in each respective hemisphere to sink at the poles. These equator-to-pole currents are known as *Hadley cells*. While Venus has one for each hemisphere, the more complicated atmosphere of the largely sea-covered and faster-rotating Earth has three dominant Hadley cells in each hemisphere (centred at latitudes of approximately 15°, 45° and 75° north and south).

The Venusian atmosphere as a whole has a rotation period of about four days. The various atmospheric motions combine to produce a swirling, recumbent chevron-like pattern in the clouds. First properly revealed by the space-borne images, the best amateur photography of the planet in recent years also shows these patterns (see Figure 6.6 later on in this chapter). Actually, the best amateur visual observations, going back many decades, had also hinted at the cloud patterns of Venus.

Mariner 10's onboard spectroscopic equipment provided information on the composition of the upper atmospheric layers. These results, together with those obtained from the preceding probes, give us a good idea of the structure and composition of the atmosphere. It is mainly composed of carbon dioxide and extends to a height of about 135 km. The clouds are chiefly composed of droplets of sulphuric acid, stratified into three distinct layers between 47 and 70 km above the surface of the planet. In addition, layers of sulphuric acid haze extend both below the clouds and above them, up to a height of 90 km above the surface.

Of all the spacecraft that visited Venus before the 1980s, only two sent back pictures of the surface – the Russian landers *Venera 9* and *10*, in October 1975. Each took one photograph before succumbing to the conditions. Two further *Venera* probes also obtained pictures of the surface in the 1980s. Each landing site consisted of a flattish landscape of grey slab-like rocks and sandy aggregates, bathed in the glow from an orange sky.

In 1978, the Americans launched their *Pioneer Venus Mission*. This consisted of an orbiting probe and four landers. The orbiter has allowed the surface of the planet to be radar-mapped to a far finer resolution than is possible from the Earth. Apart from a few elevated features (such as the areas named Ishtar Terra, Maxwell Montes, Aphrodite Montes and Beta Regio) the surface of Venus is remarkably uniform in level. It is thought that no plate tectonics are in operation on Venus and that the crust is very thick. Another interesting result is that the absence of a Venusian magnetic field allows the solar wind to slowly erode Venus's outer atmosphere.

Evidence from the *Pioneer Venus Mission* suggested that Venus might support active volcanism. Since Venus is, effectively, a 'one-plate planet', volcanism is the only possible mechanism for venting the build-up of heat caused by the radioactive decay of elements in the planet's interior. The areas suspected of volcanism certainly look like shield volcanoes and orbital data gave preliminary indications of gravitational anomalies over these areas, which were thought to be the result of crustal stressing.

However, the situation was far from being settled and, to obtain more data, another probe was sent. *Magellan* entered a polar orbit above Venus on 10 August 1990. About a week afterwards it began to fire radar-ranging signals through the clouds and down to the planet's surface to map 25 km wide stripes at very high resolutions (around 120 metres, 10 times better than before) and in 3D. As Venus turned under it, so the probe gradually built up a map of the whole of the planet's surface.

Many big surprises were beamed back by *Magellan*. The surface was found to possess vast river-like channels formed not by water but by an obviously very fluid lava (now solidified), huge and steep mountain belts, and steep-sided dome-like swellings.

Running ahead in our story for a moment, the very latest results and analyses have revealed that there are about 1600 large shield-type volcanoes (several hundred larger than 100 km across) and possibly more than a hundred thousand smaller volcanic vents of various types. An estimated 80 per cent of the surface of Venus seems to be covered by solidified basaltic lava flows.

One of the biggest puzzles is that there is no definite evidence for any significant currently active volcanism, nor any other obvious way for the planet currently to vent its internal heat. *Magellan* was expected to resolve this issue. Though it failed to provide a definite answer, perhaps a clue does come from one of the other great surprises – the morphology and distribution of the impact craters.

Studies of the 936 recorded impact craters show that they have a totally random size and distribution. Also, they are very obviously not eroded, and so are relatively young – perhaps about 500 million years in age. Putting these facts together leads to the conclusion that the current surface of Venus, itself, is only about 500 million years old!

Somehow the planet seems to have completely resurfaced itself about 500 million years ago and yet has not changed very much since that time. Don Turcotte of Cornell University voiced a theory that would explain this and also account for the escape of the heat from deep within the planet. He suggested that the sub-surface heat builds up and gradually melts the mantle of the planet over a period of time. When the melting process reaches it, the surface melts and collapses into the lower magmas, mixing with them. Once the excess heat has escaped the surface cools and solidifies once more and once again becomes quiescent. The process then starts all over again. In other words, the surface of Venus acts rather like a cyclic heat-valve.

Turcotte's theory was met with widespread derision, as most planetary scientists prefer gradual to cataclysmic processes. I can't help thinking that the high density of now-dormant volcanoes on Venus perhaps lends weight to Turcotte's theory. By his scenario, such volcanoes would surely be formed on the solidifying surface as the latest episode of heat release was coming to an end. Mind you, studies of the surface lava flows imaged by radar imply that many are older – perhaps some are older than 2 billion years. So, maybe surface volcanism has been more gradual, after all? Maybe there is some volcanism on Venus even today? Certainly, recent volcanism would explain the current amount of sulphuric acid and other sulphur compounds in Venus's atmosphere. It would also help to maintain the high concentration of carbon dioxide. Here on Earth, rain helps to wash our atmosphere clean of the gases from our currently active volcanoes.

On 11 October 1994, *Magellan*, its work done, ploughed into Venus's corrosive atmosphere and came to a fiery end. The mission was a remarkable success. More recently we have had *Venus Express*. Most of its suite of instruments are designed to study the Venusian clouds and atmosphere and their dynamics. Just to pick one result out of many studies, the downward flows of the atmosphere at each of the poles have proved to be unexpectedly complex and, at the south pole at least, rather changeable.

Venus Express was also designed to look closely at the interaction between the planet and its atmosphere and the solar wind. The mission is ongoing at the time I am putting the finishing touches to this book and much fine detail is already emerging. I have already mentioned the detection of the night-side airglow. The onetime controversial indications of the signature of lightning has been finally confirmed. Particularly notable is the fact that the deuterium-to-hydrogen ratio measured in the gases stripped from Venus's atmosphere is indicative of the planet having possessed significant amounts of water in its past history.

The lack of water vapour in the present Venusian atmosphere has long been a puzzle. It has always been supposed that both Venus and the Earth formed near their present, close, orbits. Both planets appear to possess similar quantities of carbon and nitrogen. One might suppose that they should also have similar quantities of hydrogen and oxygen (the constituents of water) but this is not the case. Free hydrogen and oxygen, as well as water, are extremely scarce on Venus.

Various theories have been proposed to explain the difference but the most likely one stems from the fact that Venus orbits a little closer to the Sun than we do. We think that the atmospheres of both planets initially contained most of the free carbon dioxide possessed by these bodies. We used to think that both planets were covered in oceans of water soon after their formation. However, modern computer simulations suggest that the surfaces of both planets remained too hot for too long. Both planets may well have had lots of water vapour in their atmospheres, though much of their initial quotas of water were probably driven completely away into space. In the case of the Earth, subsequent comet and asteroid impacts probably did the job of providing the water content of the Earthly oceans that we know and love today. In the case of Venus, it must also have suffered impacts from water-bearing celestial bodies but it seems likely (but by no means certain) that the surface and lower-atmosphere temperatures remained too high for oceans ever to form.

The primitive atmospheres of the two worlds would absorb a portion of the infrared radiation (radiant heat) from the Sun causing the planets' surface temperatures to be somewhat higher than if they had no atmospheres. This is the *greenhouse effect*. As I am sure you know, both carbon dioxide and water vapour are effective greenhouse-effect agents. On Venus, the greenhouse effect became runaway and some people think that the surface of Venus became as hot as 1200 °C, melting the surface of the planet and exposing hot lavas to the atmosphere.

The lavas then reduced the atmospheric water vapour to a mixture of hydrogen and oxygen, much of the oxygen being chemically combined with the lava and taken down below the surface of the planet with its churning motions. Most of the liberated hydrogen leaked away into space. Indeed, the solar wind exacerbated the loss of hydrogen, together with the remaining water-derived oxygen. Ultimately, Venus evolved towards its present furnace-like conditions. If this scenario is correct, an enrichment of the hydrogen isotope deuterium should occur in the atmosphere (because its atoms are heavier and move less slowly than those of hydrogen at any given temperature) and the first indications of this were found by the *Pioneer Venus Orbiter* and now confirmed by *Venus Express*. This latter probe has also detected hydrogen atoms currently being stripped from the upper atmosphere by the solar wind, together with oxygen atoms. The ratio of hydrogen to oxygen being 2:1 (the same as in water) strongly suggests that this really is the major cause of the historic loss of Venus's water.

While the temperature on Venus likely remained too high for bodies of liquid water to form, rains fell on the cooler Earth. Oceans persisted long enough for water-borne microbial life to develop. These microbes began consuming the atmospheric carbon dioxide and releasing oxygen, so averting the danger of the greenhouse effect becoming runaway as it did on Venus. Having gained a foothold, the presence of life on our world modified the conditions on it, allowing further life to develop. The primordial carbon dioxide became fixed in solid carbonates. Oxygen-breathing animals eventually appeared and evolved and the rest, as they say, is history.

6.11 PHOTOGRAPHING MERCURY AND VENUS

The first person to successfully record any of Mercury's albedo features photographically was Ferdinand Quénisset in the early twentieth century, from an observatory near Paris. A similar level of success was

Figure 6.5 Mercury imaged by Damian Peach from Barbados, a location blessed with unusually good seeing. He used his 14-inch (356 mm) Celestron Schmidt–Cassegrain telescope, working at f/42. The image was taken on 2007 May 07^{d} 22^{h} 41^{m} UT through a filter with a passband centred at 700 nm (covering deep red to near-infrared wavelengths) and captured on his Lumenera SKYnyx camera. The AVI was captured, stacked and processed in *RegiStax* and further processed in *Adobe Photoshop* and finally *Paintshop Pro*. The longitude of the planet on its central meridian was 106° at the time and the planet presented a disk of apparent diameter 7.2 arcseconds.

obtained at the Lowell Observatory from the 1930s and better results were obtained from Pic du Midi from the 1960s.

It is only in the last few years that amateur astronomers have had any real success in photographically recording surface features on this difficult planet. Recently, a small number of amateurs using digital stacking techniques have produced images that, while still blurred, do at least vaguely show details that correspond to the coarsest albedo features. You might like to search out a report: 'Recent BAA studies of Mercury' written by Dr Richard McKim in the February 2008 issue (Vol. 118 No. 1) of the *British Astronomical Association*. The report includes illustrations of many observers' visual and, particularly, webcam/CCD observations, showing what can be achieved by the dedicated and persistent practitioner.

Have no doubt about how difficult it will be for you to record any recognisable surface details on Mercury. Figure 6.5 shows what can be done by the acknowledged champion of planetary imaging, Damian Peach. You will see that it does not contain a lot of detail and yet Damian has produced images showing surface details on some of Jupiter's moons and even the odd asteroid! From the theoretical point of view, these tiny orbs should be a lot harder to photograph well enough to record surface details. They are hard to photograph. Very hard. The inescapable truth is that photographing details on Mercury is even harder.

As is the case for visually observing Mercury, the best chances to secure images showing detail occur when the planet has a reasonable altitude. This inevitably means locating and imaging the planet either in bright twilight or with the Sun actually above the horizon. As always, take care with your eyesight and with your equipment when the telescope is pointed anywhere near the Sun – don't scorch, crack or melt parts of your telescope, or fry your camera! One downside of daylight observing is that the seeing is usually much poorer than at night. Even so, the image is poorest of all when the planet is viewed low above the horizon, so we just have to make the best of a difficult situation.

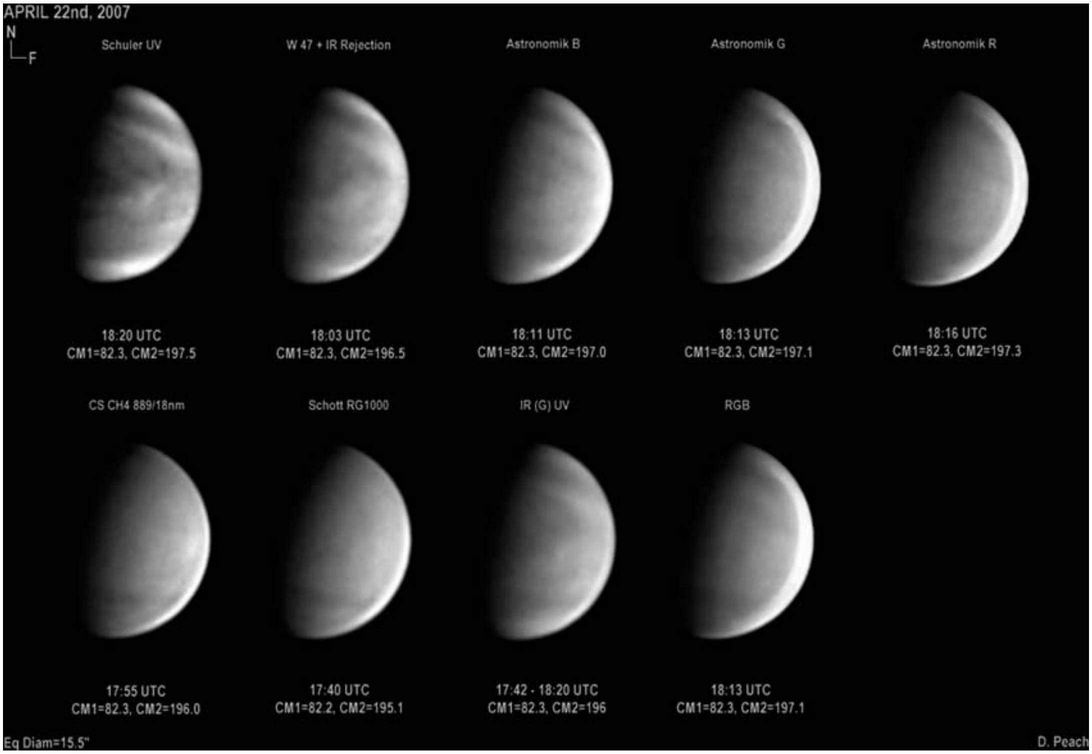
Please see Chapters 3 and 4 of this book for an in-depth treatment of planet photography. Stacking images and applying powerful processing routines is crucial to get the best possible results and this is particularly dealt with in Chapter 4.

Of special note here is that using a red filter, or maybe even a near-infrared filter (if the detector of the camera you are using is sensitive enough in the near-infrared), will help considerably when imaging Mercury. For one thing, the sky background will be darkened and the detail-swamping hazy effect of the bright sky on the planetary surface features will be much reduced. For another, the effects of atmospheric turbulence are lessened at the red or infrared end of the visual spectrum. The image shown in Figure 6.5 was taken through a filter having a peak wavelength of transmission of 700 nm. This corresponds to very deep red. The passband of this filter extends into the near infrared.

Getting the tiny image of Mercury onto the tiny chip of a webcam or other small-format fast-frame-rate camera is tricky. I strongly recommend that you use the step-by-step approach I describe in Section 4.8 of Chapter 4. Focusing Mercury against a bright background is going to be tricky because you won't even see it if its image is too distended. Having a guide mark on the drawtube marked from a prior night-time run on a bright celestial body would be of great help here.

The October 2009 issue of *Sky & Telescope* contains an instructive article 'Imaging elusive Mercury' written by veteran planet observer and imager John Boudreau. In it he details his own experiences in learning to image the planet. He relates that he first started with a colour webcam and a Celestron 11 Schmidt–Cassegrain telescope but failed to record more than the planet's phase until he upgraded to an Imaging Source DMK21AF04.AS monochrome camera and a deep red (Baader 685 nm) or near-infrared (Astronomik 740 nm) filter. He uses *RegiStax* (always upgrading to the latest version) to process his images.

Figure 6.6 Venus imaged in various wavebands by Damian Peach on 2007 April 22^{d}, using his 9¼-inch (235 mm) Celestron Schmidt–Cassegrain telescope, working at f/31 (Barlow projection) and SKYnyx 2.0M camera. The details of the filter used are shown above each image and the times of the exposures and central meridian longitudes are shown below each one. The AVIs were captured, stacked and processed in *RegiStax* and further processed in *Adobe Photoshop* and finally *Paintshop Pro*. This montage was prepared by Damian Peach and the images are presented with north uppermost. At the time, the disk of Venus subtended an apparent diameter of 15.5 seconds of arc.



In his article Boudreau presents some of his latest results. These are pretty much as good as anybody else's and are better than most. If you are able to obtain this reference, I recommend adding it to your reading list.

Much of the foregoing also applies to imaging Venus. In particular, I would say don't try to image the planet in full daylight until you have first had some experience with imaging the Moon and bright planets at night. Fortunately, Venus can often be seen with the naked eye at twilight with a good altitude, providing opportunities for the imaging tyro.

The low contrast of the atmospheric shadings on Venus makes them extremely difficult to record in integrated light. The bright phase of Venus also looks pretty blank in red and near-infrared. The cloud details are easiest to register in ultraviolet light. A Baader Venus filter would be a particularly good purchase as it is designed to pass those wavelengths (300 nm to 400 nm) at which the Venusian cloud details are most readily revealed. When imaging, be careful not to let the brightness of the planet saturate the CCD. Once an area is whited-out that is it. No amount of processing can reveal any subtle details in any area that has been saturated. Figure 6.6 shows a set of images obtained in different wavebands by Damian Peach.

Figure 6.7 Venus imaged by Damian Peach at a wavelength of 1μm on 2009 March 6^{d} 18^{h} 05^{m} UT (this is the commencement time for a run of 300 exposures, each averaging 3 seconds, spanning the next 10 minutes). Damian used his 14-inch (356 mm) Schmidt–Cassegrain telescope at an effective focal ratio of f/13.8 to make the individual exposures through a Schott RG1000 filter into his SKYnyx 2.0M camera. The images were captured, stacked and processed in *RegiStax* and further processed in *Adobe Photoshop* and finally *Paintshop Pro*. The bright sunlit part of Venus has a phase of 0.137 and the night-time part of the image can be seen dimly glowing by thermal infrared emission.

The most accomplished amateurs can occasionally make real discoveries. For instance, a particularly intense white spot on Venus was picked up in ultraviolet light by Frank Melillo of Holtsville, New York, on 19 July 2009. He used a typical amateur's set-up of a 10-inch (254 mm) Meade LX200 Schmidt–Cassegrain telescope fitted with a Starlight Xpress MX5 CCD camera and ultraviolet filter. Observers around the world followed up on Melillo's discovery. It was a few days before the spot – actually a bright cloud feature high in Venus's atmosphere – was picked up by the *Venus Express* orbiter.

As I mentioned earlier, a few suitably equipped and accomplished amateur imagers have managed to record **surface features** on Venus in near-infrared light. This requires skill, knowledge and experience using particular imaging and processing techniques. Moreover, since Venus has to be observed near to inferior conjunction, the very close proximity of the Sun to the planet in our sky makes this something not to be attempted by the beginner. If you wish to know what is involved then please let me point you to an article written by Danielle Gasparri in the October 2010 issue of *Sky & Telescope* magazine in which he explains how he goes about this difficult task. In the meantime please see Figure 6.7 for an example of what can be achieved.

6.12 TRANSITS OF MERCURY AND VENUS

It is the relative tilts of the planes of the orbits of each of the inferior planets to that of the Earth that results in solar transits of Mercury and

Venus occurring only rarely. In the case of Mercury, this angle is 7°.0 and in for Venus it is 3°.4. The Earth and the planet have each to be close to the points of intersection of the orbital planes – called *nodes* – for a transit to be seen. Mercury's orbit and Venus's orbit each have two of these nodes. The point at which the planet crosses the ecliptic plane going from north to south is known as the *descending node*, while that going from south to north is the *ascending node*. If either the inferior planet or the Earth are not close to the nodal position then the planet will pass a little to the south or north of the solar disk (as seen from Earth) at closest approach rather than being seen silhouetted against it. Of course this is the case the vast majority of times.

In our present era, transits of Mercury take place either in May (descending node) or November (ascending node). How frequently do they occur? Well, the answer to that relies on a synchronism between the Earthly year and the synodic period of Mercury. As it happens, 22 Mercurian synodic periods very nearly equals 7 Earth-years. With greater precision, 41 Mercurian synodic periods equal 13 years. A still closer coincidence is afforded by 145 Mercurian synodic periods and 46 years. However, there is another complication – the highly elliptical shape of Mercury's orbit. For May transits, Mercury is near aphelion and the limits for the planet to actually appear to cross the face of the Sun are rather tight, more so than for November transits, when the planet is at perihelion. As a result, November transits are twice as common as May ones.

The upshot of all this is that after a specific November transit another is possible after 7 years, probable after 13 years and extremely likely after 46 years. A particular May transit will not be followed by one 7 years later and may or may not be followed by one 13 years later, though is likely to be followed by one 46 years later.

Johannes Kepler was the first to make a definite prediction of a Mercurian transit. This enabled Pierre Gassendi – astronomer, mathematician and Canon of the church at Digne in France – to actually observe the event of 7 November 1631. As far as we know he was the first to do so and properly record it.

Of course, every subsequent transit of Mercury has been very well observed. Figure 6.8 shows part of a sequence of photographs I took of the 2003 May 07 event, with details included in the caption. The next six visible from at least somewhere on the Earth occur on 9 May 2016, 11 November 2019, 13 November 2032, 7 November 2039, 7 November 2049 and 9 Nov 2052. If you live near the international date line (for instance in New Zealand) please beware that in some cases your local date for the event is one day different than the UT dates given here.

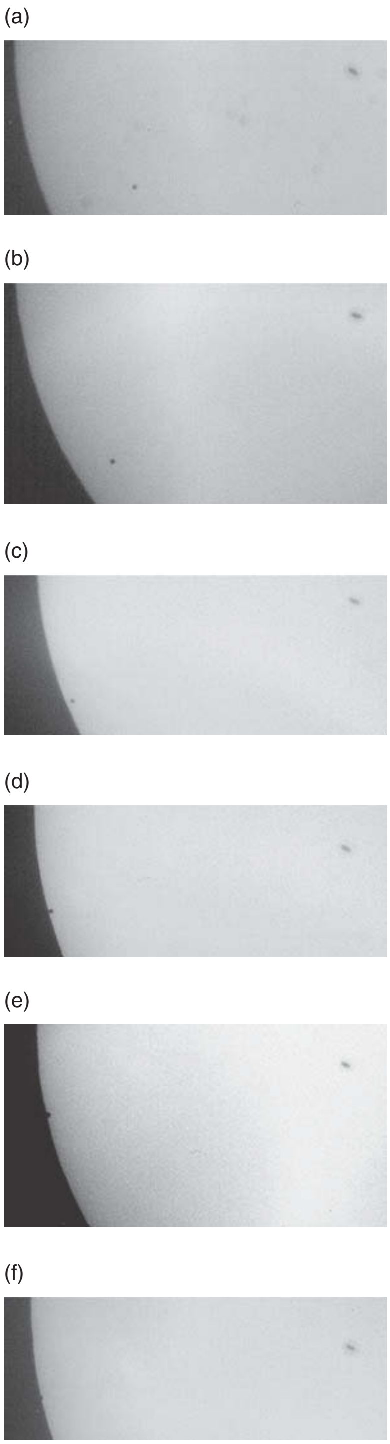


Figure 6.8 The latter stages of the transit of Mercury across the solar disk on 2003 May 7^{d} photographed by the author. He hand-held his camera to a 25 mm Kellner eyepiece plugged into his 8½-inch (216 mm) Newtonian reflector, fitted with a 62 mm off-axis Mylar filter and yellow eyepiece filter. The seeing was poor (ANT. IV) and varying amounts of thin cloud covered the Sun during the period. Exposures of 1/500 second were made onto 'Trueprint' 400 ISO colour print film. The images presented here are sectional enlargements of scans of the photographic prints. It is the relative shift of Mercury from frame to frame that reveals it, even though it appears here as a mere black dot. Note that it appears smaller than the sunspot which is visible in the upper-right of each frame, even though the Sun was 1.6 times further away than the planet at the time! The times for each of the photographs in this sequence are:
(a) 09^{h} 06^{m} UT;
(b) 09^{h} 58^{m} UT;
(c) 10^{h} 25^{m} UT;
(d) 10^{h} 29^{m} UT;
(e) 10^{h} 30^{m} UT;
(f) 10^{h} 31^{m} UT.

Transits of Venus across the Sun are much less frequent than those of Mercury. The circularity of Venus's orbit does, though, make the occurrences of Venusian transits more regular than Mercurian ones. They occur either in June (descending node) or December (ascending node), in pairs 8 years apart. The pairs are separated by either 105½ or 121½ years, which makes observing any one pair of Venusian transits at best a once-in-a-lifetime experience. As far as we know, the first Venusian transit to be seen by human eyes occurred on 24 November 1639 – and only two people in the world got to see it!

Jeremiah Horrocks was a 20-year-old live-in tutor for the children of the family living in Carr House in a small village called Much Hoole, near Preston in north-west England. He had a keen interest in astronomy and had obtained a small refracting telescope. His painstaking observations uncovered discrepancies in the astronomical positions given in official tables. He took it upon himself to examine and recalculate the tables. One day in the course of this work he realised that the planet Venus would come into extremely close conjunction with the Sun – and it would happen in less than a month's time! He did his best to let the astronomical community know of his discovery but the lack of a speedy postal service meant that only his brother in Liverpool, his friend William Crabtree in Manchester, and Samuel Forster in London, could be alerted in time.

He arranged a wooden apparatus to allow him to project the image of the Sun onto paper on 24 November but everything conspired against him. He was a religious man and it is thought that he had assigned duties at the local church. The 24th of November was a Sunday and so the day was particularly heavy with church services and duties. The weather was also unhelpful, with clouds coming and going all day. The Sun would tease him by coming out while he was in church but then taunt him as clouds would roll across the Sun whenever he could get back to his telescope. However, late afternoon the clouds cleared for him to see the black silhouette of Venus on the Sun's disc. He had less than an hour before sunset but did manage to record three positions and timings of Venus's orb on the Sun.

William Crabtree observed the transit but, the story goes, was so overcome with emotion that he failed to secure any meaningful positions and timings! Horrock's brother had nothing but cloudy skies from Liverpool and the weather also defeated Samuel Forster. Jeremiah Horrocks deserved great recognition but never really got it. Tragically, he died a year later, aged just twenty one.

In the late-seventeenth century Edmund Halley realised that transits of Venus would look different from different locations on the Earth.

The planet would appear to take a different path across the face of the Sun and the careful timings of these passages would generate important information, including a measure of the distance of the Earth from the Sun. Until then, the ratio of the radii of the Earthly and the Venusian orbits were accurately known, thanks to observation, but the actual distances could only be estimated.

For each of the following transits, those of 1761, 1769, 1874 and 1882, teams of observers were sent to locations over the Earth in order to make careful observations and timings. The results were not particularly satisfactory from the 1761 transit. The 1769 event produced the biggest advance in accuracy and the figure for the astronomical unit (the Earth–Sun distance) generated was within one per cent of the modern accepted value. Photography was employed for the 1874 and 1882 expeditions but failed to produce the expected further refinements in accuracy.

Surely every amateur astronomer born in the twentieth century hoped to live long enough to see that special day – 8 June 2004 – when we would get to experience our very own transit of Venus. I certainly did and was not disappointed. Incredibly for those of us living in the United Kingdom almost all of us had weather which was nearly perfect for the entire event. I observed and photographed and a few of the photographs are shown in Figure 6.9.

I also took timings to the nearest half-minute of the times of first contact (when the limb of Venus first touched the solar limb), second contact (when the whole of Venus just achieved full immersion onto the solar disk), third contact (the limbs of the departing Venus and the Sun just touching) and fourth contact (the last remainder of disk of Venus just breaking free of the solar disk). Of course these timings were only for interest – there was never any hope of further refining the value of the now very accurately known astronomical unit!

I looked for but did not see any sign of an effect called the *black drop*, where a bridge of shadow momentarily seems to extend from the limb of the Sun to the orb of Venus at second and third contacts. Historically, this effect was responsible for seriously reducing the accuracy of the timings. Poor seeing and/or poor optics coupled with the soft outline of Venus due to its own atmosphere combine to produce the black-drop effect. Many, including me, had remarkably good seeing for the Venus transit of 2004. Many, again including me, will also have had modern, good-quality optics to use so it is not surprising that few saw the black drop in 2004.

A reportedly illusive effect I was delighted to see was a ring of light completing Venus's circular outline while it was in the process of leaving the Sun's disk. This ring of light is Venus's atmosphere backlit by the Sun.

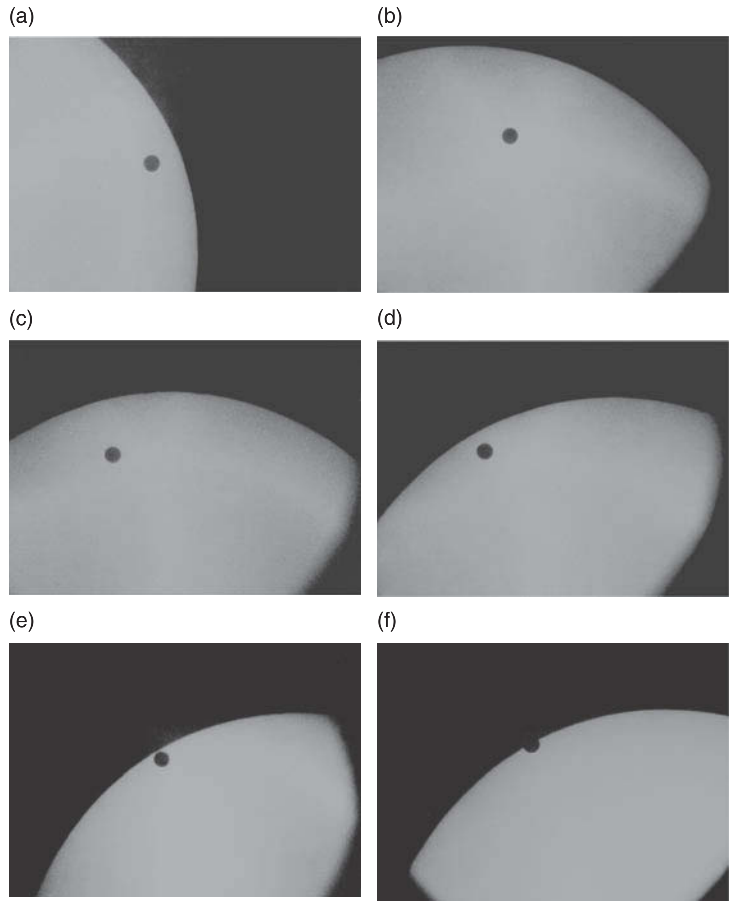


Figure 6.9 Transit of Venus 2004 June 8^{d}, photographed by the author onto Kodak Ultra (400 ISO) print film. He hand-held his camera to the 18 mm Orthoscopic eyepiece plugged into his 8½-inch (216 mm) f/7.74 Newtonian reflector, with a fitted Mylar solar filter of 62 mm aperture (off-axis). A further green filter was fitted into the eyepiece. Seeing variable ANT. IV/III and thin cloud sometimes crossing the Sun. Exposures varied from 1/500 second to 1/125 second depending on whether the Sun was in clear sky or thin cloud. The times for each exposures are:
(a) 06^{h} 09^{m} UT:
(b) 08^{h} 17^{m} UT;
(c) 10^{h} 01^{m} UT;
(d) 10^{h} 49^{m} UT:
(e) 11^{h} 03^{m} UT;
(f) 11^{h} 12^{m} UT.

The 2004 transit was the first to be observed in wavelengths other than the visible, as well as the first to be observed by certain space probes. It was also, of course, the first Venusian transit to be broadcast live on television and being able to momentarily come in from the garden at intervals to see what was happening on the live programme (which I recorded for properly watching later) greatly added to the enjoyment.

Now, as I write these words there is, for you and me, just once chance left to observe a transit of Venus, as the next is due on 7 June 2012. The trouble is the publication of this book is most likely to occur at pretty much the same time, maybe even shortly after. Most probably this date will have come and gone by the time you read these words. If so, I hope that you got a safe look at it. I am sorry to report that the next pair occur on 11 December 2117 and 8 December 2125.

Observing transits of Mercury and Venus across the Sun's disk requires that the solar disk, itself, be observed. **Unless you are already a practising solar observer please carefully read Chapter 12 before even attempting to do this.** If you attempt to observe directly through any telescope without the use of a **special solar filter** attached to the sky end of any type of telescope, binoculars or other optical device you will be blinded. **In particular, it is not enough just to dim the visible image to any level you think sufficient. To avoid severe eye damage (and remember, this may not be evident immediately) the filter MUST also greatly attenuate the invisible infrared and ultraviolet radiations. Any non-specific darkened glass or plastic will definitely not do this. Only a specialised solar filter is safe – and then only if the manufacturer's guidelines are strictly followed.** One final warning: **If you happen to have a telescope (probably this will be an old one) with a supplied small 'solar filter' that is designed to screw into the barrel of an eyepiece then please DO NOT use this filter. These are liable to break under the concentrated heat without warning! If this happens you will not be able to remove your eye from the eyepiece quickly enough to avoid receiving a damaging dose of solar radiation.**

I have given the dates of upcoming transits of Mercury (and Venus, if it is not too late) earlier in this section. For each transit I must leave you to find out whether or not you will be able to see the event from your location – and, if you can, what are the precise times. Astronomy magazines and the Internet will be of help here.

You might simply wish to watch, or you might like to time each of the four contacts as precisely as you can. You might want to undertake photography (**again, please refer to Chapter 12**). The wider astronomical community will be interested in your observations provided you make detailed and precise notes and submit these to your astronomical society along with any sketches or photographs you produce. Please, though, also take the time to savour these memorable celestial occurrences.

CHAPTER 7

Mars

If you are middle-aged or older I am sure you will remember seeing live broadcasts of the Apollo astronauts walking on the surface of the Moon. I vividly recall those exciting times. Sadly for most of us, the thrill of watching broadcasts of humans landing on the 'Red Planet', Mars, is likely to be experienced by only the very youngest readers of this book.

By way of compensation there has been a recent surge in unmanned orbiting probes, landers and even surface-roving vehicles sent to Mars. We have discovered much about the planet as a result, though plenty more remains to be learned. There are indications that Mars has a dynamic early history and maybe its surface has seen even some significant changes in the relatively recent past. We telescopists cannot hope to answer the major questions but there is some active meteorology to be observed. There are also some slight transient changes together with some year-to-year minor variations in the surface features to record using our backyard telescopes.

7.1 THE NATURE AND ORBIT OF MARS

Mars is a small world, having an equatorial diameter of 6787 km and a mass of only about one-ninth of that of the Earth. Its axial rotation period is 24 hours 37 minutes, very similar to the Earth's 23 hours 56 minutes. The inclination of Mars's rotation axis is 24°, again similar to the Earth's 23½° tilt. The mean density of Mars is 3933 kg/m^3, rather less than the 5515 kg/m^3 mean density of the Earth.

When well placed, Mars is a brilliant object in our night sky, appearing like a coppery-pink coloured star. The overall albedo of its rock-and-sand-strewn surface is 0.15, which means that it is roughly twice as reflective as the surface of the Moon or the planet Mercury.

When at its very brightest, Mars can shine with an apparent magnitude of $-2^{m}.8$, though much of the time Mars is rather less brilliant than that.

Mars orbits at a mean distance of 228 million km from the Sun. This qualifies Mars as the first of the *superior planets* – planets which orbit the Sun at greater distances from it than the Earth. Mars has the highest orbital eccentricity of all the major planets. The radius of its orbit varies from 208 million km at perihelion to 250 million km at aphelion. The sidereal period of Mars (the time taken for the planet to go once round the Sun) is 687 Earth-days.

7.2 OPPOSITIONS, CONJUNCTIONS, AND THE PATH OF MARS ACROSS THE SKY

Being a superior planet, Mars does not show phases like Venus or Mercury, and usually appears very nearly 'full'. However, at extremes, Mars can display a phase rather like the Moon two or three days before or after full. Such a phase is known as *gibbous*.

At the time when Mars is best placed for observation it forms a straight line with the Earth and the Sun, the Earth being between Mars and the Sun (see Figure 7.1). We say that Mars is then at *opposition*. Mars is then very nearly as close to us as it can be. We then see Mars at its highest in a midnight sky.

Since Mars and the Earth both orbit the Sun in the same directions, the *synodic period* of Mars (the time interval between successive oppositions) is longer than its sidereal period. It averages 780 days. There are large variations in the Martian synodic period due to the non-circularity of the orbits of the Earth and Mars (mainly Mars), which causes the orbital speed of both planets (mainly Mars) to vary as each goes round the Sun. As an aside, it is the ellipticity of the orbits that causes the date of closest approach of Mars to us often to slightly differ from the date of opposition.

As Figure 7.1 shows, roughly 390 days after opposition Mars will appear very close to the Sun as viewed from the Earth and it is then said to be in *conjunction* with the Sun. Owing to the ellipticity of the orbits of the Earth and Mars not all the oppositions of the planet are equally favourable, the minimum distance of the planet from the Earth varying between 56 million km and 101 million km. At conjunction the Earth–Mars distance increases to around 400 million km.

As seen from the Earth, all the superior planets appear to move through a band of sky known as the *zodiac*. You are undoubtedly aware that the zodiac passes through each of the birth-sign constellations so beloved of astrologers. The orbits of the Earth and the other major planets all lie in virtually the same plane. As we see it from the Earth,

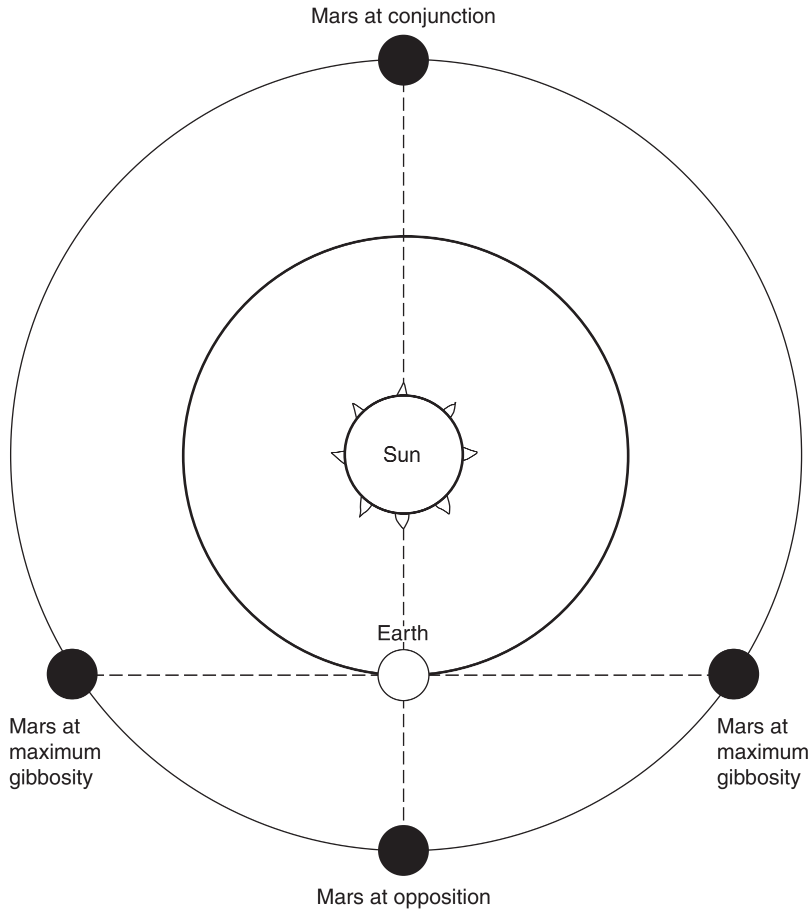


Figure 7.1 Mars at opposition and conjunction.

the path that the Sun appears to move round the sky in the course of a year is known as the *ecliptic*. The fact that the other planets move in their orbits in planes that differ very little from that of the Earth and each other results in the ecliptic being contained within the zodiac.

The position on the sky that Mars takes when it comes to opposition itself moves through the zodiacal constellations with each successive opposition. In the case of Mars, its opposition point takes about 16 years (a period covering approximately seven oppositions) to go once round the zodiac.

The apparent motion of Mars is not always steady and unchanging. Mars moves slowly against the starry background when near conjunction and moves rapidly, with an obvious nightly shift through the stars, around the time of opposition. Spanning a period to either side of opposition, Mars even stops its 'forward', or *direct*, motion through the starry patterns and, for a few weeks, appears to move ‘backwards’, or *retrograde*, before once again continuing its direct motion. Small changes in declination combine with the to-and-fro movements to produce thin loops in Mars’s apparent path across the sky at these times.

This retrograde looping effect is not hard to understand and is simply due to the difference in orbital velocities of the Earth and the planet Mars. Since the Earth moves around the Sun at a mean speed of 30 km/s whilst the planet Mars moves round at only 24 km/s, around the time of Mars’s opposition the Earth appears to catch up and overtake Mars. Then, for a short period of time while the planets are close, Mars appears to move backwards. Figure 7.2 illustrates the principle.

The positions when Mars briefly stops to reverse its direction are known as *stationary points* in its path across the sky. The other superior planets also show this retrograding effect but to a substantially lesser extent because of the much greater distances of these planets from the Earth.

7.3 SETTING YOUR TELESCOPE ONTO MARS

The brilliance and ruddy colour of Mars against the night sky makes identifying it very easy for weeks around the time of opposition. At other times the planet is still distinctive, thanks to its brightness and colour. In common with the other planets, Mars appears to twinkle far less than the stars owing to the fact that it presents a sizeable disk to us, rather than a point of light. That is one easy way to identify a planet against the starry background without optical aid if you have any doubt as to which of the star-like objects really is the planet.

If you have a ‘GOTO’ type telescope, its database will most probably include planetary ephemerides and so you can automatically set on Mars, or any other planet you choose. If not, then running one of the common planetarium software suites, such as *Starry Night Pro*, will provide all you need to help you find the planet and set on it manually. An alternative is to refer to any printed charts that might be published in your favourite astronomy magazine. If you prefer the really old-fashioned approach then you could plot the ephemeris position for a given night (such as that given in the annual *Handbook of the British Astronomical Association*) onto a photocopy of the relevant page of a star atlas (such as *Norton’s Star Atlas*).

A general point – before you intend relying on your finder-scope to help you set your telescope onto any celestial body, do make sure that you have it properly aligned. You can if you wish set the telescope to a distinctive distant object during daylight hours and then adjust the

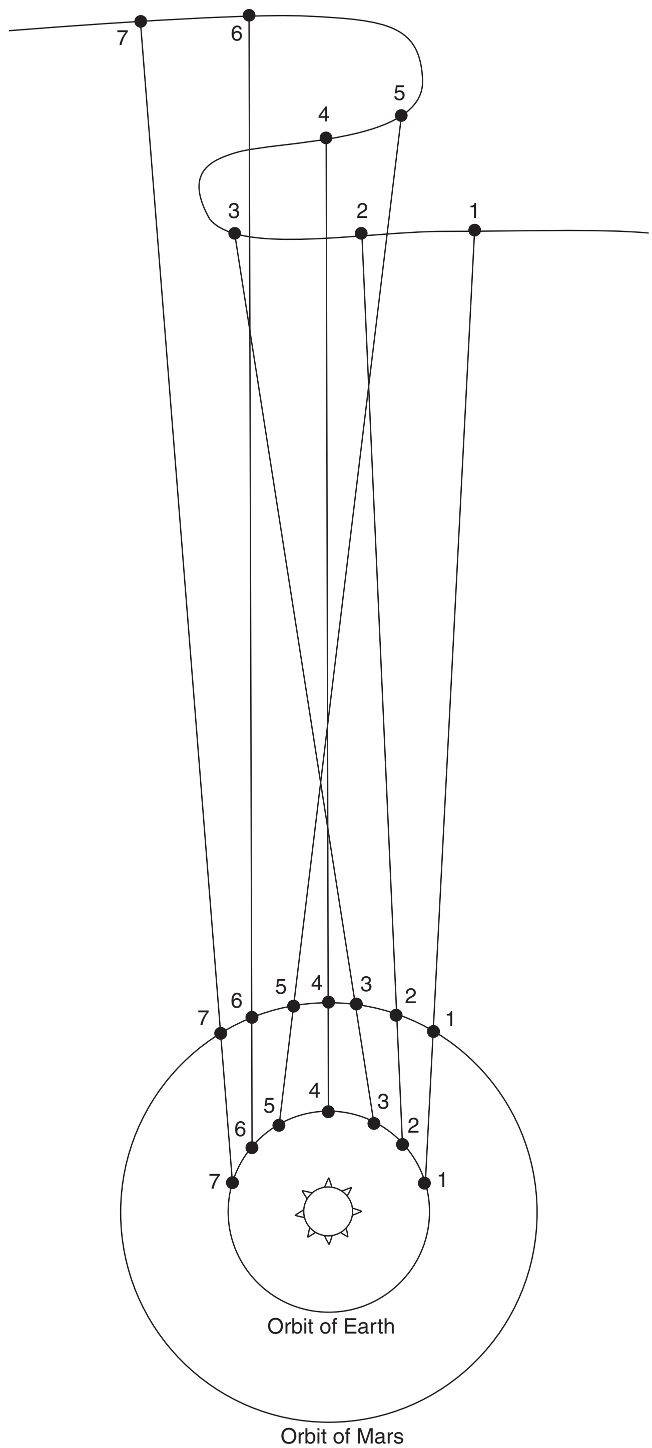


Figure 7.2 The retrograde motion of Mars. When the Earth is at position 1, Mars is at position 1, as shown on the lower part of the diagram. Mars then appears in a position in the sky represented by position 1 in the upper part of the diagram. The same is true for each of the other numbered positions, so illustrating how the apparent looping path of Mars in the sky is generated.

finder until it is pointing at the same object. You should refine this adjustment at night using a bright celestial object because the parallax error in aiming at the relatively nearby earthly target will be significant.

7.4 MARS THROUGH THE TELESCOPE – DIFFICULTIES AND ILLUSIONS

Seeing any more than the coarsest of the surface details on Mars through the telescope is far from easy due to the planet's small apparent size. At a particularly favourable opposition Mars can subtend an angular diameter just over 25 arcseconds. A magnification of $\times 80$ will then produce a view of the planet similar in size to the full Moon seen with the unaided eye. At unfavourable oppositions the disk can be slightly less than 14 arcseconds in diameter, and at such times a magnification of about $\times 140$ is needed to enlarge the disk to the same extent as before. Of course, in normal seeing conditions these magnifications can be increased somewhat but still the disk of Mars will look small through your telescope.

The period for which the planet subtends an apparent angular diameter greater than 7 arcseconds spans from seven months for a time roughly centred on an aphelic opposition to around ten months for a perihelic one. Seeing much on Mars when the disk of the planet appears any smaller demands a large (10-inch, better 12-inch or larger) aperture telescope of excellent optical quality and observing conditions good enough to exploit the potential of such a large aperture. The most dedicated observers, who are sufficiently well equipped, follow Mars throughout the time the planet subtends an angular diameter greater than about 4 arcseconds. This period can span a terrestrial year or more. Modern high-resolution imaging techniques are especially useful when trying to capture details on a planetary disk as small as that in typical seeing conditions.

At the time of conjunction the disk of the planet shrinks to about 3.5 arcseconds, when the planet appears too close to the Sun in the sky to be observable, anyway. I have never been lucky enough to live anywhere where seeing sub-arcsecond details on a planet is routine. Most nights I get mere glimpses of arcsecond-level detail and I find that the nights I can do any better are rare.

Observers sited in the Earth's northern hemisphere are at a distinct disadvantage over those in the south because the closest oppositions of Mars occur in the summer when the zodiac (and therefore the planet) appears at it lowest. A planet seen low in the sky is particularly badly affected by the turbulence and spurious colour-fringing generated by our atmosphere. So, the opposition of Mars in March 2012 was unfavourable thanks to the planet being then only 13.9 arcseconds in apparent diameter but at the same time favourable in that it rode as high as it ever could do in the night sky (of course here I am assuming that you are a resident of the Earth's northern hemisphere). The next occasion that Mars appears near its maximum size (24.3 arcseconds at maximum) will occur in July 2018 but the downside is that the planet will then appear particularly horizon-hugging as viewed from even mid-northerly latitudes.

Mars's pinkish-ochre hue is evident through even the smallest telescope. This colour covers most of the visible surface. A 2.4-inch (60 mm) refracting telescope can show some dusky markings on the surface of Mars when near opposition as well as any white polar cap that may be presented. If you intend a proper observational study I recommend you stretch your finances to obtain a good-quality telescope of at least 200 mm aperture. Mind you, going bigger will not always give you superior results (see Figure 7.3(a)).

I find that through a small telescope the markings on Mars tend to appear blue-green in colour, but through larger telescopes the markings appear grey-green or grey. Most of the published amateur images show the dark regions as distinctly olive-green or even bluish-green. Undoubtedly the visual colours are augmented by contrast with the ochre-coloured areas. The colours produced by three-colour imaging can be quite far from true. The technique that many employ of synthesising the green channel from an average of the red and blue channels produces an image with colours even further removed from reality. In addition, one has to be careful about colour balance whenever processing images. Published space probe images show the colours of the Martian dark areas as mostly greys and greyish-browns. Undoubtedly these colours are the closest to reality. Some of the Martian meteorology can produce genuinely blue tints, especially around the limb but more about that later.

Many early observers reported seasonal changes in the visible markings on Mars. The Martian seasons are roughly twice as long as those on the Earth. In the hemisphere experiencing Martian winter the dark markings were noted as pale and brownish in tint, but in the Martian summer a 'wave of darkening' was reported that swept from the polar to the equatorial regions, when the markings assumed their summer shade of green! This was confidently taken to indicate the seasonal growth and dying away of vegetation. Sadly, we now know such observations to be mistaken. There really are some changes in albedo and even some slight variations in colour but certainly no seasonal darkening and global brown-to-green colour transformations.

Features of the planet which do show real and considerable seasonal variations are the polar caps. Depending upon the tilt of the planet (and hence which pole is presented to us) either one, or both, of the polar caps

(a)

Figure 7.3 (a) Pencil-shaded drawing of Mars, from an observation by the author on 1988 October 28^{d} 00^{h} 20^{m} UT, using a 36-inch (0.9 metre) f/15 Cassegrain reflector, at a magnification of ×312. The Martian longitude on the central meridian at the time of the observation was 325°.5. The seeing was ANT. IV and so a lower magnification would have been preferable if one had been available. Note the bright south-polar ice cap to the upper-right of the drawing and the large, dark V-shaped formation of the Syrtis Major to the left.

are visible. In a small or moderate telescope they show up as glistening areas of whiteness and they vary their shape and extent as the Martian seasons progress. When the northern hemisphere of the planet is experiencing winter the northern polar cap is at its fullest extent, covering the ground even down to a latitude of about 60 °N, whilst the southern cap is very small and irregular (if the tilt of the planet allows it to be seen at all). When the southern hemisphere experiences winter the situation is reversed. We now know that the Martian polar caps are composed mostly of water-ice and are covered in variable amounts of frozen carbon dioxide. Past mistakes did not end with the reported 'wave of darkening' ...

Mars has been studied through telescopes since the seventeenth century. As telescopes improved in quality and size, so more and more detail was recorded. Some observers produced maps of the Martian surface, labelling the features they could see with their own nomenclature.

The year 1877 was one of the most notable in the history of the telescopic study of Mars. The opposition of the planet in the September

(b)

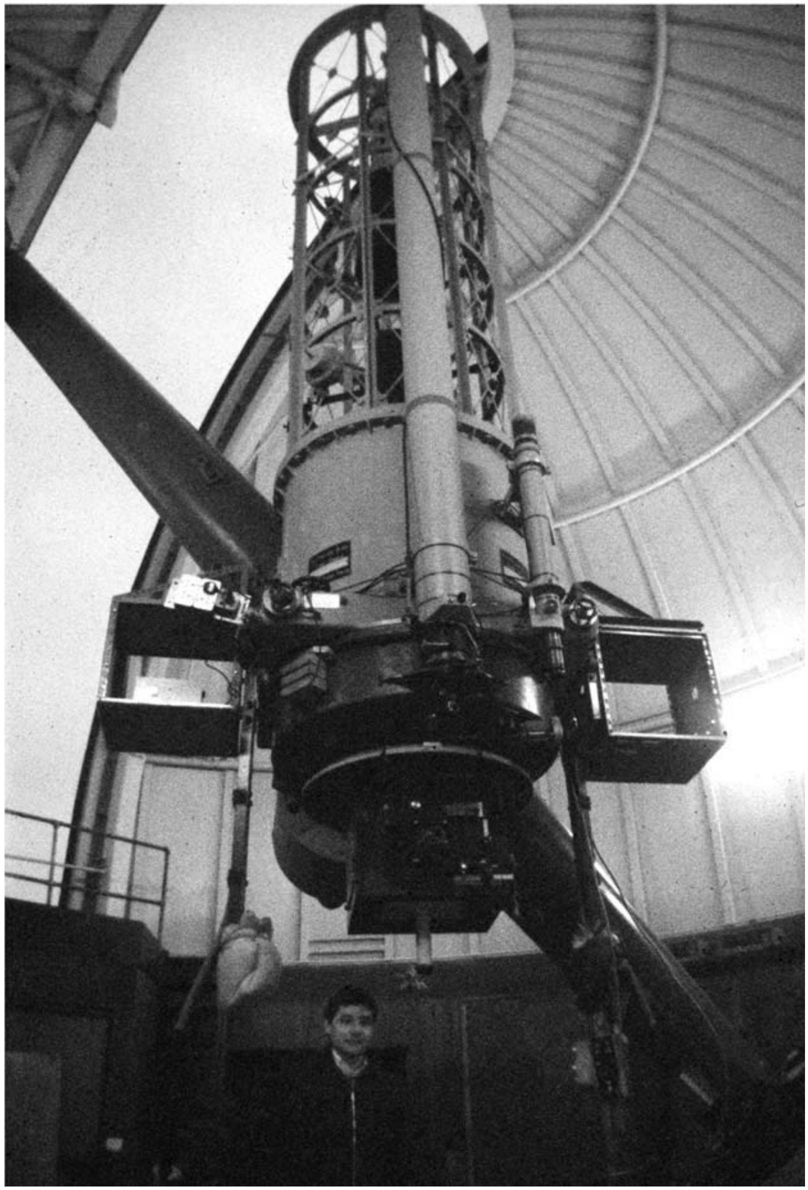


Figure 7.3 (*cont.*) (b) The author can be seen beneath the Cassegrain focus of telescope he used to make the drawing of Mars shown in (a), also the drawing of Venus shown in Figure 6.3. This instrument is housed in 'Dome B' at the site of the former Royal Greenwich Observatory (RGO), at Herstmonceux in England. While engaged in other research at the RGO the author used this telescope extensively for planetary observing, despite the thermal characteristics of the telescope and building being far from ideal for this type of work!

of that year was a particularly favourable one. Giovanni Schiaparelli used the 8¾-inch (222 mm) refractor of the Brera Observatory in Milan to study Mars and he produced a map which was better than any of its predecessors. He replaced the older nomenclature with his own and it is true to say that his nomenclature, albeit in a revised form, survives today.

Schiaparelli's drawings showed something new: a network of many fine lines across the surface of the planet. His lines were either straight or gently curved and they seemed to intersect at either small or large dark patches. In all, Schiaparelli observed and mapped about forty of these lines in 1877. He called them 'canali' (channels). Perhaps inevitably, the moniker 'canals' caught on. Many astronomers were sceptical about these canals but in the following (less favourable) opposition in 1879 many observers reported seeing them. Schiaparelli himself recovered all his old canals and added further ones. He even found that many of his canals were doubled into two running parallel to each other.

The wealthy businessman-turned-astronomer Percival Lowell even went so far as to found an observatory in Arizona in order to study Mars and its canals. He equipped the observatory initially with an 18-inch (0.46 m) refracting telescope; and then with a 24-inch (0.61 m) refractor of 32 feet (9.8 m) focal length.

Even though the seeing at Lowell's observatory was often better than at most others, the majority of the time he found the images best defined when he stopped his telescope down to 16 inches (0.41 m) aperture or less by using an iris diaphragm fitted in front of the object glass.

As well as the question of atmospheric turbulence, it is also true that the secondary spectrum produced by a classical crown-flint object glass of nineteenth-century vintage is strong enough to make itself very obvious when the full 24-inch diameter of that telescope's f/16 objective is used. Please note that this has nothing to do with the accuracy with which the optician worked the surfaces of the glass lens elements. In fact, the optician did a particularly good job in the case of the Lowell refractor. It is simply down to the properties of the glass types that were available in large enough sized disks to the lens-maker at that time. Stopping the telescope down, so reducing its effective aperture as well as increasing its effective focal ratio, substantially reduced the deleterious effects of the secondary spectrum.

Lowell energetically observed Mars using his great, albeit stopped-down, refractor. He recorded on his drawings canals that looked even more artificial than those of Schiaparelli. Lowell published books about Mars in which he postulated that the canals were genuine waterways constructed by intelligent Martians. In Lowell's mind, the Martians laid their canals to convey water from the frozen poles of the planet to irrigate the arid mid-regions. The Martian lives depended on water and the vegetation it could promote.

Undoubtedly Lowell's books fuelled much public interest in Mars and directly led to the tremendous surge in Mars-centred science fiction –

involving strange malevolent aliens, flying saucers and heroic humans landing their rocket-ships on the Red Planet – that arguably really got going with the famous *War of the Worlds* novel of H. G. Wells. While it is always good to have the general public interested, to astronomers and those working in other scientific disciplines it is science fact that is important and science fact was not on the side of Lowell.

The great planet observer Eugene M. Antoniadi studied Mars in the 1920s with the 33-inch (0.83 m) refractor of the Meudon Observatory in France and he considered the canals to be illusory. At most, he found unconnected spots and small streaks and he reasoned that the canals were formed by the unconscious tendency of the observer's eye and brain to join them up into lines. We now know that Antoniadi was mostly correct, though the majority of the reported canals actually do not coincide at all with any genuine albedo features. The canals were the result of imaginative brains behind eyes that were straining to work beyond their limits.

It is particularly significant that different astronomers observing at around the same time as Schiaparelli and Lowell showed completely different arrangements of canals; and that none were seen before 1877. It seems certain that few observers would have recorded canals if they had not heard of their 'existence' beforehand. This is not to question the honesty of the observers, just the effects of human subjectivity. It is very easy to convince oneself of the apparent reality of such features as faint streaks and spots on an object as difficult to observe as the planet Mars. This provides an object lesson that is just as relevant to observers today.

The requiem for the canals finally came in 1965 when the space probe *Mariner 4* bypassed Mars and sent back 21 moderately clear pictures of a limited area of the planet. **No** canals were visible on any of the photographs.

7.5 VISUALLY OBSERVING AND DRAWING MARS

If you haven't done so already, I recommend that you read Sections 6.5 and 6.6 in the last chapter, where I go into detail about visually observing planets and recording observations. All that I had to say there is also applicable to the observation of Mars. Also, the entirety of Chapter 2 is devoted to telescopes and ancillary equipment for visual planet observing. To use the space in this book economically I must assume that you have already read at least those parts of it and here just add some details specific to the observation and drawing of Mars.

In order to standardise drawings, most observing groups adopt a scale of 50 mm to the planet's full diameter. Circular outlines should be prepared to this size on a sheet of paper that allows plenty of room for adding supplementary notes. Your observing group co-ordinator/director may provide you with observing blanks, otherwise you can easily prepare your own.

In most ways the procedure for observing and drawing Mars is the same as that previously described for recording Mercury or Venus. Initially, spend some time getting your eye used to the scene through the eyepiece. Use a range of magnifications. Low powers will allow low-contrast shadings to be more easily seen, though fine details require higher magnifications. High magnifications are also desirable to help you represent the true sizes and positions of markings on the planet's disk as best as you can.

You might find that glare swamps out the finest details, especially when using low magnifications. Temporarily cutting down the brightness of the image might be desirable, to see if doing that reveals more detail. You might like to try a neutral-density (grey) or polarising filter. If you have gone to the trouble of making one, you might like to try the effect of an apodising screen fitted to the end of your telescope (please refer back to Chapter 2, Section 2.7, for a discussion about this device). If your telescope is larger than 12 inches (305 mm) aperture you might like to try the effect of an off-axis stop (also previously discussed in Section 2.7). Certainly the apodising screen or the off-axis stop may well help to improve the image sharpness and contrast levels on nights when the seeing conditions are poor. They will also very likely produce an improvement in image quality if the optical quality of the telescope is itself wanting or is in a poor state of collimation (shame on you if it is – please see Appendix 1 for the remedy!).

Begin work on the drawing by faintly outlining in pencil the positions of any sharply defined features, such as the polar caps and any gibbosity of phase. Then shade in the overall hue of the planet. If, as is most likely, you are working with pencil on white paper you can achieve a smooth greying effect by rubbing the shaded area with the end of your finger. Obviously a soft grade of pencil will be the easiest to use to produce broad shadings. I find that the common HB and 2B graphite pencils are usually all I need to make planetary drawings, though an additional extremely soft grade of pencil is very occasionally useful.

Some observers use an artist's stump, or an artist's chamois, dipped in charcoal to apply the shadings. If you are a practising artist you will undoubtedly use whatever media, materials and techniques you prefer. By contrast, my own drawing techniques have always been at the simple end of the market!

What matters most is the end product. Does it accurately represent what was visible through the eyepiece? If the answer is, 'No', then it might well be the most artistically beautiful depiction created by using all the finest artistic techniques and materials – but as a piece of scientific recording it will be utterly worthless. Practise and use whatever techniques and materials work best for you to produce the most scientifically accurate representation of the planet as you see it through the eyepiece. Here I will offer advice based on my own (very simple) mode of working. If you are a beginner I hope that the following notes may be of use in getting you started. Undoubtedly you soon will develop your own way of working with your favourite materials.

Build shadings onto the drawing by adding darker and darker layers of pencil to represent the darkness of each of the visible markings on the planet. Take special care with the positional accuracy and sizes of the details you represent. The apparent centre of the disk and the limb are good reference points when positioning details. When you have drawn the polar cap it can also serve as a reference point for positioning further details. Use a clean rubber when making alterations. A pointed rubber can be used to create highlights. Start with the most major features and add smaller and smaller details. At the end make sure that you have left nothing out.

For many observers the work at the telescope consists of making a simple line-drawn representation indicating the relative darkness of the features as numbers (as I previously described for making drawings of the Moon (see Chapter 5, Section 5.11) and Venus (Chapter 6, Section 6.5)). That may be the finished product, or the numbered outlines may be used to create a sketch containing all the half-tones after the end of the observing session. I do have reservations about using this procedure but many skilled observers do it this way and successfully produce accurate final drawings. If you decide to adopt this mode of working then I recommend that you keep the telescope set up and check the appearance of the drawing against that of the planet immediately after the final version of the drawing is finished. This will not always be possible due to clouds or perhaps the planet setting too low in the sky. I prefer to prepare what will be the one and only final drawing at the telescope eyepiece by simple pencil-work.

With practice, you should be able to make an accurate sketch of the planet in under 20 minutes. You should note the orientation of the image on the drawing (but not actually on the disk of the planet). If you are unsure of the orientation of the image produced by your telescope, nudge the sky end of the telescope slightly towards the direction of the pole star, Polaris. The image will then appear to move towards the **south**. Mark *s* for south and, of course, *n* for north. With the telescope drive switched off the planet will appear to head in the **preceding**

Figure 7.4 Drawings of the planet Mars by Andrew Johnson.

direction. Mark this direction *p* on your drawing (again, not actually on the area representing the disk of the planet). The opposite direction is termed 'following' and should be marked *f*. The same convention is followed when making drawings of any of the other planets.

As is the case for any record of an observation, remember to include all relevant details of telescope, date, time, magnification, filters used, etc. in your notes to accompany the drawing. Though not essential, it will be a convenience for anyone who analyses your observation if you record the Martian longitude of the *central meridian* (the imaginary line that passes from the south pole down the centre of the visible disk to the north pole) at the time of your drawing. This can be readily found from an ephemeris, though you may have to interpolate the figures to find the value at the time of your observation.

A few descriptive notes may usefully be added to accompany your drawing, especially notes concerning any perceived colours. Also, make a note of any details in the image which you have difficulty in representing accurately on your drawing. Examples might be: 'South polar cap appears glistening white', or 'Miridiani Sinus shown a little too far north on my drawing'.

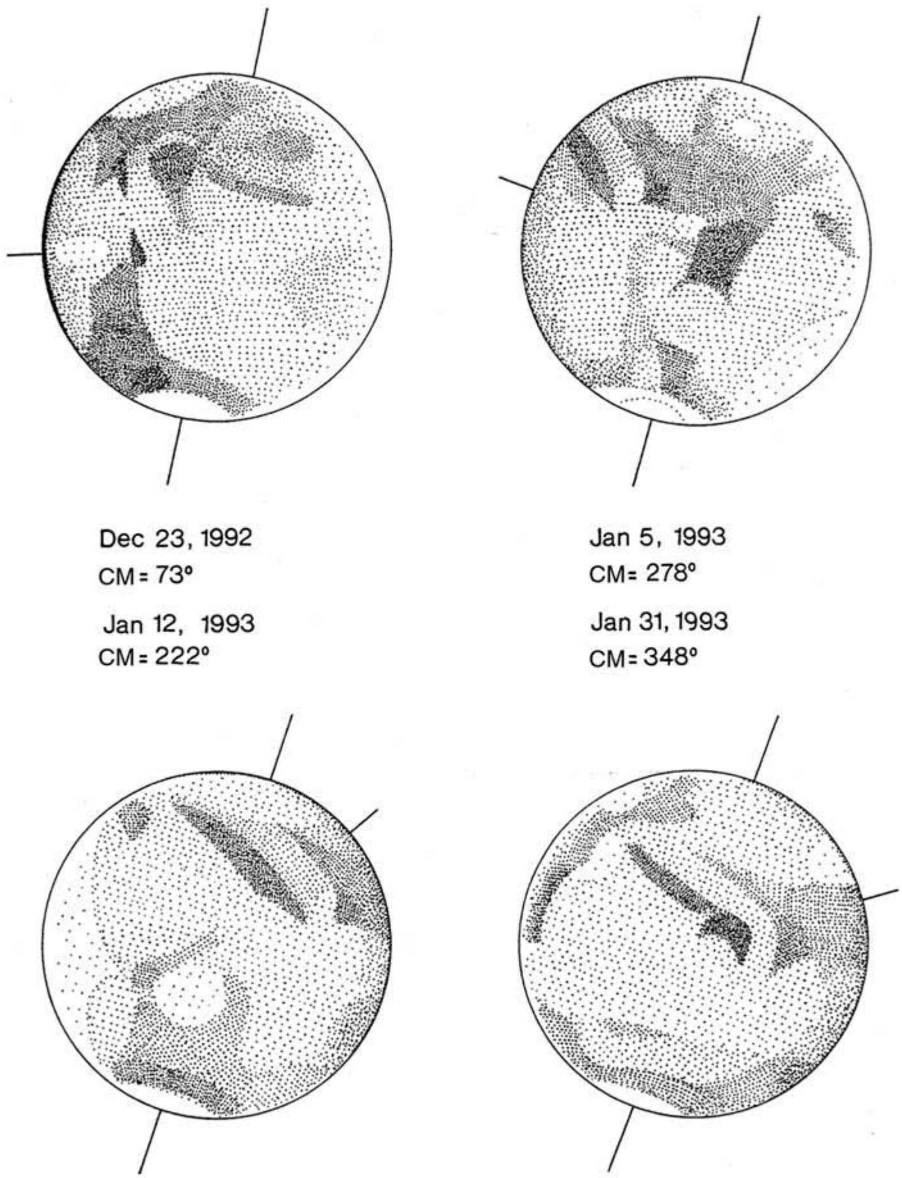
Figure 7.4 shows what a skillful observer can record in good conditions with a relatively modest telescope. Indeed, if you compare those drawings with one of my own in Figure 7.3(a) made with a much larger professional observatory telescope (Figure 7.3(b)) it is my drawing that is sadly lacking in detail. In my defence it was the ANT. IV seeing that was the limiting factor during that observation. Moreover, even on nights of excellent atmospheric conditions, the thermal inertia afflicting that telescope – with its 152 mm thick, quarter-tonne, primary mirror set within its multi-tonne iron castings, all housed within a substantial building – would seriously interfere with its capacity to resolve the finest details. The moral in this tale is don't despair if you own only a relatively small telescope. Provided it is of good optical quality you have the potential to see and record details maybe as fine as anybody using a rather larger one.

As I already said, for those lacking drawing skills an alternative to a monochrome drawing is a sketch marked with dotted boundaries and numbers representing intensity estimates, like that shown in the last chapter for Venus (see Figure 6.2). For Mars, the Association of Lunar and Planetary Observers (ALPO) and the British Astronomical Association (BAA) prescribe a scale of 0 = absolutely black to 10 = brightest.

For those with sufficient artistic ability another possibility is making a coloured drawing. However, I would suggest first making a monochrome one. Then, if you desire, go ahead and make a sketch using coloured pencils. One thing to beware of is that the light you draw by could distort the colours. If you draw by a red light you might well

Views of MARS Around Opposition.

Andrew Johnson



All observations made with a 210mm F7.5 Newtonian, x195.

receive a shock when you come to view your drawing in daylight! It is certainly true that there is a subjective element when recording by eye and pencil. Colour perception is even more in the eye of the beholder. I urge you only to send in for analysis observations and drawings you can be sure really are accurate.

7.6 MAPS OF MARS

I like to go to the telescope without knowing which hemisphere of Mars is on view. In that way I can try to ensure that my observations are not biased by what I expect to see. Admittedly it is true that any experienced observer of the Red Planet will quickly recognise certain main features visible, which will then inform them of the face that Mars has on display.

In any event, as I have already said, recording the longitude of the central meridian at the time of the observation is useful for the person analysing your report as it also is for you when you come to compare your observation with a map of the planet. Your favourite planetarium software suite will probably present you with the longitudes of the central meridian of Mars or of any other planet you are observing at the time of your observation. However, it is always wise to check up on its accuracy. Of course this must include checking that the clock on your laptop or PC is also accurately set! A standard ephemeris, such as that issued annually by the BAA, will provide you with the data you require.

Now we come to the maps themselves. Those of most use to you are the ones generated by Earth-based photography of the planet. Almost all the ones easily available to you are generated by advanced amateur imagers.

I especially like the maps generated by Damian Peach, one of which is presented here in Figure 7.5. Other maps and further information can be obtained via the Mars observing directors/co-ordinators of the national astronomical associations (such as the BAA and ALPO).

7.7 SOME SPECIFIC SHORT- AND LONG-TERM CHANGES IN MARTIAN FEATURES

That fact that Mars and the Earth turn on their axes at almost the same rate means that it can take many weeks to survey right round the planet's globe during a typical programme of nightly vigils from the observer's back garden. In fact, if you were to observe – perhaps taking a picture, or rapidly making a sketch – at the same time every evening you would see an apparent slow backwards rotation of the planet with a nightly shift of about 10° of longitude.

We have long realised that there is an atmosphere on Mars, but until the Space Age its composition and extent were not definitely known. It turned out to be chiefly composed of carbon dioxide and the ground-level pressure turned out to be less than 1% of that at the Earth's surface.

White clouds, composed of tiny ice crystals, are often seen in the Martian atmosphere. On rare occasions they can take on very large proportions, even covering significant areas of the planet. *Orographic clouds* are those that appear associated with high structures, such as mountains. The appearances of puffy or streaky orographic clouds, sometimes exhibiting a definite 'W' formation, at the known locations of the great volcanoes of the Tharsis region should be especially watched for. These tend to appear mostly when the region is experiencing either early morning or late evening.

Other cloud formations are known as *discrete clouds* if they are seen to recur at the same sites, such as Hellas and Chryse. A discrete cloud associated with the Lybia basin sometimes encroaches over the northernmost section of the Syrtis major and sometime alters its colour to a distinct greenish-blue. This effect was especially prominent in 2010. *Evening clouds* are those that tend to appear near the evening terminator (and hence near the preceding limb of the planet) and *morning clouds* tend actually to be *fogs* or *frosts*, rather than genuine high-level clouds, that appear close to the morning terminator (and so near the planet's following limb).

Limb hazes (they are hence also close to the morning and evening terminator, since Mars can only appear between gibbous and full phase from the Earth) can often be seen. They often appear noticeably blue in colour, especially on colour webcam/CCD images. *Limb arcs* are brightenings of the limb caused by scattered light from very high-level crystals of frozen carbon dioxide, maybe together with some dust. Clouds and hazes are often seen over the Martian poles, particularly over the pole experiencing spring.

Great *dust storms* are sometimes seen on Mars. These often start as small localised areas of yellow haze or cloud, as seen in the telescope. These small-scale dust storms often shift their locations, tracking over the Martian surface as seen from night to night. Sometimes they merge and erupt into a largely planet-wide covering of airborne dust. At those times Mars can appear as an almost blank yellowish disk through the telescope.

Major Martian global dust storms usually persist for several weeks at a time, maybe even for two or more months. They are most likely to occur during summer in the Martian southern hemisphere (and hence the southern hemisphere is well on view from Earth). This time coincides with the planet being near perihelion.

As the Martian seasons progress so the ever changing ice caps alter their shape and wax and wane and clouds and fogs become either more

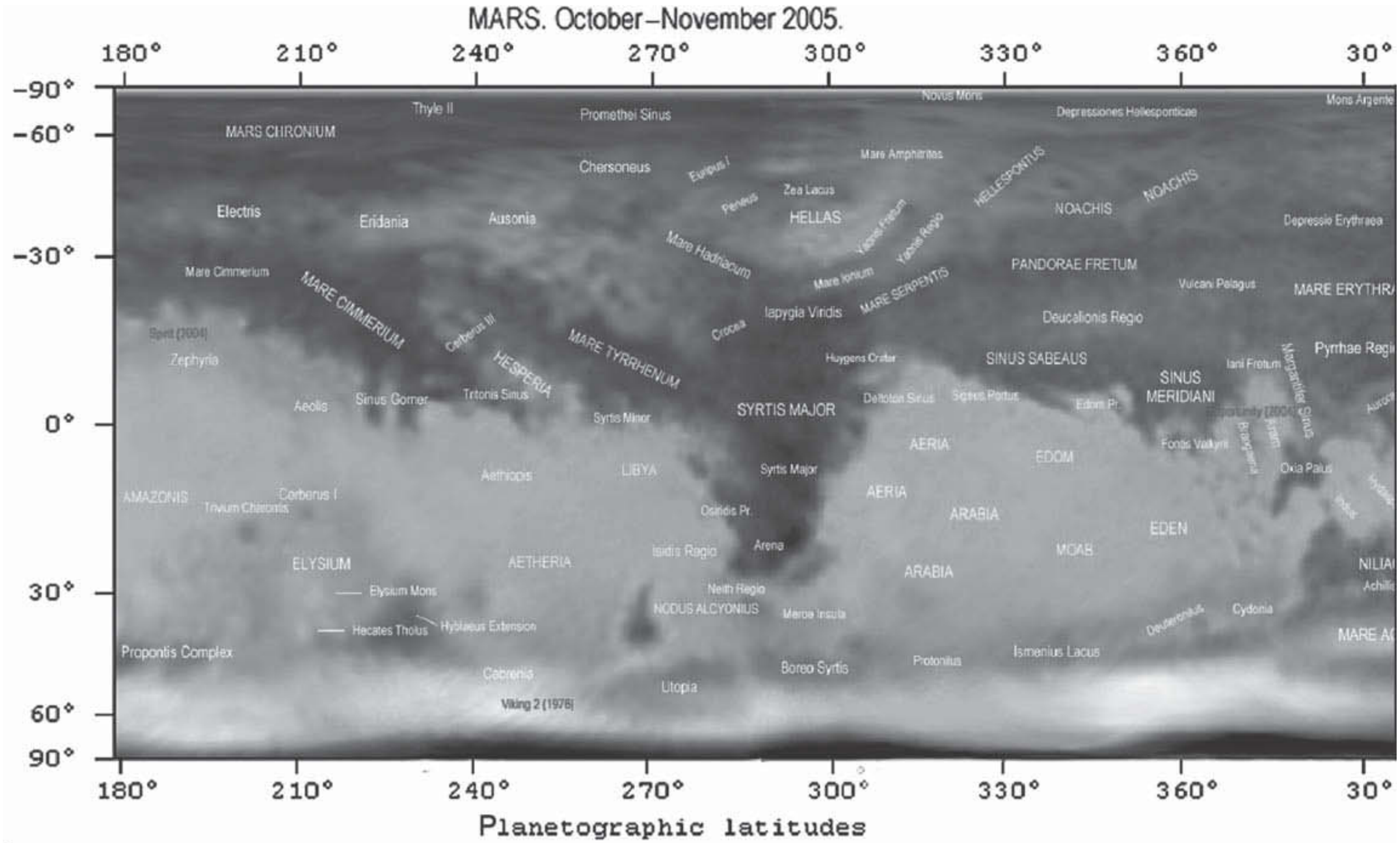
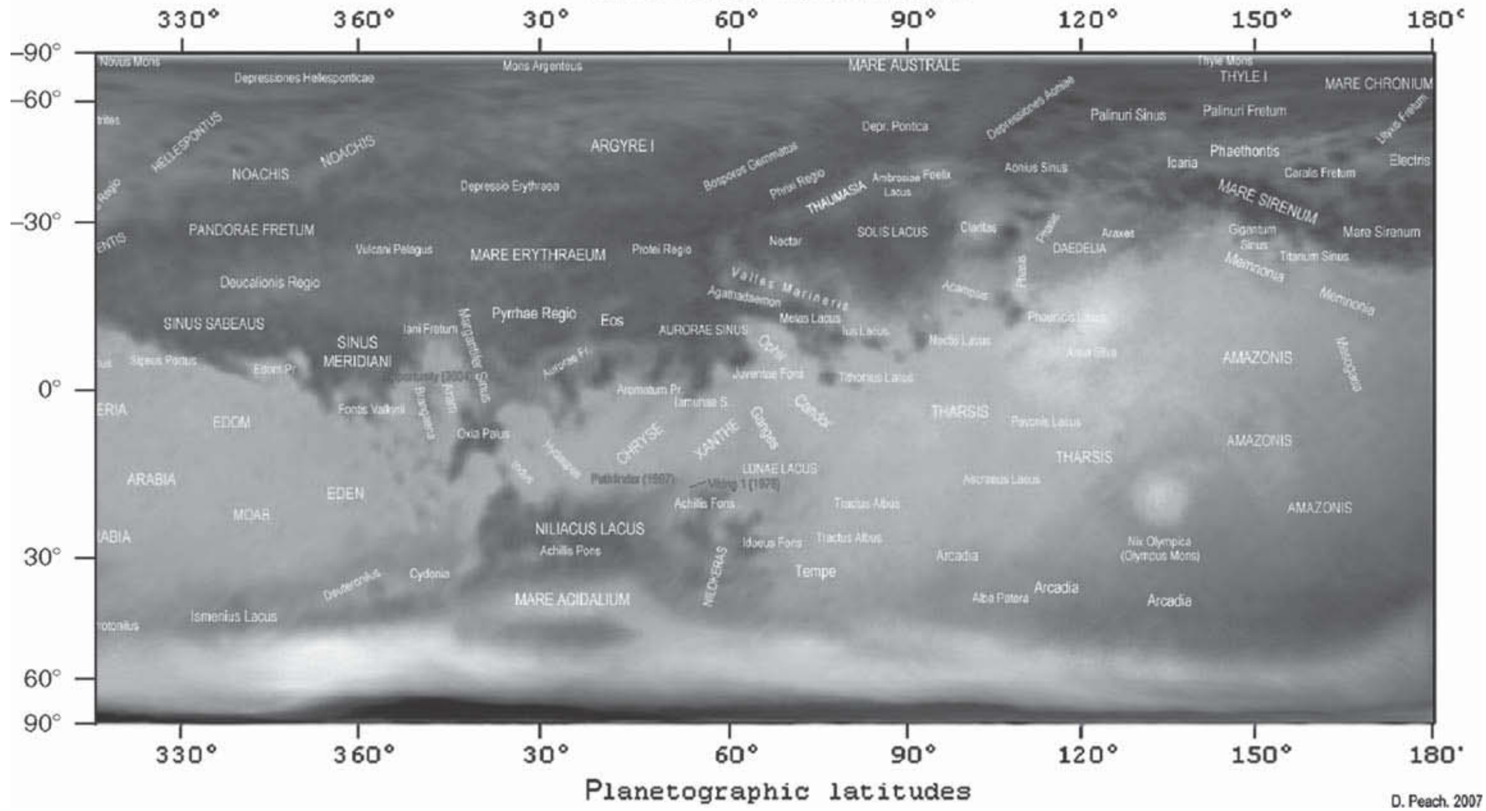


Figure 7.5 Map of Mars prepared by Damian Peach from his images taken during the period October to December 2005. There are small variations from year to year but this map will remain valid and of use to you for very many years to come.

MARS. October–November 2005.



or less frequent at different locations on the planet. As you would expect, a shrinking ice cap unloads much water vapour into the thin and cold Martian atmosphere, taking it very near to a state of water-vapour saturation, and consequently prone to cloud and fog formation.

Martian winds cause the finest sands to be swept up and blown about to re-settle at differing locations. These can cause slight changes to the intensities and shapes of the dark markings. Solis Lacus and the region of Trivium-Cerberus are particularly prone to year-by-year albedo variations. So, all is most definitely not constant on Mars and therefore this planet will repay the most careful close scrutiny both in the short term and in the longer term.

7.8 MARS SEEN THROUGH COLOURED FILTERS

Applicable to both photography and visual observation, the use of coloured filters is particularly useful in the case of Mars. By and large, we can say that an orange filter is best at revealing details on the surface of the planet. Such a filter can also produce a slightly sharper and steadier image in any given seeing conditions. Using coloured filters will also reduce the effect of chromatic smearing visible when any planet is low above the horizon. Using filters coloured at the blue end of the spectrum generally allows more to be seen of Mars's atmospheric phenomena and less of the dark surface markings. Of course any filters inserted into the optical train must be clean and of good optical quality.

Some people like to use filter holders, consisting of slides or wheels mounted in units that plug into the telescope drawtube (the eyepiece then plugs into the unit). This certainly side-steps the hassle of unscrewing the filters from the bottom of the eyepiece each time a change is made, with its attendant risk of dropping either the filter or the eyepiece. On the other hand, it is yet another piece of kit to purchase and I find that the body of the unit can come uncomfortably close to the nose. I only infrequently use filters so a filter wheel for visual observing is not really for me. A habitual filter-user will undoubtedly find a filter holder a very useful piece of kit. They can be especially so for multi-colour photography. Most suppliers of telescope accessories will carry them.

Here concentrating on Mars, atmospheric white clouds and hazes are most prominent when seen through green, blue, or violet filters (W58, W38A, or W47 – exchange the 'W' for '#' for the equivalent Lumicon filters). So-called blue clouds are much more prominent seen through blue or violet filters than through green filters.

I should warn you that the #47 violet filter is very dark and is really only well suited to a large-aperture telescope. It is especially good for revealing the shapes and structures of high-level clouds and for hazes that sometimes occur over the polar caps. Usually Mars's atmosphere is rather translucent in violet light but occasional clearings occur. Historically, these are inaccurately referred to as 'blue clearings'. At these times the surface markings on Mars can appear much more prominently than usual when seen through a violet filter.

Water-ice clouds and limb hazes are perhaps best seen through the #38A blue filter. For a small-aperture telescope the lighter-blue #80A filter may be a better choice. A green #58 filter makes the polar caps stand out prominently against the overall hue of the planet and tends to show up the dark collar that is often seen bordering the ice cap. The so-called yellow clouds, really plumes of wind-blown desert dust, are fairly easily seen in green filters but are most easily seen in yellow or orange (for instance #23A or #15) filters. A yellow #15 filter is usually the best bet for detecting and following Martian dust storms.

A red (#25) filter can show the Martian surface details to the best effect when used on a large telescope thanks to the transparency of the Martian atmosphere to red light. However, this filter will dim the planet a lot and so an orange filter may be better for use with a small or moderate amateur telescope.

Martian surface frosts can be distinguished from clouds by their variations in appearance when seen through different coloured filters. Without a filter, a surface frost may appear as a small bright patch, shaped by the local topography. If the patch is most clearly and sharply defined through a green filter (and still well seen in an orange filter) rather than blue, it is most likely to be a surface frost, though it could also be a ground-hugging fog.

7.9 PHOTOGRAPHING MARS

A fast-frame-rate camera, ranging from the humble webcam to the more expensive and sophisticated cameras manufactured by Lumenera, Atik, etc., allied to suitable software such as *Registax*, can now be used to routinely produce images that would have stunned amateur and professional astronomers of a mere decade ago. Hence, I have devoted two full chapters in this book – Chapters 3 and 4 – to modern imaging techniques. Please read these chapters first. Here I will add just some specific additional details concerning the imaging of Mars.

The eye-and-pencil drawings of Mars made yesteryear tended to show very little until the planet was at least 6 or 7 arcseconds across. The best-quality images of the planet taken these days show a useful amount of detail even when the planet has a diameter of less than 5 arcseconds. Provided you have a good-quality telescope of at least 8 inches (203 mm) aperture and a good camera you potentially could follow the planet over a period spanning something like six months before and after its date of opposition, and secure a long and really valuable series of images of the planet. Those images would really show all the seasonal changes, as well as transient events, which affect the surface of the planet and its atmosphere.

Obviously the techniques you employ have to be tailored to the equipment you are using. The surface brightness of Mars is sufficient to allow you to use reasonably large effective focal ratios – perhaps in the range f/30 to f/50, even if you are utilising a relatively low-end camera such as a cheap one-shot colour webcam. Experiment to find out what gives you the best results with whatever equipment you have to hand.

If you are using a monochrome fast-frame-rate video camera with separate red (R), blue (B) and green (G) filters, then you might be best advised to increase the gain setting for the blue-filtered run as the low sensitivity of the CCD to blue light could result in an overly weak and noisy B image. Remember also that even when using separate R, G and B filters you must also include an infrared-blocking filter in order to prevent infrared light polluting the R, G and B channels and skewing the RGB colour rendition of the final image.

At times where the seeing is poor you might consider making R and B runs only and using the processing software to synthesise an equivalent green (usually indicated as (g)) image. This is then combined to form a R(g)B image. The planet can appear in rather low contrast in green light and not so easy to focus when the seeing is rough. The relatively slow rotation of the planet does at least allow a window of opportunity of several minutes for all the runs needed to generate the final stacked and processed image and this is a big help when the seeing is poor.

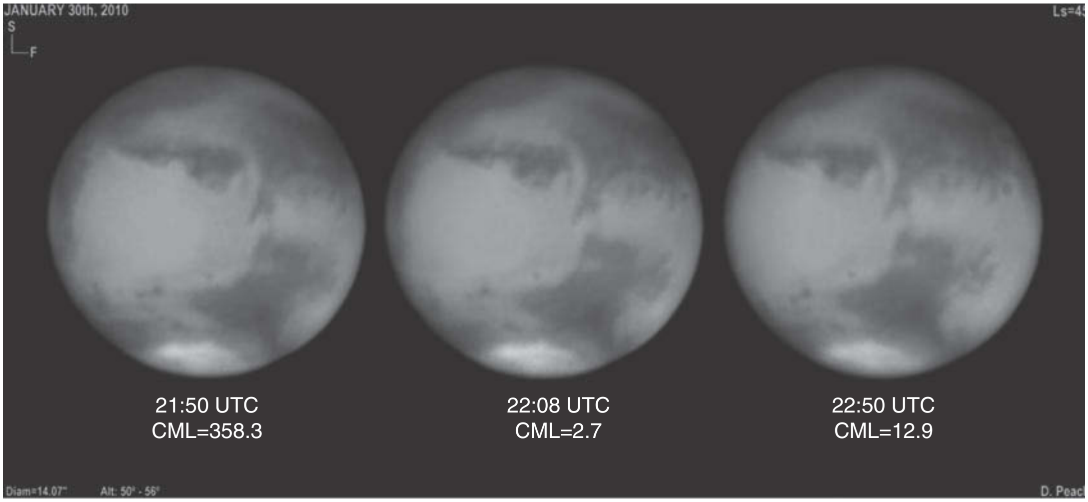
Always, and I do mean always, include full notes on the method of photography and the processing used when submitting your images to any observing-group director or co-ordinator. Please see Figure 7.6 for a small sample of Damian Peach's output of Mars imagery.

Figure 7.6 Mars imaged by Damian Peach using his 14-inch (356 mm) Schmidt–Cassegrain telescope, working at f/42, with his Lumenera SKYnyx camera and RGB filter wheel. The images were captured, stacked and processed in *RegiStax* and further processed in *Adobe Photoshop* and finally *Paintshop Pro*.
(a) This sequence of three images was taken on 2010 January 30^{d}. The exact times are shown below each image (UTC), together with the corresponding longitude of the central meridian (CML) in each case. The rotation of the planet is noticeable over the one-hour span of the images. The Syrtis Major is disappearing to the left and the Sinus Medii is moving towards the central meridian. Clouds are prominent over Tharsis/Tempe, extending into Chryse.
(b) Just one day later, notice the changes to the clouds. Also notice the tiny white spot projecting from the upper (southern) edge of the north polar cap. This is actually the frosted crater Lomonosov.
(c) This sequence of three images was taken on 2010 February 10^{d}. Syrtis Major is prominent (appearing here to the left of the central meridian). Also notable are the bright orographic clouds visible over the Elysium region. [These images are also reproduced in colour as PLATE II between pages 304 and 305].

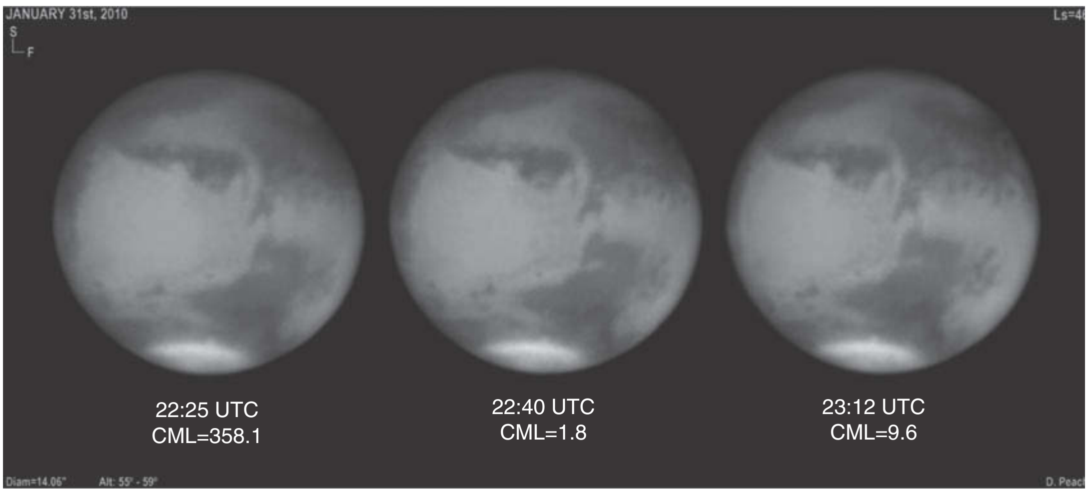
7.10 MARS AS REVEALED BY THE EARLY SPACE PROBES

After initial Russian and American failures, the first space probe success came in 1964 with *Mariner 4*. This device flew by the planet and returned the 21 close-range pictures I mentioned near the end of Section 7.4. These showed that the dark regions of it were not as sharply defined as they had seemed from Earth-based observations. Also, the surface of the planet was not as flat as had been assumed and a number of lunar-like craters were photographed.

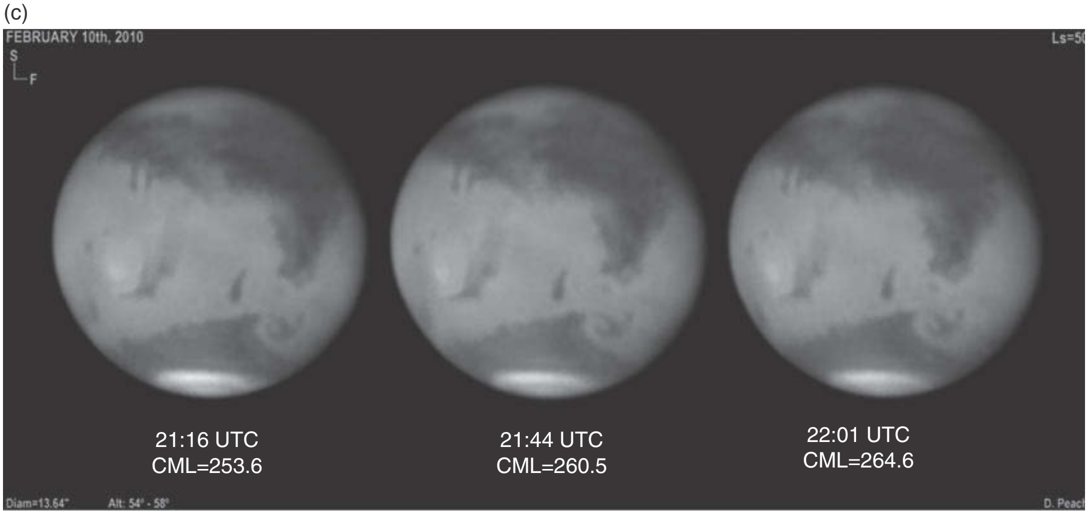
(a)


JANUARY 30th, 2010
S
F
21:50 UTC
CML=358.3
22:08 UTC
CML=2.7
22:50 UTC
CML=12.9
Diam=14.07"
Alt: 50° - 56°

(b)


JANUARY 31st, 2010
S
F
22:25 UTC
CML=358.1
22:40 UTC
CML=1.8
23:12 UTC
CML=9.6
Diam=14.06"
Alt: 55° - 59°

(c)


FEBRUARY 10th, 2010
S
F
21:16 UTC
CML=253.6
21:44 UTC
CML=260.5
22:01 UTC
CML=264.6
Diam=13.64"
Alt: 54° - 58°

Altogether, *Mariner 4* had pictorially sampled a mere hundredth of the surface area of the planet. Perhaps the most significant result from *Mariner 4* was the estimate of the atmospheric pressure on Mars. The spacecraft achieved this by sending radio signals back to the Earth as it was about to pass behind the planet. Just before the signals were cut off their distortion caused by the Martian atmosphere was analysed and this gave reliable information about its composition, density, temperature and pressure.

Russia was next to attempt a Mars mission but it turned out a failure. In 1969, America sent *Mariners 6* and *7* and each achieved a flyby of the planet and sent back many pictures. Many more craters were revealed, with diameters up to 200 km, and in the hemisphere's winter the rims of many of these were seen to be covered in frosty deposits.

Scientists changed their opinions about Mars. Before, they thought life on Mars was probable, even if only in the form of flora. Now, they realised Mars was a barren, desolate, almost lunar-like, place of high mountains and large craters and with a poisonous atmosphere too thin to hold out any hopes of supporting anything more evolved than microbial life. The space probes sent to Mars also detected no significant protective magnetic field or radiation zones surrounding the planet.

After further American and Russian failures (actually the Russians did successfully land a probe onto the Martian surface in 1971 but it sent back no data), a big step forward in the study of the Red Planet came with the dispatch of the American vehicle *Mariner 9* . . .

It is a quirk of fortune that all the space probes until 1971 passed over the less interesting regions of Mars. Scientists jumped to the conclusion that the rest of the planet was similar to these regions. *Mariner 9* was soon to change that view. Put into orbit just over 1600 km above the surface of Mars, it sent back over 7000 pictures. These revealed a highly eroded surface. Great valleys and canyons were discovered, many of which appeared to have been formed by the cutting action of a (now absent) flowing liquid. Could that liquid have been water?

Several enormous volcanoes were also discovered. These are of the 'shield' type and are the largest such structures in the Solar System. Unexpectedly, Mars was found to be split into two distinct hemispheres. The southern hemisphere is more densely cratered. Indeed, its landscape is vaguely reminiscent of the Moon's highland regions. The northern hemisphere consists mostly of sparsely cratered plains.

Nearly all the young volcanic features are found in the sparsely cratered northern hemisphere. Volcanoes have been found in the southern hemisphere as well, but these all seem to be much older and highly eroded. The largest volcano on Mars, Olympus Mons (previously seen from Earth as a light spot named Nix Olympica), is an incredible size.

It has a shield over 500 km across and a summit that reaches 23 km above the surrounding plains.

To say that the *Mariner 9* results caused surprise in the astronomical community would be an understatement. Undoubtedly the most exciting discovery was of the features that so closely resembled dried river beds. If they were really formed by running water, where is this water now? Certainly the present atmospheric pressure on Mars is now too low to allow for the presence of liquid water. It would vaporise immediately.

The spacecraft that followed *Mariner 9* were all failures until two very ambitious American probes – *Viking 1* and *Viking 2* – were launched in the late summer of 1975. They were each two-part vehicles, one part of which would orbit Mars while a specially designed lander descended to the surface in order to take various scientific measurements, including the taking and analysis of soil samples for signs of life.

After a revision of the selected landing sites, on 20 August 1976 the lander of *Viking 1* came down in Chryse (in the northern hemisphere). The probe immediately began transmitting pictures, many of them in colour. These pictures showed a landscape of sand-dunes and pebbles, all of a rusty-red colour. The colouration was attributed to the mineral haematite, which is mostly an oxide of iron (specifically Fe_2O_3).

Even the sky was discovered to be a pinkish colour, due to fine particles of dust swept from the surface of the planet by the winds. The atmosphere was found to be composed of 95% carbon dioxide, 2.7% nitrogen, 1.6% argon and 0.13% oxygen, the remainder being made up of various elements in trace amounts. The atmospheric pressure at the *Viking 1* site varied from 6.7 millibar to 8.8 millibar. For comparison, the average atmospheric pressure at sea level on Earth is 1000 millibar.

Viking 2, which landed on 3 September 1976 in Utopia, found a rather different landscape. Here, the area round the lander was cluttered with rocks of varying types – some fine-grained and some vesicular (porous and sponge-like), with small pebbles and fine sand in between the larger rocks.

The atmospheric pressure at the *Viking 2*, at a lower height on Mars than the *Viking 1* site, varied from 7.4 millibar to 10.4 millibar.

While most of the Press attention focused on the pictures sent back by the landers, the orbiters were equally busy sending back much useful data and many spectacular pictures. The great canyons, cliffs, craters and volcanoes (all inactive) and ancient river-beds of Mars were seen in fabulous detail.

Temperatures over the planet were measured by the onboard instrument. Measurements have continued with the missions since the *Vikings*, so now we have a fairly good picture of the global temperatures on Mars and how they vary. Perplexingly, authorities vary in the precise figures they give. Having never visited the planet myself with a thermometer in hand, the best I can do here is give a 'personally weighted average' set of figures!

Mars is generally a very cold planet. The average global temperature is a decidedly chilly −63°C, with the temperature falling to something like −130°C in the polar regions in the depth of winter. Carbon dioxide is freezing out onto the existing polar ice sheets at this low temperature, greatly expanding the visible area of the bright cap as seen from Earth. This process releases latent heat of fusion from the carbon dioxide and so acts as a buffer inhibiting the temperature from falling lower still.

In the tropical regions, on the balmiest summer days, the temperature at the surface can actually reach something around +26°C in the early afternoon according to some authorities (others set a lower maximum temperature, some say the temperature never rises above 0°C). However, the thermal conductivity of the soil is low, so going more than a few centimetres down the temperature must surely remain sub-zero even at the tropical zones in summer. The summer night-time surface temperature at the same location plummets to a low, typically about −110°C just before dawn.

The data from Viking probes confirmed the notion that the polar caps of Mars are composed of two parts – a permanent cap made up of frozen water and a seasonal covering of carbon dioxide frost. The relative abundance of water once again raised hopes of finding some evidence of Martian life.

The *Viking* landers were each equipped with a scoop to dig up soil samples, which were analysed and subjected to various experiments onboard the craft. Samples were heated to see if any ingestion of carbon-14 (from a supply of carbon-14-'labelled' carbon dioxide gas) took place. No conclusive result was obtained from either lander. Next, carbon-14-labelled nutrients were added to samples of the Martian soil in order to detect possible microbial activity. Again, the results were neither entirely negative nor entirely positive.

To other samples water, and then water plus nutrients, were added, and any gaseous emissions were measured. At first there was a flurry of activity from the samples but after a short while they became inactive. It is now thought that the results obtained were most likely due only to chemical action (involving superoxides) and so once again the possibility of current life on Mars, at least at the microbial level, is thrown open to debate.

You might have heard about a 'Martian meteorite', found on Earth, which was said to hold definite evidence of microbial life on Mars. What happened was that in the summer of 1996 NASA scientists had been examining a meteorite, catalogued as 'ALH 84001', which had been thought to have been 'chipped off' Mars about 16 million years ago when an asteroid impacted with it. This particular rock eventually arrived on Earth. The NASA scientists found tiny structures within the rock sample, which they took to be the ancient microfossils of tiny Martian bacteria. NASA made the announcement that they had found the evidence for past life on Mars and, of course, the story received prominent Press coverage.

Typically, the Press have not as prominently reported the fact that other scientists soon started to have their reservations about this conclusion. The situation today is that most of the specialists who are sufficiently well qualified and experienced in the relevant fields do **not** support the assertion that the structures are really the fossilised remains of bacteria. Mars might have harbored life at some stage in its history but at the time I write these words we do not have conclusive evidence of it.

7.11 THE NEW MARS

The discovery of supposed fossils in the Martian meteorite ALH 84001 came at a time of heavy financial cutbacks for NASA. Predictably, this trend was reversed and several missions to Mars were planned. The $800 million *Mars Observer* was launched but failed three days before encountering the red planet.

Subsequently NASA adopted a policy of 'Faster Better Cheaper' for their planned 'Mars Surveyor Programme' series of missions. Other of the world's space agencies also rapidly drew up plans to send probes to the Red Planet. Many of the new wave of Mars probes have already been launched, though not all of them have been successful: *Mars Polar Lander* and *Mars Climate Orbiter* each suffered technical failures, arguably because 'Faster' and 'Cheaper' conflicts with 'Better'. I am sure that you will also remember the British *Beagle 2* probe which was thought to have been damaged by a too-heavy landing and never transmitted any data from the Martian surface.

However, there have also been many spectacular successes. Using a complicated sequence of slowing by heat shield, then parachute, then finally retrorockets, the *Mars Pathfinder* probe approached touchdown on 4 July 1997. A large cocoon of airbags inflated around the craft just in time for it to drop onto the Martian surface. Bouncing several times it eventually came to rest. As planned, the airbags deflated and the probe successfully righted itself on the alien terrain.

The probe had been landed in the Ares Vallis region of Mars. This is an ancient outwash flood plain. This being a long-dried river delta, scientists expected it to be strewn with rocks and general detritus washed down the Martian river and deposited in the plain. The craft beamed images of its surrounds back to Earth and these showed that the scientists predictions were correct.

The real coup of this mission was a small roving vehicle, the 'Sojourner', which was eventually dispatched from the lander to trundle about the immediate vicinity of the craft and examine several of the rocks close up. It even had a device on it which took small samples and mineralogically examined them, sending its data back to Earth for interpretation.

In terms of expanding our detailed understanding of the Red Planet the *Mars Global Surveyor* spacecraft, launched in 1996, must rank as particularly fruitful. This probe entered Martian orbit in September 1997. Its onboard suite of instruments allowed extremely fine-detailed photography, compositional analysis of the surface (by means of the reflectivity variation at different wavelengths) and radar altimetry to be undertaken. Other highly successful probes have been the American *Mars Odyssey* and the European *Mars Express*.

We have also had the phenomenally successful *Mars Reconnaissance Orbiter*, which sends us images of the Martian surface with sub-metre resolution, and the even more spectacular *Mars Exploration Rovers* mission with its landers *Spirit* and *Opportunity*, which have been roving over the Red Planet's surface since January 2004. They have sent back hundreds of thousands of photographs. In addition, they have used a variety of remote-sensing and direct-contact instruments to explore and analyse the Martian rocks and the probes' environments.

Spirit was landed in a small formation called Gusev Crater, selected because it appeared to be an ancient lake-bed once fed by a long-dried river. In fact, appearances were deceptive and the initial findings indicated that the feature was primarily volcanic in origin. The rover was later sent on its way to the nearby rim of Bonneville Crater and then several more kilometres towards a cluster of mounds known as Columbia Hills. Its roving days ended in May 2009 when it got stuck in soft sand.

Meanwhile, the rover *Opportunity* was itself providing spectacular results. It was landed in a small crater called Endurance, situated in an upland plain named Meridiani. That was its starting point. After exploring Endurance Crater it was commanded to climb out of the crater and head towards an 800 metre wide, 75 metre deep crater called Victoria. After a 21-month journey – observing, sampling and analysing all the way – it arrived at the crater rim in September 2006. In a spectacular photo-call it was imaged there, in an overhead view by the *Mars Reconnaissance Orbiter*! Next, it undertook the treacherous decent into the bowl of the crater. After exploring there it climbed back out and, as I write these words, it is embarking on a 12 km trek to the large, and apparently ancient, crater named Endeavor. It will be an amazing feat if *Opportunity* gets to its new target. Both rovers were designed to last only to April 2004 on the surface of Mars and cover just a few hundred metres each!

In May 2008, retro-rockets fired on the American *Pheonix* probe to bring it to a soft landing onto the Martian arctic (latitude 68 °N) plains of Vastitas Borealis. There it photographed its surrounds and dug soil samples for onboard analysis. Straight away it found sub-surface ice. The top-soil seemed chemically a little different than the other sampled sites, most notably being rather alkaline and containing carbonates, clay minerals and various chemical salts including perchlorates. The onset of local winter brought the work of *Pheonix* to an end in November 2008. Before then, *Pheonix* even photographed snow falling through the Martian air at a location about 4 km from the probe. However, like the acid rains of Venus, the snow evaporated before it reached the ground.

In the last few years we have learned enough about Mars to fill several large-volume books. Yet I have space enough here to briefly mention a mere few of the latest findings. Similarly, I would have loved to display here a great many of the thousands of spectacular new photographs of Mars but space (and the publication economics of this book) does not allow it. However, I can go some way to make up for both deficiencies by suggesting a website at which you can find much information and thousands of images (and there are other useful websites you could unearth by using a search engine):

mars.jpl.nasa.gov

There are also some books published by Cambridge University Press you might like to add to your reading list: *The Martian Surface: Composition, Mineralogy, and Physical Properties*, edited by Jim Bell (published 2008); *Mars: An introduction to its Interior, Surface and Atmosphere*, by Nadine Barlow (published 2008); *The Surface of Mars*, by Michael H. Carr (published 2007); *The Geology of Mars: Evidence from Earth-based Analogs*, edited by Mary Chapman (published 2007). There is also a book on comparative surface planetology of relevance titled *Planetary Crusts: Their Composition, Origin and Evolution* by S. Ross Taylor and Scott McLennan.

To mention a few of the key new findings here, laser altimeter results have shown that the northern hemisphere of Mars is low-lying and rather smooth, while the southern hemisphere is elevated and much rougher. Gravimetric data, in combination with laser altimetry, revealed that the outer crust of Mars averages about 40 km in thickness in the northern hemisphere and is about 70 km thick in the southern hemisphere.

Crater counts made from *Mars Express* images have revealed that much of the planet has been resurfaced on at least five occasions by periodic volcanic activity. Identified episodes of global volcanism happened 3.5 billion, again 1.5 billion, then 400–800 million, 200 million and finally 100 million years ago.

Mars's polar ice caps are elevated and are rather complicated in structure, containing swirling patterns of valleys and complicated layered deposits of ice and sand, each several kilometres deep. The permanent component of the north polar cap is dominated by water-ice mixed with dust, while that of the southern cap is much 'cleaner' ice. As already noted, each cap has a variable covering of carbon dioxide, of greatest extent in the local winter.

There is evidence for sub-surface ice on Mars even at its mid-latitudes. The *Mars Reconnaissance Orbiter* radar instruments have even detected glaciers several kilometres across and up to a kilometre thick, the tops of which exist less than a metre under the Martian soil surface!

Clearly there is much frozen water now locked away beneath the surface of the Red Planet. An important question is, did it ever flow on its surface, or were the canyons and apparent dried river valleys we see actually created by the flowing lavas from ancient volcanic eruptions? There are stratified layers of sandy deposits in craters and in some of the Martian valleys – just the sorts of deposits that would have been formed in Mars had there been extensive deposits of liquid water in the past. One can imagine some of the impact craters and ancient volcanic calderas containing large lakes.

In connection with past water, scientists expected to find deposits of carbonates. However, what *Spirit* and *Opportunity* unearthed are deposits of sulphates rather than carbonates. That came as a shock and indicates that the waters that flowed on the parts of Mars sampled so far contained at least some sulphuric acid! *Opportunity* also found little beads of the mineral haematite (one of the oxides of iron) among its samples from under the surface of Victoria Crater. These 'blueberries', as they are nicknamed, can only be formed in an aqueous environment. Interestingly, the occurrence of these blueberries was found to increase with sample depth, suggestive of underground liquid water billions of years ago.

Further, spectral analysis carried out by the *Mars Reconnaissance Orbiter* probe has uncovered wide-ranging deposits of the mineral olivine on the planet and even substantial deposits of opal (hydrated silica). The chemistry is complex but, suffice it to say, in combination with the other minerals present this is a strong indicator that Mars was a wet planet as little as two billion years ago. There just might have been surface water even more recently than that.

We are now certain that water really did flow on the surface of Mars in the distant past. This also means that Mars must at one time have had a dense atmosphere. What about life on the Red Planet, though? Did it ever get started? If so, does anything remain alive on the planet today? Undoubtedly ultraviolet radiation from the Sun (easily passed through Mars's currently thin atmosphere) has long sterilised all the exposed surfaces on the planet. In addition, the highly oxidising composition of the Martian surface materials will also have a sterilising effect. Could there be any microbial life active today – maybe underground even if not on the surface?

A recent surprise has been the discovery of variable trace (parts per million) amounts of methane in the Martian atmosphere. These seem to be emanating from specific areas of the Martian surface such as Syrtis Major and Nili Fossae. Could this be an indicator of current microbial activity on, or under, the surface of the planet? At the time I am writing these words, nobody knows for sure but the majority opinion tends towards a geological rather than biological cause for the methane – and I think I am safe in stating most definitely that the methane is not produced by any Martian cows!

The fact that the core of Mars cooled and solidified relatively quickly after its formation has meant that its early magnetosphere also quickly weakened and disappeared. In turn, that left its early atmosphere exposed to the corrosive effect of the solar wind. In addition, the weak surface gravity of the planet also exacerbated the leakage of its early atmosphere. With its atmosphere thinning, any free-standing liquid water on the surface of Mars would have evaporated. The result of all that is the Mars we see today.

7.12 PHOBOS AND DEIMOS

Until 1877 we thought that Mars was as moonless as Mercury and Venus. In that year Asaph Hall, an astronomer in the USA, was occupied on a deliberate search for a satellite of Mars. He used the 26-inch (0.66 m) refractor at the US Naval Observatory, Washington, which was at that time the largest refracting telescope in the world. At first he was unsuccessful but then, within a single week, Hall found the two satellites, which he subsequently named Phobos (translated as 'fear' or 'terror') and Deimos (meaning either 'flight' or 'panic').

The inner satellite, Phobos, orbits the planet at a mean distance of 9378 km with an orbital period of 7 hours 39 minutes and thus goes round the planet quicker than the planet rotates on its axis. Deimos orbits the planet at a mean distance of 23 459 km, with an orbital period of 30 hours 18 minutes.

Space probe images reveal both satellites to be small, irregularly shaped, and rocky. One can say that the shapes of Phobos and Deimos approximate to ellipsoids with dimensions of 18 × 22 × 27 km and 11 × 12 × 15 km, respectively. The density of Phobos is 2200 kg/m^3 and that of Deimos is 1700 kg/m^3. Both have surface reflectance spectra very similar to the C-type (carbonaceous type) of asteroids (for more about asteroids see Chapter 10). Indeed, many think that these bodies are indeed C-type asteroids which were gravitationally captured by Mars at some time in the remote past. Or at least, that is what we thought until recently. Now there seems to be some doubt about Phobos. Phobos is peppered with impact craters up to 10 km in diameter and has a complex grooved and ridged surface. Deimos is smoother with no craters larger than about 2.5 km across.

The orbiter of ESA's *Mars Express* mission made a dozen close passes of Phobos in the spring of 2010, photographing proposed landing sites for a Russian mission to land a probe on the surface and return soil samples to Earth. That mission should be on its way by the time this book is published. Gravimetric data from the *Mars Express* orbiter indicates that Phobos is perhaps as much as 35 per cent porous. One can speculate that there might be large underground caverns. At any rate, it is certainly safe to assert that Phobos is a very loosely assembled body. In fact, detailed observations have caused us to revise our assessment of Phobos's composition. It now seems rather unlike any other asteroids or meteorites we know of so far. This leads us to wonder about how it formed and got into Martian orbit.

Both of the Martian satellites are difficult to detect from the Earth because they never appear far from the brilliant disk of Mars, and are thus swamped in the bright glare from the planet. If the satellites could be seen on their own they would appear to be star-like points of around the twelfth magnitude ($11^{m}.6$ for Phobos and $12^{m}.8$ for Deimos at an average Martian opposition). If you position your telescope to put Mars just outside the field of view and charge it with a high magnification you might be able to catch sight of Phobos or Deimos as a faint speck of light. You will probably need to use a telescope of at least 12 inches (305 mm) aperture of excellent quality, and with clean optics, to have any chance. Success, though, will depend upon the clarity of the sky – and particularly freedom from the usual halo of light scattered from Mars – more than the actual size of your telescope. Good luck!

CHAPTER 8

Jupiter

The small, rocky, innermost worlds of the Solar System collectively form the *terrestrial planets*. Further from the Sun are the large gaseous bodies of Jupiter, Saturn, Uranus and Neptune. These are known as the *gas-giant planets*. The name of the first of these, Jupiter, has linguistic links to good humour and jollity. Indeed, 'Jovian', pertaining to Jupiter, is the origin of 'jovial'. This major planet is the easiest on which to see details through any telescope of limited size. Also, those details are subject to such rapid changes that one can never be sure what Jupiter will look like anytime one goes to the eyepiece. These attributes ensure that Jupiter is always a rewarding target for observers of all levels of experience.

8.1 THE JOLLY CREAM GIANT

Jupiter is the largest planet in our Solar System, having a volume 1300 times that of the Earth. Its bulk contains the equivalent of 317 Earth-masses but its average density is very much less than the Earth's, being a mere 1300 kg/m^3. This great globe orbits the Sun at a mean distance of 778 million kilometres, i.e. 5.2 astronomical units (AU).

Jupiter takes 4332.6 days to trundle once round its orbit, so the Earth does not have to go a lot further than once round the Sun to catch up with it as each successive opposition comes round. Consequently oppositions of Jupiter come along every 399 days, on average.

To the naked eye, Jupiter appears as a brilliant, cream-coloured 'star'. Jupiter is always more bright than Sirius when at opposition and attains an apparent magnitude of $-2^{m}.4$ to $-2^{m}.9$, so that it really cannot be mistaken for anything else. After your first time or two, I doubt that you will need any planetarium programme or other aid to find the planet in the sky. Whenever it is somewhere in the area of night sky visible to you I am sure you will recognise it.

8.2 JUPITER THROUGH THE TELESCOPE

Owing to its size, Jupiter is very easy to observe except when near conjunction with the Sun. At opposition, the planet subtends an apparent equatorial diameter of up to 50 arcseconds, shrinking to 33 arcseconds when near conjunction. There are small variations in these figures from year to year because of the slight non-circularities of the orbits of Jupiter and the Earth. This is the same reason that the maximum brightness Jupiter attains at opposition varies a little from year to year. When it is at opposition a magnifying power of ×40 is enough to render the image of the planet through the telescope approximately the same size as the full Moon seen with the unaided eye. Even when it is close to conjunction you only need a power of about ×60 to produce the same effect.

Seen through the telescope, it is obvious that the disk of the planet is not perfectly round. Jupiter bulges at the equator at the expense of being flattened at the poles. The figures for the equatorial and polar diameters are 143 800 km and 133 500 km, respectively. This amounts to a flattening of one-fourteenth of the equatorial diameter.

A refracting telescope of 40 mm aperture with an applied magnification of ×40 is certainly enough to show that Jupiter is crossed by a couple of dark bands spanning east to west across the planet, one just above the equator and one just below it. A higher magnification applied to a 2.4-inch (60 mm) refractor or 3-inch (76 mm) reflector will reveal at least one more, thinner, dark band – maybe two or three more – plus dark hood-like regions at each of the poles. A good-quality Newtonian reflector of 8-inch (203 mm) aperture can reveal any further dark bands that might be present, together with a lot of fine detail in the Jovian markings.

On the very best nights, when seen through a top-quality telescope of 14 inches (356 mm) or more aperture, the Jovian bands and other details can take on a finely and intricately swirled 'chocolate ice-cream ripple' effect. I must admit that I have rarely seen the planet like that but you might be luckier than me with the atmospheric conditions where you live. If you take video sequences using a fast-frame-rate camera and subsequently process the result in software such as *AviStack* or *RegiStax* you will record this level of fine detail very much more often through the telescope than you can see with your eye looking through it.

I would say that a 6-inch (152 mm) Newtonian reflector used visually is perhaps nowadays no longer considered quite powerful enough to conduct serious observational research on Jupiter, though the same telescope used with the best imaging equipment and techniques most certainly is. An 8-inch (203 mm) or larger telescope of excellent quality is

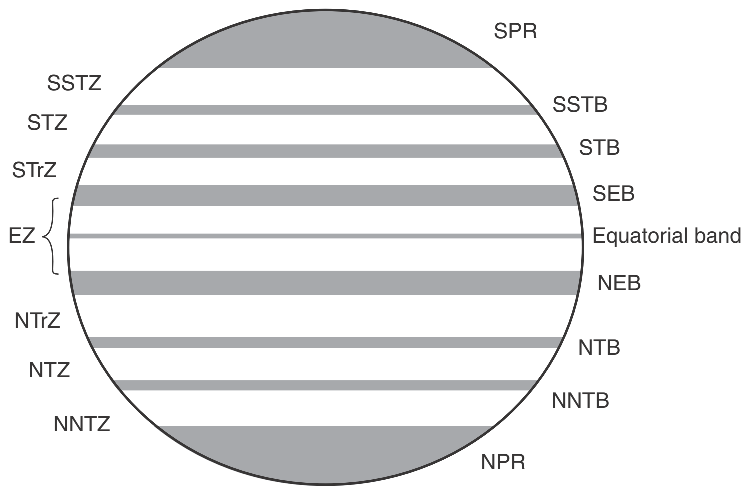


Figure 8.1 The nomenclature of Jupiter. With increasing latitudes north and south the belts tend to be less permanent and even an equatorial belt can, though rarely, disappear. There are long periods where the Equatorial Band is not visible.

KEY:	NPR = North Polar Region
SPR = South Polar Region	SSTZ = South South Temperate Zone
SSTB = South South Temperate Belt	STZ = South Temperate Zone
STB = South Temperate Belt	STrZ = South Tropical Zone
SEB = South Equatorial Belt	EZ = Equatorial Zone
NEB = North Equatorial Belt	NTrZ = North Tropical Zone
NTB = North Temperate Belt	NTZ = North Temperate Zone
NNTB = North North Temperate Belt	NNTZ = North North Temperate Zone

enough to produce worthwhile results even when the recording of detail is done using old-fashioned eye and pencil.

The dark bands are properly termed *belts* and the light regions between them are termed *zones*. It is obvious from observing the planet that the visible ‘surface’ is decidedly fluid in nature. In fact, we long ago realised that our observations are actually of Jupiter’s soupy cloud-topped atmosphere. The Jovian vista is constantly changing. Many of the details are transient. In addition, as the various features are carried across the disk by the rotation of the planet they travel at different rates. The apparent rotation of the planet as deduced from observations of features near the planet’s equator is faster than that for features moving at higher latitudes. More about that in Section 8.3.

Astronomers long ago standardised the nomenclature of the visible surface features, and the basic scheme is given in Figure 8.1. The belts near the equatorial regions of the planet are fairly permanent features, though they often display variations in width, colour and intensity. On odd occasions, though, they have even been known to temporarily vanish! Actually, at the time I am writing this the South Equatorial Belt is just beginning to reappear once more after just such a disappearing act (see Figure 8.8(a) further on in this chapter).

The belts can also drift a little in latitude. The higher-latitude belts are of a less permanent nature, usually being much less prominent and often merging with the polar hoods. The zones are usually pure white or cream coloured. The belts are usually various shades of brown but can have streaks and swirls of greys, dull blues and greens mixed in. The Jovian colour scheme can be subjected to changes both on the small scale and on the larger scale. The average albedo of the visible disk of the planet is 0.51, meaning that it reflects away 51 per cent of the sunlight falling on it.

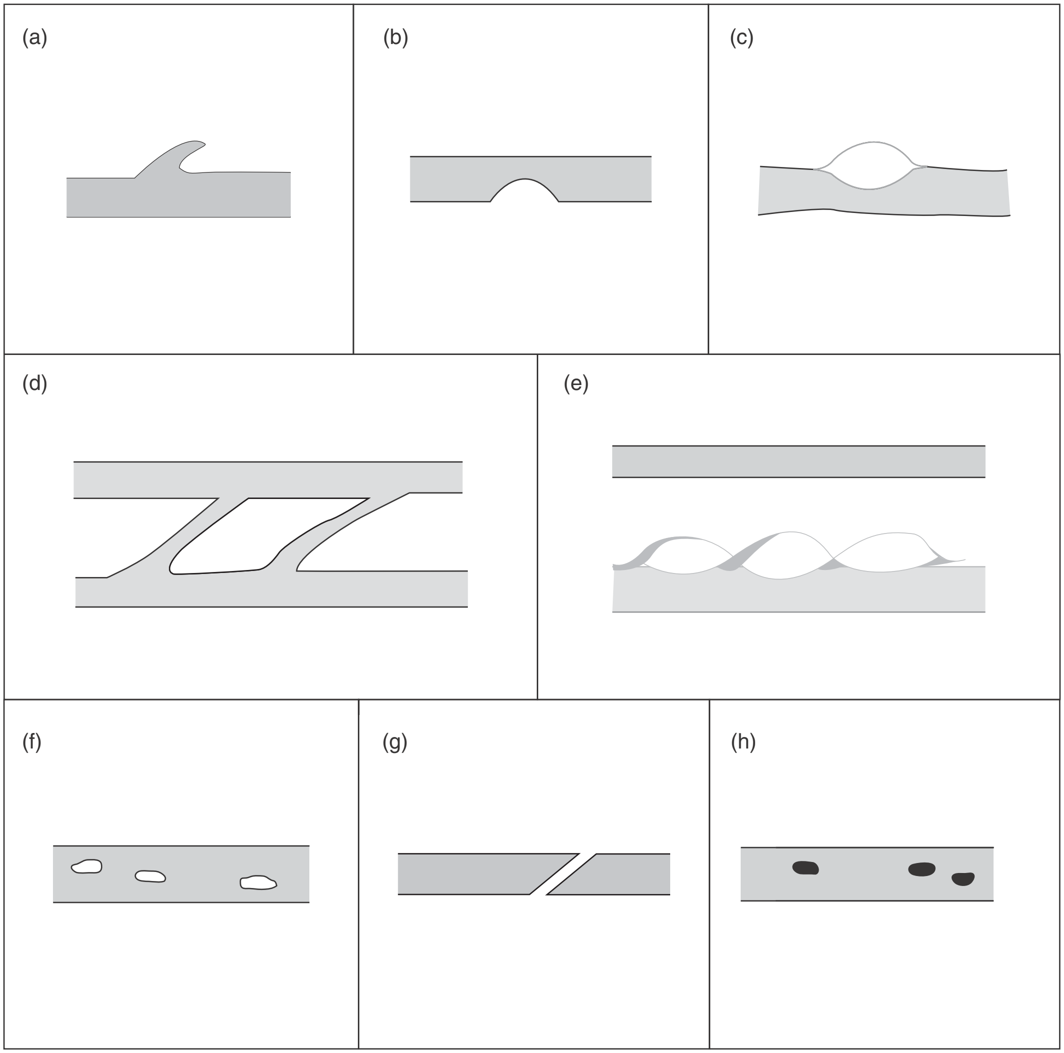
Projections and other irregularities are often seen in the belts and zones and white spots often appear. More rarely, dark-coloured spots sometimes occur. Sometimes these features can interact with each other in fascinating ways. To cite a recent example, between 1998 and 2000 three small white spots merged to create a more substantial one. We now call this feature ‘Oval BA’. For a while Oval BA turned a dark reddish-brown colour. Then it faded. At the time I am writing these words it is still visible and has recently taken on a strongly orange hue. Much later on in this chapter you will see it in Figure 8.8 close to the feature known as the Great Red Spot, as well as in Figure 8.13 where it is shown in near-infrared wavelengths.

Thanks to long-term studies we realise that Jupiter’s atmosphere moves in vast, circulating currents and the spots are caused by eddies in adjacent jet streams. The panoply of Jovian features such as the spots may appear, develop, and then vanish in a few hours, a few days, or a few months, and the telescopic observer nearly always has a variety of interesting detail to study.

Please refer to Figure 8.2 for illustrations of the main types of features that can be visible, along with the descriptive names usually assigned to them. These are simplistic representations for the sake of clarity. The real Jovian scene is almost always rather complex. I have not included the medium- and large-sized spots in this illustration as they are obvious when visible. You might like to take some time to carefully examine the various drawings and images presented in this chapter. If so you will find plentiful examples of spots and the other types of features you can identify from their representations in Figure 8.2.

It is remarkable that the established belts and zones of Jupiter have persisted for so long. Some of the spots can also be long-lived. One famous feature that has persisted for centuries is the *Great Red Spot* (*GRS*). This

Figure 8.2 Simple representations of some common Jovian visible features. The common large spots (such as the GRS and Oval BA) plus other features can be seen in other figures in this chapter and are not illustrated here. Here, in each case the grey stripes represent sections of a cloud belt.
(a) ‘Projection’;
(b) ‘Bay’ or ‘White cloud’;
(c) Formerly ‘Oval’ or ‘White oval’, now better identified as a ‘White plume’. Usually seen extending into the EZ;
(d) ‘Festoons’. Blue features that span the EZ;
(e) ‘Garlands’ or ‘Wisps’;
(f) ‘White Spots’. Extensively seen visually across the globe in good seeing and in high-resolution images;
(g) ‘Rifts’. Really thin strands of high cloud seen over a belt;
(h) ‘Barges’. Small, dark ovals and spot-like concentrations which migrate through belts.



feature is prominently displayed in Figure 4.1, shown in Chapter 4. It can also be seen in Figures 8.4(a) and (b), 8.5(a) and (b), and 8.6(b) later on in this chapter. This is an immense elliptical area situated in the South Tropical Zone, which has been visible for at least 300 years. The first person definitely to record its appearance was the astronomer Cassini in 1665, although it is possible that an observation made by Robert Hooke in 1664 actually refers to the feature. Over a period of time the GRS exhibits changes in latitude, longitude, size and colour. Indeed, it has actually wandered several times right round the planet over the centuries it has been properly observed!

As you will see from the figures presented in this chapter, the GRS is somewhat changeable in its appearance. At some times the GRS is the darkest feature on the planet, then taking on a strong reddish hue, while at other times it becomes virtually invisible but leaves a white *hollow* in its place. Sometimes the GRS and its hollow can appear together, the GRS being slightly separated or displaced from it – a weird effect. I well remember the strikingly vivid reddish-magenta hue of the GRS in the early to mid 1970s as seen through my childhood 3-inch (76 mm) Newtonian reflector. I also remember finding it very pale and hard to see through my 18¼-inch (0.46 m) telescope early in the 1980s. The spot has darkened again since, but is still not as prominent as it was in the 1970s. In the last few years, its colour has seemed to me to be more of a muted brownish-orange rather than red. A recent change is that it has developed a darkish spot at its centre and a mildly dark rim at its edge. At the time of writing its colour has deepened once more to a strong orange, a change that has been seen before to accompany an episode of fading and subsequent re-emergence of the SEB.

Historical records show that the GRS was at its largest in the 1880s, but by the 1980s had shrunk to a length of about 26 000 km. This is about half its former value. Its width had remained fairly constant during that period at about 14 000 km, and so it became very much less elliptical than it used to be. In recent years it has shrunk some more, this time in width as well as length. Its width is now about 10 000 km and its length about 17 000 km. What changes will the next decades bring? Its current strong orange hue is probably transient. Are we witnessing the slow demise of this feature or will it one day suddenly re-invigorate to something like its nineteenth-century splendour?

Spectral analysis from the Earth showed the presence of large amounts of hydrogen, methane and ammonia in the atmosphere of Jupiter, and infrared measures had indicated that the average cloud-top temperature is in the region of −130°C. The GRS shows up as a particularly cold spot. Many theories were concocted to explain the appearance and longevity of the feature, but observations from space probes were required before we really could begin to make sense of it.

8.3 SPACECRAFT TO JUPITER

The American space probes *Pioneers 10* and *11* bypassed Jupiter in the Decembers of 1973 and 1974, respectively. A large number of coloured images were taken and radio-relayed back to Earth, as were other instrumental data. These showed that the transient small spots and the GRS are great swirling vortices in the atmosphere.

The zones and belts consist of gaseous substances plus liquid droplets and solid particles, at different altitudes and temperatures. It turns out that the zones are the highest and coldest of the atmospheric features. They consist almost entirely of frozen ammonia crystals and this explains their whiteness. At lower levels in the 1000 km-thick atmosphere the temperature is above the freezing point of ammonia. It is in these levels that most of the coloured compounds reside. So the belts are really just the lower, coloured-chemical-rich, levels that we can see down to in the gaps between the high-level white cloudbands!

If the observers of long ago had realised this then I imagine they would have called the white bands 'belts' and the darker regions in-between 'zones' – but they didn't and we are stuck with the nomenclature we now have. It does seem to me that astronomy is a subject whose nomenclature and conventions are often fettered by historical baggage.

Infrared measures proved surprising. These indicate that Jupiter radiates twice as much heat into space as it absorbs from the Sun. The collected data have been used to construct theoretical models of Jupiter's atmosphere, and these models predict that the pressure and temperature increase rapidly with depth. It is the outflowing convective heat currents that produce the differential features. In other words, gas warmed by the planet's internal heat decreases in density and consequently rises through the denser atmosphere to form an uppermost cloud deck of ammonia crystals suspended in gaseous hydrogen. At the edges of the clouds, the ammonia descends into the lower, coloured, atmospheric layers.

The rapid rotation of Jupiter (the cause of the appreciable flattening of the globe) generates forces which wrap the clouds around the planet, so producing the characteristic series of belts and zones. Dynamic instabilities result in the formation of the various transient loops and swirls, together with the spots. We think that the colours result at least in part from free sulphur and phosphorus, as well as their compounds. I must say, though, that the physics and chemistry of the Jovian colour-scheme are not as well understood as you might think they should be by now.

It is interesting to contrast our terrestrial weather systems with those of Jupiter. While incident sunlight drives most of our terrestrial weather, the source of much of the energy of the Jovian weather systems comes from within the planet. We learned much from the two *Pioneer* probes but more was yet to come from the *Voyager* craft in 1979.

American space scientists took advantage of a rare alignment of the outer planets to launch two probes that would use the gravity of each major planet to 'sling-shot' the probes on to the next. The two identical probes, *Voyager 1* and *Voyager 2*, were launched in the summer of 1977. *Voyager 1* bypassed Jupiter in March 1979, and Saturn in November 1980.

This probe then continued on its way, heading out of the Solar System and into interstellar space. *Voyager 2* passed Jupiter in July 1979, Saturn in 1981, Uranus in January 1986 and Neptune in September 1989. It too is now heading into the interstellar void.

As *Voyager 1* approached Jupiter, it became obvious that the atmospheric motions were more complex than astronomers had first thought. Small-scale vortices were seen to dominate the planet-wide picture. The counterflowing atmospheric currents and jet streams were observed in remarkable detail and a large number of cloud and spot interactions were studied.

As a result of the two *Voyager* probes, we now think that features like the GRS are *solitons.* These are solitary waves that develop as vortices between currents that flow with different velocities. The GRS appears to be a truly gargantuan anticyclonic (anticlockwise) whirlwind, which draws coloured materials up from the lower levels of the atmosphere to well above the clouds of frozen ammonia.

The radio signature of lightning from Jupiter was also detected by the craft. In fact, it soon became clear that the Jovian lightning bolts are much more powerful than earthly lightning strikes. The *Voyager* craft were highly successful, leading to a huge increase in our knowledge of the outer planets and their satellites. Next to visit Jupiter was *Galileo* . . .

After a decade of delays before its launch and a six year journey, the two-part *Galileo* spacecraft finally arrived at Jupiter in December 1995. One part – the probe – successfully parachuted into the Jovian atmosphere. The other part – the orbiter – set itself into an orbit about the Jovian planet that took it through the Jovian satellite system. Various malfunctions had troubled the spacecraft on its way to Jupiter, and much of what was planned had to be scrapped. However, some of the problems were overcome and many images (from the orbiter only) and much data have been received.

The information sent back by the probe proved particularly interesting to planetologists as this was the first time any such active device had penetrated below the clouds of one of the gas-giant planets. The probe registered an increase in pressure from 0.3 atmospheres (1 atmosphere = Earth's atmospheric pressure at sea level) near the cloud tops to 22 atmospheres at a distance of roughly 160 kilometres below that point.

The corresponding atmospheric temperatures were −144 °C increasing to +152 °C, at which point the probe ceased to function, 57 minutes after it had begun to transmit. The descending probe was swept along by winds of around 150 m/s. These were expected to lessen with increasing depth but, if anything, the reverse seemed to be the case.

The expected upper cloud layer of ammonia crystals was registered. Below this the expected clouds of ammonium hydrosulphide were also found. Below that, however, the scientists had expected to find clouds of water crystals but to everybody's surprise the atmosphere seemed to be incredibly dry, confounding the meteorologists models. Scientists also expected the probe to register the characteristic radio signature of lightning. It didn't.

There are plausible explanations for these unexpected results, and it should be emphasised that the probe has sampled only one very small location on the vast planet (it dropped through a clearing at the edge of the North Equatorial Belt), so the data it obtained were very likely atypical.

The *Galileo* mission was originally set to continue to about the end of 1997 but it was extended several times, more than making up for the original difficulties. After undertaking multiple flybys of three of Jupiter's moons, the *Galileo* orbiter was finally sent ploughing into destruction in the giant planet's atmosphere in September 2003.

The space probes have told us much but of course we amateurs are constrained to observe the planet from terra firma, so it is now about time that I turned to what we can do with the equipment we have at our disposal.

8.4 JUPITER OBSERVED BY EYE AND RECORDED BY PENCIL

The general procedures are the same as those I have detailed for making detailed visual observations and drawings of the other planets. In particular, see Chapter 6, Sections 6.5, 6.6 and 6.9; also Chapter 7, Sections 7.4, 7.5 and 7.8. Also the entirety of Chapter 2 is given over to the selection of astronomical equipment. Here I will assume that you have read at least those parts of this book and merely add a few details pertinent to scrutinising and recording Jupiter.

Using filters

Not everybody will be able to see the natural colours of Jupiter. Certainly, though, anyone should be able to notice significant differences in the appearance of the planet when it is seen through filters of differing colour. A blue filter will apparently darken reddish, yellow or brown features such as the Jovian belts. A red filter will have the opposite effect but will apparently darken any of the green and blue tinted features that sometimes appear. Green features – the polar hoods can appear greenish in tint – will show up at their apparent relative brightest when seen in a green filter. Coloured features at the threshold of vision can be rendered much more noticeable when seen through a filter of contrasting colour.

If your telescope is of small aperture then you should not use filters of too strong a tint. If the image appears too dim then any advantage in increasing the contrast of selected features will be lost. For use with a small telescope maybe an orange filter (W21, equivalent to #21 from Lumicon) and a pale blue filter (W80A, equivalent to #80A from Lumicon) might be best.

Reporting visual impressions, and particularly drawing the appearance of the planet, through specific filters is still useful even if the majority of the scientific analysis is carried out from CCD images these days. As always, it is best practice to use good-quality filters of well-established spectral characteristics, such as the Wratten series of coloured filters (or the equivalent filter set marketed by Lumicon).

The making of whole-disk drawings

The general procedures are the same as those detailed for making disk drawings of the other planets. However, a circular outline cannot be used since in reality Jupiter is markedly flattened at the poles. Most co-ordinated observing groups will issue their observers with report forms containing ‘blanks’ drawn to the correct outline. The usual scale adopted is 64 mm to the equatorial diameter of the planet. If you are really stuck then you could find a suitable high-quality drawing or image of Jupiter in a magazine (or perhaps this book!), trace its outline, then photocopy either reducing or enlarging your tracing to achieve the correct standard size of blank. Then use that as a master to run off a set of stock blanks for you to use in the future. Alternatively, you might be able to use your computer kit to print an ellipse for you of dimensions 59.4 mm×64.0 mm.

As always when you have just set your telescope pointing to a planet, experiment with the available magnifications and spend some time just looking while your eye adjusts to the Jovian scene. Begin your drawing by faintly sketching in the outlines of the largest features. Then use these as a basis for filling in the finer details, again just in outline. At this point make a note of the time. Jupiter rotates so rapidly on its axis that you must complete your outline sketch in no more than about 10 or 15 minutes from starting. If you take longer than that distortions will make themselves apparent in your representation.

Then you can spend some time filling in the outlines to their correct relative intensities and adding in the very finest details you can see. Take very special care with the widths and the latitudes of the belts. For instance, I know that I have always had a tendency to draw the equatorial belts too thin and too close together. Please see Figure 8.3 for one of my early drawings, which shows that defect. Become accustomed to critically comparing the finished drawing with the view through the

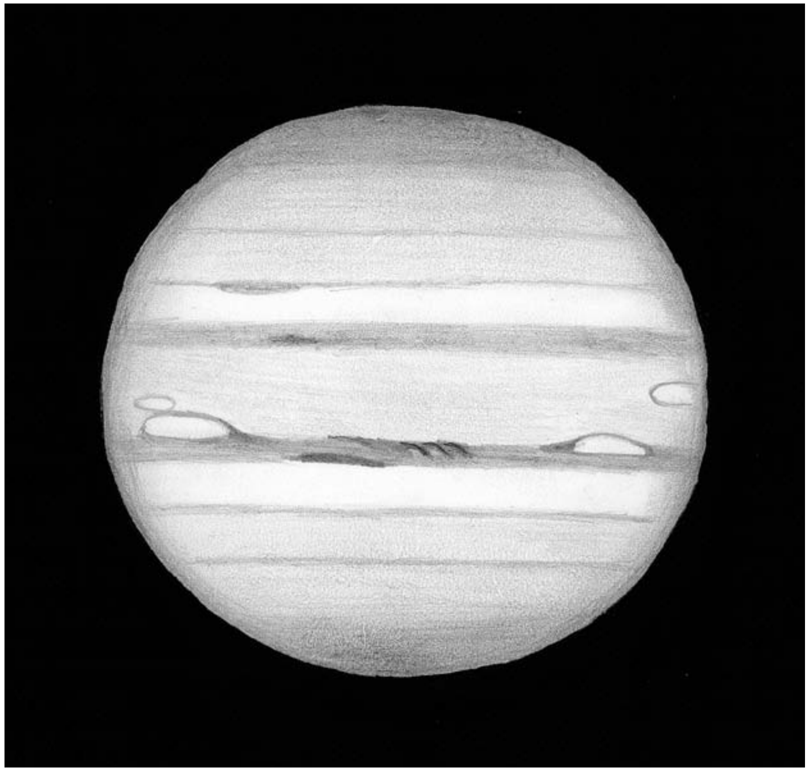


Figure 8.3 Drawing of Jupiter by the author, using his 18¼-inch (0.46 m) Newtonian reflector, magnification ×288, on 1977 December 30^{d} 23^{h} 25^{m} UT. At the time the atmospheric transparency was poor due to haze. This reduced the image contrast but the seeing was a fairly steady ANT. III.

telescope. Referring again to my drawing presented in Figure 8.3, the conditions were not good at the time but the main reason for the poor rendition was my lack of drawing ability. I got better with practice but I never achieved the artistic skill level of Robert Bullen, whose magnificent drawings are presented in Figures 8.4(a) and (b) and 8.5(a) and (b).

You will probably find that as you approach the finishing stages of your drawing you will really begin to notice the shifts in details across the disk caused by the planet's fast rotation. Unless you have made some very obvious positional errors in the first stages of your drawing please resist the temptation to 'move' the drawn features to their new positions. Provided you have been as careful as possible with the placement of your initial outlines then you should leave them as originally placed.

I find that the natural darkening of Jupiter's globe close to its edge, known as *limb darkening*, is really quite difficult to appreciate when seen visually at low magnifications. It becomes more apparent at higher powers. Yet it is very obvious in photographs. The discrepancy is due to the contrast of the bright limb of the planet against the dark sky background offsetting the actual limb darkening present. This is a sharp

(a)

Figure 8.4 Robert Bullen's superior drawings of Jupiter made using his 8½-inch (216 mm) Newtonian reflector, with a magnification of ×216. Green, yellow and orange filters were used during each session to help him see and record the maximum amount of detail. (a) 1999 October 25^{d} 22^{h} 35^{m} UT, using a magnification of ×216;

reminder of just how subjective human vision is. I always try to represent the amount of limb darkening in my drawing with the amount I see at the magnification used for making it. To represent the effect I very lightly shade close to, and up to, the edge of the planet's disk with a soft pencil and then use the end of a finger – mostly running round the edge, though when necessary rubbing inwards – to smudge the shading.

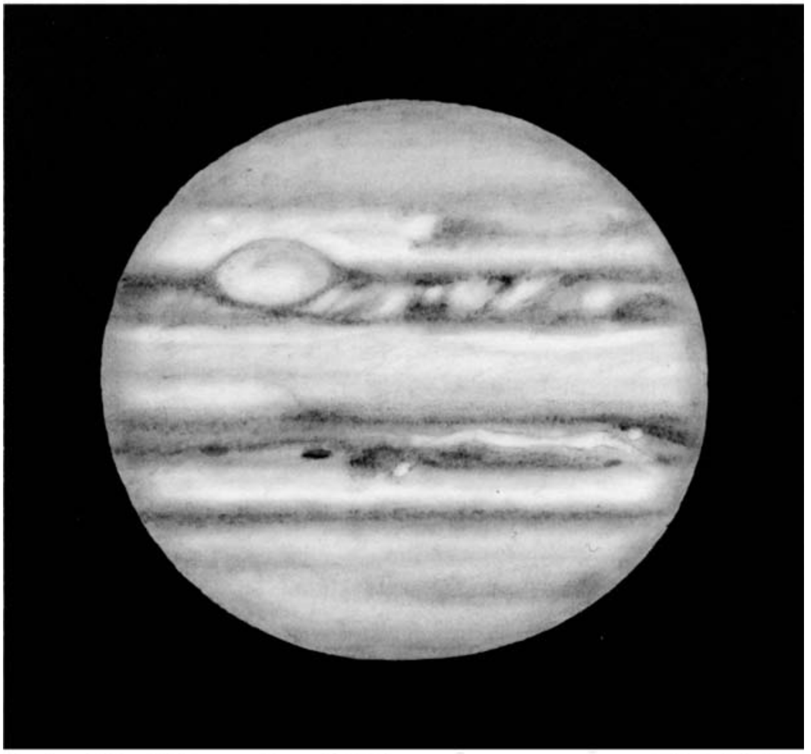
As ever, please do remember to include all the relevant details with your observation (as detailed in Chapter 6, Sections 6.5 and 6.6).

8.5 PHOTOGRAPHING JUPITER

Chapters 3 and 4 in this book cover the methods of photographing the Moon and planets, so here I will add only a few extra details pertinent to imaging Jupiter. The Jovian world presents us on Earth with a large and bright disk containing well-contrasted detail, so it is undoubtedly the

Figure 8.4 (*cont.*) (b) 2001 December 22^{d} 22^{h} 28^{m} UT, using a magnification of $\times 216$ and $\times 266$. Notice the dramatic alteration in the appearance of the planet over a period of just 13 months.

(b)



Date: 22nd December 2001 U T 22.28

Longitude for C M System 2: 103.4°

easiest of the major planets to image. Mind you, there is one difficulty that the astrophotographer has to face. Jupiter's limb darkening and the absence of reliably sharp-edged features on the disk of the planet make achieving the best focus a little tricky. Yes, you can certainly set half way between equal amounts of slight defocus. However, there is something handy to focus on – Jupiter's four brightest moons. I shall be discussing them more fully later in this chapter but suffice it to say for now that one or more of Jupiter's moons are always visible against either black sky or against the disk of the planet. They present tiny disks, between 1 and 1.7 arcseconds across. It is a rare thing that at least one of them is not visible against black sky close to the planet and this makes them an ideal aid to focusing.

To see them clearly with a webcam or other fast-frame-rate camera you might have to momentarily turn up the gain while you are adjusting the focuser. Jupiter will then be rather bleached out. Your aim is then to get the target moon looking as small as possible, whether or not your

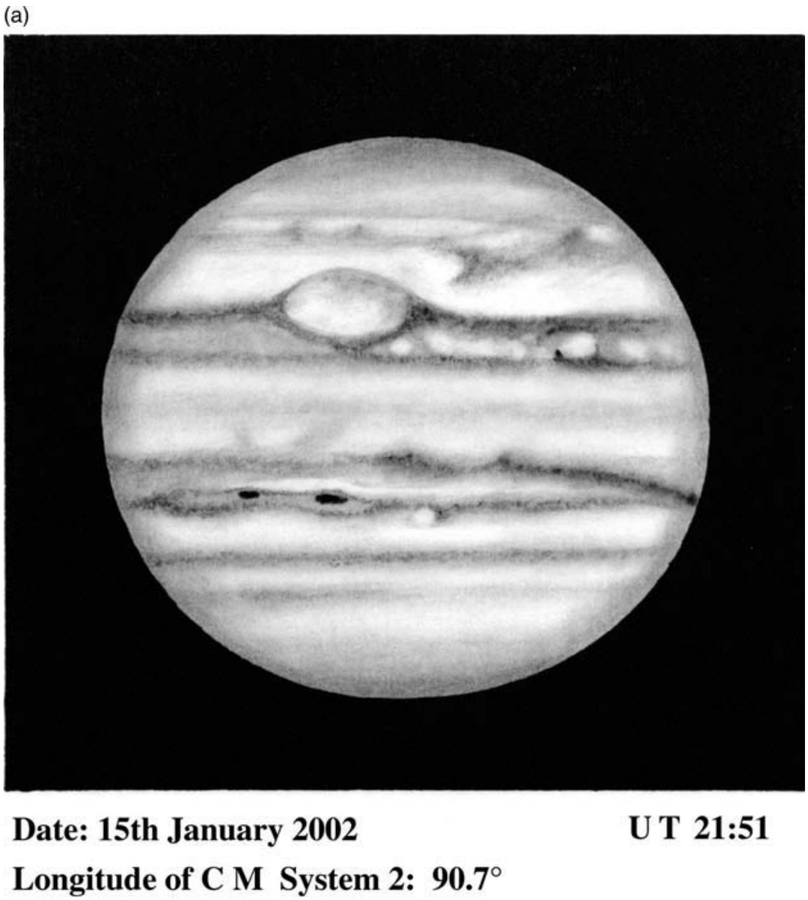


Figure 8.5 A pair of Robert Bullen's superb drawings of Jupiter just a couple of weeks apart, showing dramatic changes in that short space of time. He made both using his 8½-inch Newtonian reflector and during each session employed coloured filters to help him see and record the maximum amount of detail. (a) 2002 January 15^{d} 21^{h} 51^{m} UT, using yellow, green and blue filters and magnifications of ×216 and ×266;

set-up and the conditions will allow it to be clearly resolved as a disk. Once you are happy, you can reset the gain and adjust the other imaging parameters under your control to optimise for imaging the planet.

Of course you can take single images of Jupiter if you wish to but the best results will always come from taking AVIs and stacking and processing the results in software such as *RegiStax* or *AviStack*. However, there is a potential problem caused by Jupiter's rapid rotation. Any complete run that lasts longer than about 2 minutes (that includes the total time span for the individual exposures taken through the separate colour filters) will result in an east–west image smear of about half an arcsecond at Jupiter's equator. You might even generate coloured fringes to the borders of a feature as it moves between separate exposures through each filter. Still, Jupiter is plenty bright enough to set your camera to short exposures and a rapid frame rate and so you should not need long AVIs to generate up to a thousand individual frames. That should be enough to give you plenty of good frames for the software to stack.

(b)

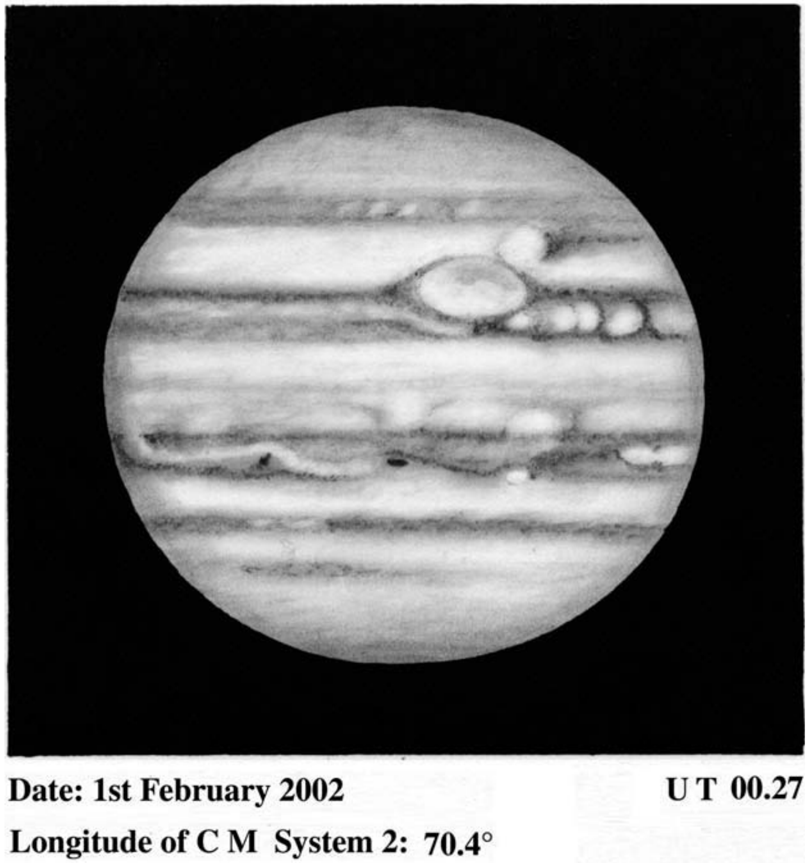


Figure 8.5 (*cont.*) (b) 2002 February $01^{d}\ 00^{h}\ 27^{m}$ UT, using green and yellow filters and magnifications of $\times 216$ and $\times 266$.

Two-minute runs ought to be plenty, provided you include a filter wheel or slide-mount plugged into the telescope drawtube before the camera. Taking the camera out each time to screw in the next filter and refocusing, etc. will certainly not allow you to complete an RGB or LRGB run within 2 minutes. Of course using a full-colour webcam or other camera will avoid this problem but you will still need to keep the AVIs to within the 2-minute limit. I must say, though, that the world's premier planet imagers, such as Damian Peach, Christopher Go, Eric Ng, *et al.*, all go down the LRGB or RGB route.

A monochrome camera will also allow the use of a methane-band (such as 893 nm) near-infrared filter to obtain instructive methane absorption images of the Jovian atmosphere. More about that in Section 8.11. You can also take monochrome images through specific coloured filters in order to bring out details of contrasting colours in the same way you can visually.

All the foregoing illustrates how the chasm that used to divide professional and amateur observers of the Solar System has been spanned in

(a)

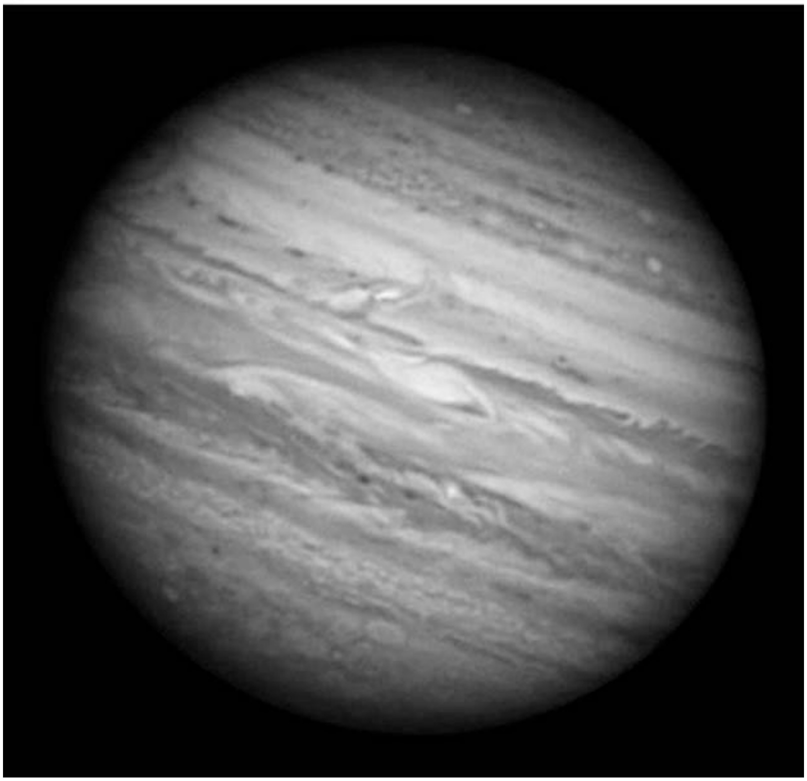


Figure 8.6 Jupiter imaged by Damian Peach from Barbados. He used his 14-inch (356 mm) Schmidt–Cassegrain telescope, working at f/33, and Lumenera SKYnyx camera with a RGB filter wheel. The images were captured, stacked and processed in *RegiStax* and further processed in *Adobe Photoshop* and finally *Paintshop Pro*. (a) 2007 May 25^{d} 04^{h} 28^{m} UT;

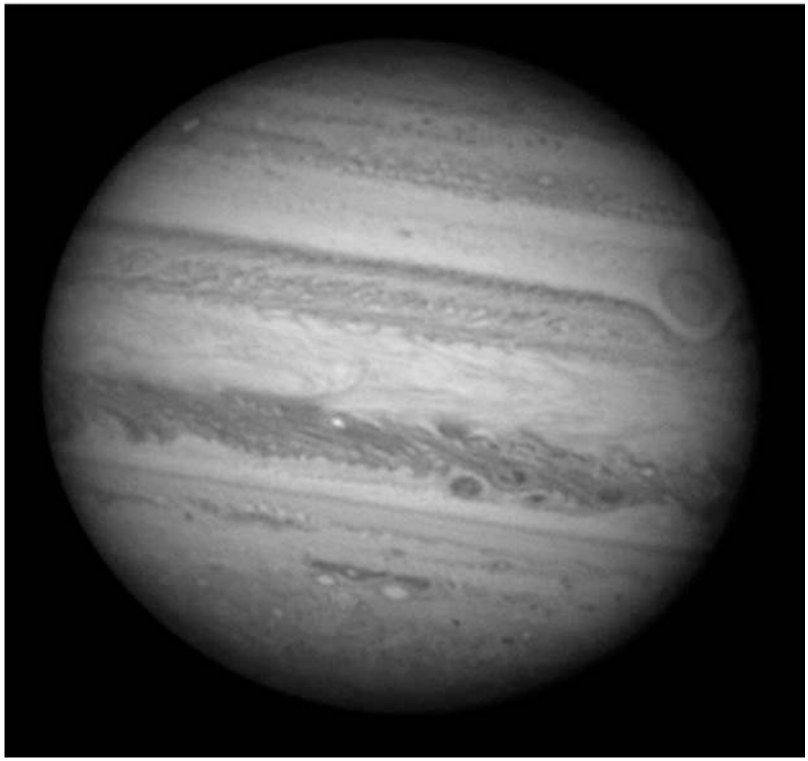
modern times. The high-resolution-imaging revolution that swept through the amateur astronomy scene just a few years ago has allowed amateurs to study the Jovian jet streams, eddies and other atmospheric phenomena in the level of detail that was only possible from the space probes of previous decades. If you can submit images of high enough quality to the BAA, ALPO, or other national observing group then you can be assured that your work will certainly be used for amateur and professional studies of Jupiter and the other Solar System bodies. For a small sample of Damian Peach's stunningly good images of Jupiter, see Figures 8.6(a) and (b), 8.7 and 8.8 together with Figure 4.1 back in Chapter 4. You'll also find plenty more images in his 'Views of the Solar System' website.

8.6 CENTRAL MERIDIAN TIMINGS AND STRIP SKETCHES

The director of the Jupiter observing section of your national astronomical society will, as part of his/her job, be busy analysing all the high-quality images of Jupiter he/she receives. One line of work is to establish latitudes and longitudes of particular Jovian features and to track their

Figure 8.6 (*cont.*) (b) 2009 August 31^{d} 02^{h} 56^{m} UT.

(b)



movements over time. The observing-group director will do this using the best images imported into the database of a software suite such as *WinJUPOS*. If you are interested you can also carry out such measurements on your own results. You can also use *WinJUPOS*, or perhaps you might prefer a more old-fashioned approach to your analysis . . .

For instance, well before the advent of computers, amateurs determined the longitudes of features by noting the precise time they crossed the north–south line that joins the poles of the planet. This line is properly known as the *central meridian*, often abbreviated to *CM*. Each time on a given date corresponds to a certain Jovian longitude.

A table in a current ephemeris (for example *The Handbook of the British Astronomical Association*) gives the longitude on the central meridian as zero hours UT on the day in question and a subsidiary table allows one to work out the precise longitude on the CM at the exact time the feature of interest was on it. One complication is that, as already noted, the apparent rotation rate of Jupiter's cloudy mantle varies with latitude. Consequently, a workable 'fudge' has long been settled on.

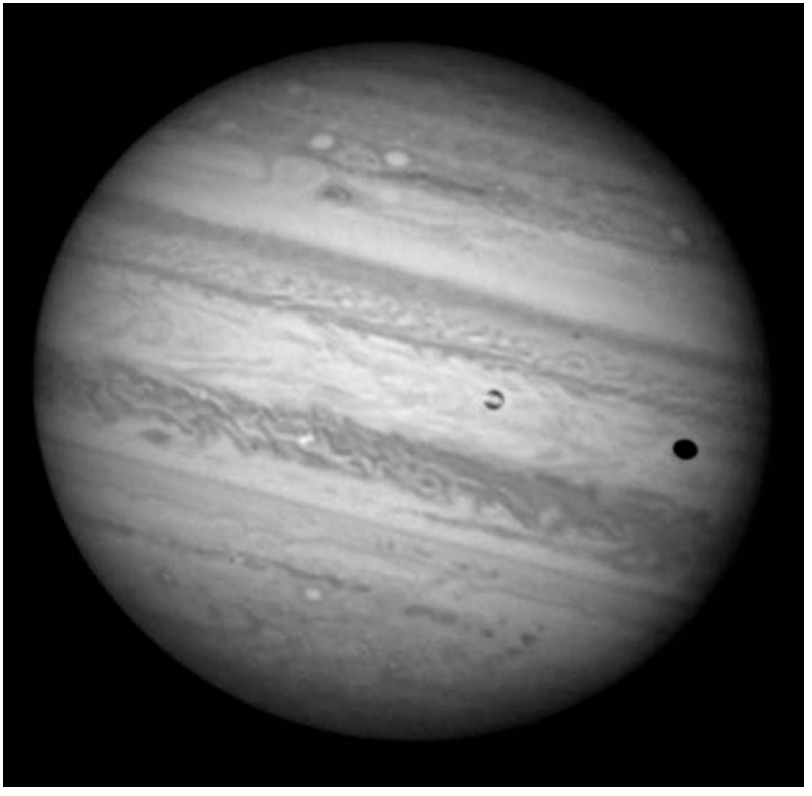


Figure 8.7 Jupiter, with satellite Io transiting the giant planet, imaged by Damian Peach from Barbados on 2009 September 11^{d} 03^{h} 35^{m} UT. Equipment details are the same as for Figure 8.6. Some of the broader details are visible on the disk of Io and its black shadow can be seen on the right of this image. This shadow is ovaled by the rotundity of the planet. [This image is also reproduced in colour as Plate III between pages 304 and 305].

In order to define Jovian longitudes two co-ordinate systems, *System I* and *System II*, are used.

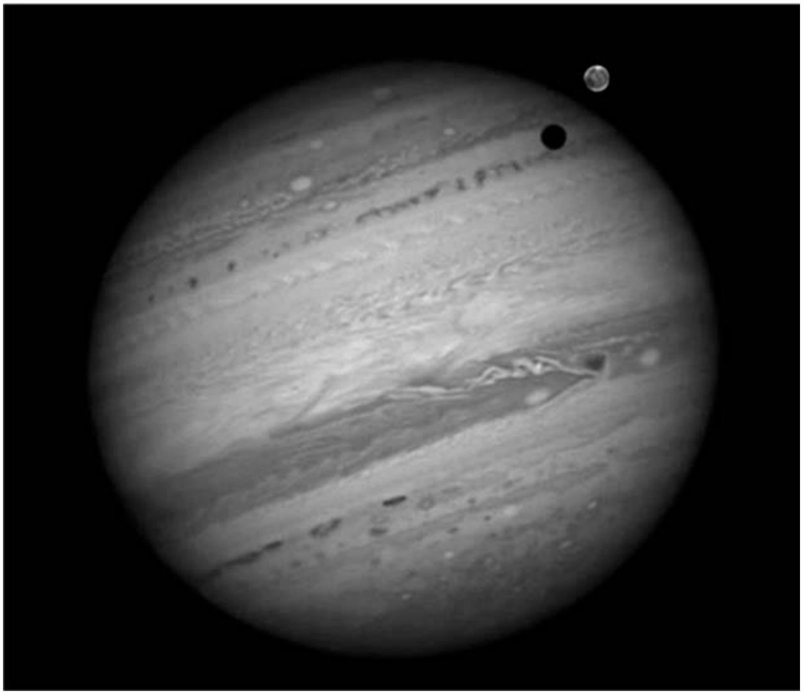
System I operates in the Equatorial Zone of Jupiter, including everything from the southernmost edge of the North Equatorial Belt and from the northernmost edge of the South Equatorial Belt and encompassing the Equatorial Zone in-between them. This is a range of Jovian latitude spanning from roughly 9°N through the equator to 9°S. System I is based on an average motion of once round the planet in 9 hours 50 minutes and 30 seconds. The rest of the planet is taken to rotate at an average rate of 9 hours 55 minutes and 41 seconds, this defining System II.

So, your first task is to decide whether a feature on Jupiter should be included in the System I zone of longitudes or the System II zone. In the ephemeris you will find tables of figures for each. For this work use an eyepiece with as high a magnification as you can that still gives a fairly sharp and reasonably contrasted image of the feature you are interested in.

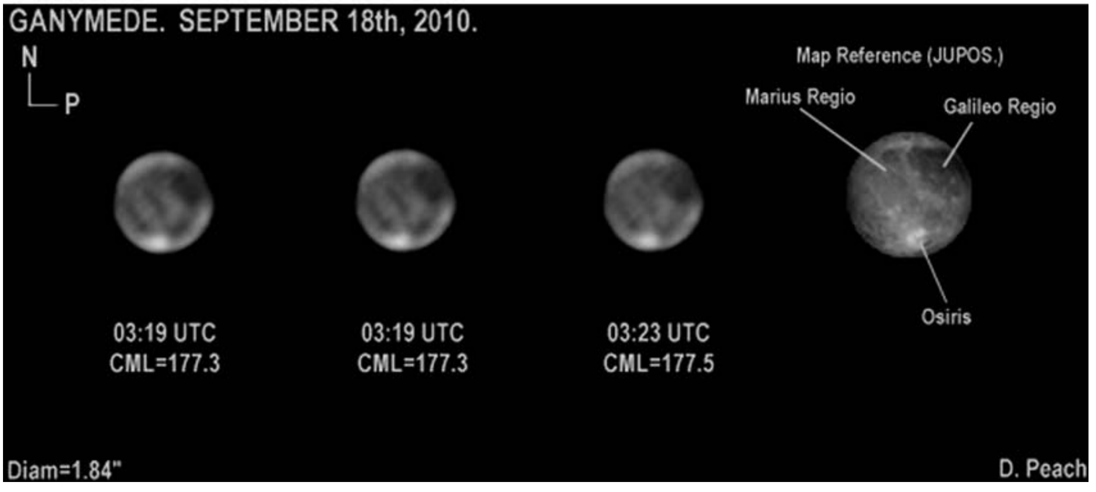
You should find that you are able to conjure in your imagination a thin black line that spans from pole to pole. Of course, if you have

Figure 8.8 (a) Transit of Ganymede across Jupiter imaged by Damian Peach on 2010 September 18^{d} 04^{h} 10^{m} UT using his 14-inch (356 mm) Schmidt–Cassegrain telescope and a Barlow lens to project the image to f/33 into a Lumenera SKYnyx camera and RGB filter wheel. (b) Many of the main albedo features are visible in this sequence taken by Damian in the same imaging run as for (a). Damian created this panel displaying Ganymede with some of these features labelled and compared to a labelled *Voyager* image of the satellite (the latter by courtesy of NASA). [Figure 8.8 (a) is also reproduced in colour as Plate IV between pages 304 and 305].

(a)



(b)



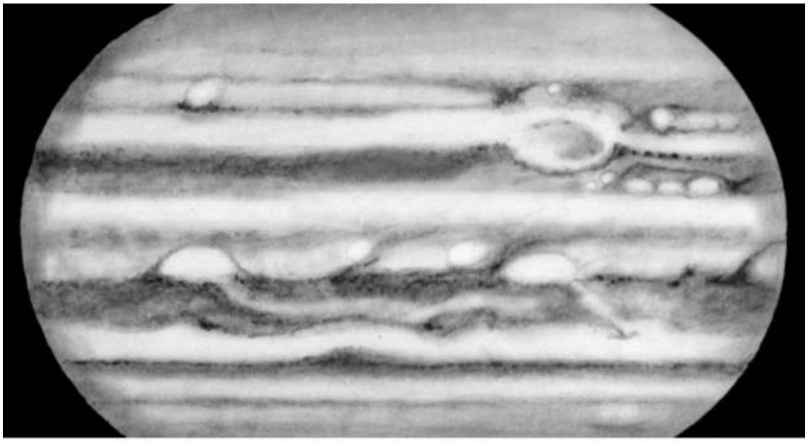


Figure 8.9 Strip sketch of Jupiter by Rob Bullen.

a suitable crosswire eyepiece and the drive of your telescope is good and steady then you can use an actual thin black line to mark the CM. Believe it or not, though, with a little practice you can get results that are just as accurate using your imagined black line!

You watch the feature approaching the CM and at the instant you judge the feature to be on the line note the exact time. If you make sure the timepiece you use is set and running accurately – check it before and after the observing period – then you can potentially get the time of CM crossing accurate to about a minute. That will potentially allow you to calculate the Jovian longitude of the feature to an accuracy of about $\pm 0^{\circ}.6$.

Another long-established practice of visual observers that a few still carry out is the creation of *strip sketches*. Instead of making a full disk drawing, the observer draws just the north–south strip of the planet as it crosses the CM. The observer continues the process, drawing more as more of the planet crosses the CM. The new details are added from left to right on the drawing, the position corresponding to the time that part of the drawing is made. The result is a band of Jupiter drawn free of the distortion that arises from the rotundity of the planet. The whole range of latitudes going almost from pole to pole could in theory be drawn, or maybe just a small range that includes some particular feature of interest. Recording the times on the strip sketch allows the System I and System II longitudes to be subsequently calculated.

Figure 8.9 shows a strip sketch prepared by Robert Bullen. This method does require a particularly long observing session to record a broad range of longitudes. Certain software suites such as *WinJUPOS* can re-map and re-scale individual images to produce the same effect as strip sketches. Individual portions can then be stitched together to create a full 360° strip map of the planet (see Figure 8.10). In theory you could do the same with your disk drawings as the source, using a geometric drawing technique called cylindrical projection. I will leave you to research this last technique for yourself as space here is pressing and not many visual observers do this anymore.

8.7 LATITUDE MEASURES

Until late in the twentieth century, a few suitably equipped amateur astronomers employed a device variously called an *eyepiece micrometer*, or *filar micrometer*, or *bifilar micrometer* to measure the latitudes of features on planetary surfaces. I doubt very much that anybody is still determining latitudes this way. If you are interested in this technique could I refer you to my book *Advanced Amateur Astronomy* (published in its second edition by Cambridge University Press in 1997).

As already noted, the various planet observing directors of your national astronomical association will be busy using computer software applied to the best of the images they receive in order to measure latitudes and longitudes of features. You can do the same with any of your images or scanned-in drawings. Again, as already noted, there is a particular piece of software called *WinJUPOS* that will enable you to do this. However, I should warn you that using it involves climbing a rather steep learning curve. Here is a website that will enable you to find a good user's guide to *WinJUPOS* plus a link to download the software for your own use:

alpo-j.asahikawa-med.ac.jp/Latest/WinJUPOS/winjuposcuide_english.html

I think it might be useful for some readers if I present a simple low-tech alternative way for you to find latitudes on your drawings or your photographic images. To avoid marking your original drawing or image your first step ought to be either making a copy of it or marking a thin black line down the centre of an acetate overlay sheet. If you are using an overlay sheet align the marked thin black line with the CM of the planet. In the case of Jupiter you can use the east–west run of the belts and zones to estimate the position of the CM. If you are working on a copy of the original image or drawing then use a plastic ruler to help guide a sharp pencil to the correct position and draw in the CM.

Please refer to Figure 8.11 for the measures needed to deduce the latitude, θ, of a particular feature, *J*, on the planet. First measure the pole-to-pole diameter, *D*, of the planet along the CM. Then measure the distance,

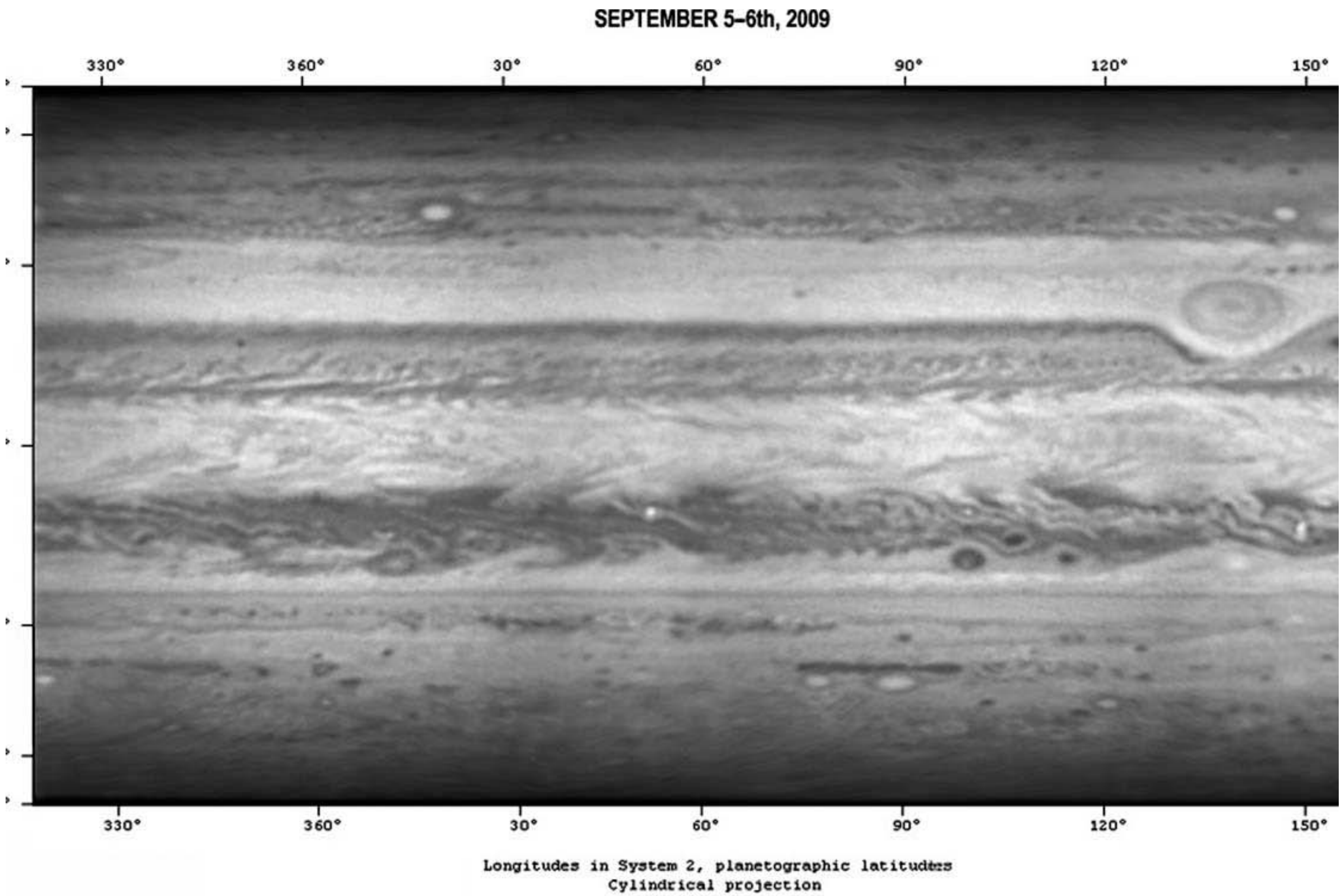


Figure 8.10 Cylindrical projection map of Jupiter constructed by Damian Peach from his images.

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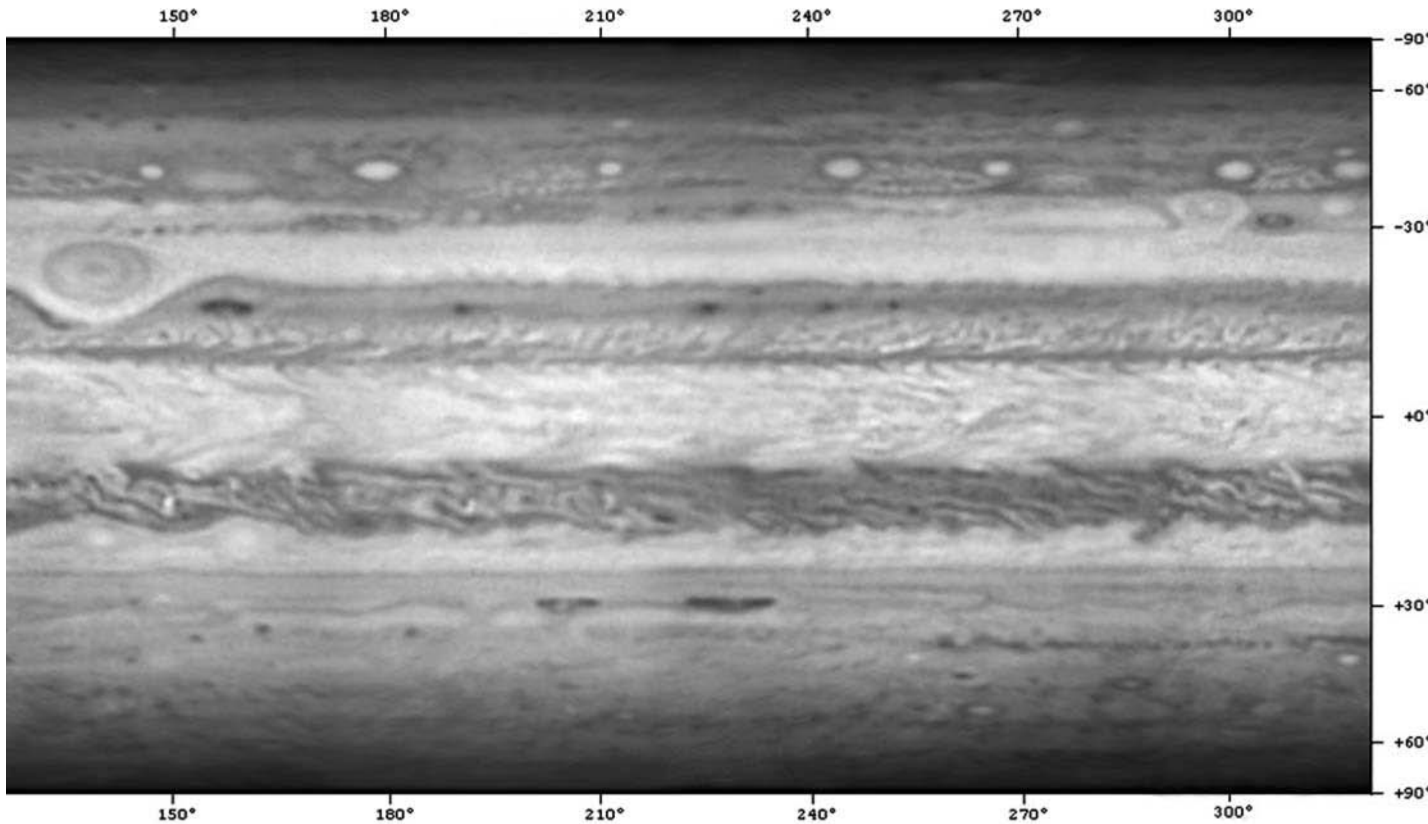


Longitudes in System 2, planetographic latitudes
Cylindrical projection

D. Peach

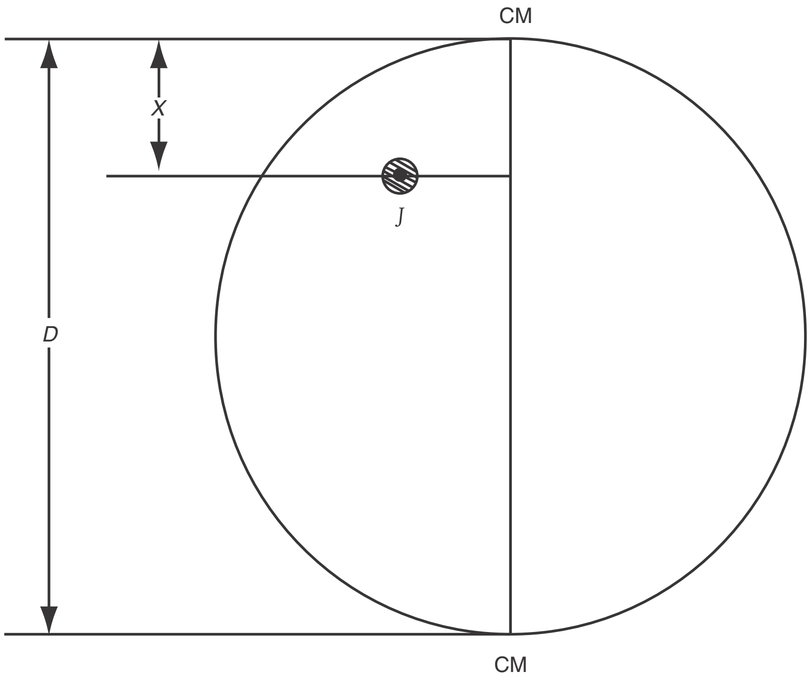


Figure 8.11 A simple manual procedure for finding planetary latitudes from a drawing or image. This method is applicable to any planet. The central meridian of the planet must first be established. This is marked CM on the diagram. D on this diagram is the polar diameter of the planet, as measured along the CM. If J is the location of a particular feature then the distance from the nearest pole to J is measured (by projection) along the CM. This is marked as X on this diagram. A simple calculation plus one correction will determine the latitude of the feature at J as described in the main text.

X, along the CM from the nearest pole to the feature J. At this point make a rough estimate of the latitude of the feature but ignore any negative sign. You will be using this rough value, θ_{est}, in the following equation:

$$\sin\theta = \frac{2\left(\frac{D}{2} - X\right)}{D + 0.07D\cos\theta_{est}}$$

Notice that the value of θ_{est} makes only a very small difference to the final value of the required latitude, θ. So, unless your initial estimate is greatly in error, it should not produce much error in the final answer. If you are worried about this simply repeat the calculation again using the latest value of θ as the new value of θ_{est}. You will find your new answer varies very little from your first. Any remaining error due to this factor in the calculation is likely to be less than errors in your measurement.

Of course, the equation gives $\sin\theta$ as the answer, so you have not quite finished. You need to input the number and press the 'arc sine' button on your calculator (this may alternatively be labelled '$\sin^{-1}$') and the correct answer should be displayed in degrees. Make sure you know which hemisphere of the planet feature J is in. If J lies north of the equator then its latitude is positive. If it is in the southern hemisphere its latitude is negative.

Actually, you have still not quite finished. The final step is to allow for the tilt of Jupiter's rotation axis towards or away from us. You will find the axial tilt in any common ephemeris (such as the annual *Handbook of the British Astronomical Association*, free to members and purchasable at a small cost by non-members). If you look up the value of tilt for the observation date you will find it has a **positive** value if the **north pole of Jupiter is tilted towards us** and a negative value if the north pole is tilted away.

As an example, if the value of θ as given by the equation is 30°, the feature lies in the southern hemisphere (so the value of θ is negative) and the tilt of Jupiter's axis at the time of the drawing/image is $+3°$, then the actual latitude of the feature is $-30°+3°$. Of course this is equal to $-27°$.

When presenting latitudes in your written notes you can either use a negative sign for southerly latitudes or alternately add the 'S' (for instance, $-23°$ or 23° S). Using 'S' or 'N' does have the advantage of reducing the chance of scripted errors or ambiguities creeping in.

The figure of '0.07' that appears in the bottom line of the equation is the fractional amount that the polar diameter of Jupiter is less than its equatorial diameter. Provided you substitute the correct figure in each case you can use this same method to find the latitudes of any features on any of the other planets (or indeed the Sun or the Moon if you have whole-disk images of them).

8.8 THE GREAT ORB OF JUPITER, ITS MAGNETOSPHERE AND ITS RADIATION BELTS

We believe that the overall composition of Jupiter is very similar to that of the Sun – roughly 90% hydrogen and 10% helium, with minor amounts of other elements and compounds. Using this as a basis we can theorise about the structure within. Various measures from the space probes have helped refine the theoretical models but I should add that the precise details are nowhere near as certain as you will find reported in most popular astronomy books.

We are sure that the gaseous envelope of hydrogen and hydrogen compounds extends down to a depth of about 1000 km below the cloud tops. Both the pressure and the temperature increase with depth. At this level is a planet-wide ocean of liquid hydrogen. The pressure at this depth is reckoned to be about 5600 atmospheres and the temperature something around 1700 °C. At a depth of about 23 000 km, where the pressure and temperature have increased to 3 million atmospheres and 12 000 °C, the liquid molecular hydrogen changes to its liquid metallic state. In this form, hydrogen behaves rather like a metal in that it can conduct electricity.

We think that there is a solid core at the center of Jupiter, with a mass perhaps 14 to 18 times that of the Earth. It probably comprises a rocky body something like 14 000 km across, with a layer of 'ices' on top of it. Bizarrely, these ices remain solid because of the huge pressure, despite the high temperature. This ice layer might be about 7000 km deep. The metallic hydrogen zone probably extends down to this core, where the temperature probably reaches about 30 000 °C and the pressure reaches a staggering 100 million atmospheres.

The acceleration due to gravity at the visible surface of Jupiter is 2.6 times that at the surface of the Earth. Put in more familiar terms, this means that if it were possible for you to somehow stand on Jupiter's visible surface you would weigh 2.6 times as much as you do on Earth! Jupiter's strong gravity has prevented much of its primordial atmosphere from leaking away into space. Consequently the composition of the planet has not radically changed in the 4.6 billion years since its formation.

As might be expected from its metallic hydrogen mantle and its rapid rate of rotation, Jupiter has a magnetic field of a similar overall structure to the Earth's field but on a far grander scale. The magnetic-field strength at Jupiter's cloud tops is 12 times that at the surface of the Earth. The vast magnetosphere extends from 25 to 50 times the diameter of Jupiter in the sunward direction, whilst the magnetotail extends the other way to well beyond the orbit of Saturn. As is the case with the Earth's magnetosphere, the gusty solar wind causes variations in the shape and size of Jupiter's magnetic field, though the variations are greater for Jupiter.

In the same manner as does the Earth's magnetic field, the Jovian field traps particles to form enormous radiation zones around the planet. In the case of Jupiter, the zones extend out to about ten times the planet's diameter. The maximum radiation intensity is 10 000 times stronger than the peak intensity within the Earth's Van Allen zones. *Pioneer 10* came close to being put out of action by the intense radiation, and *Pioneer 11* was rerouted to carry it over the south pole of Jupiter and so pass through the most dangerous regions as rapidly as possible.

8.9 JUPITER'S MAIN SATELLITES AND FAINT RING

Use a small telescope to observe Jupiter over a period of a few nights and it will be obvious that at least four moons, or satellites, orbit the planet. Galileo was first to declare that he had discovered them in January 1610. However, in 1611 Simon Marius of Germany announced that he had independently discovered them in late 1609. The honour of discovery has been shared since they became known as the *Galilean satellites* and have the names given to them by Marius: Io, Europa, Ganymede and Callisto.

These Jovian moons are bright and are easily seen through a good pair of binoculars that are very steadily held. Their apparent magnitudes are: $4^m.9$ (Io), $5^m.3$ (Europa), $4^m.6$ (Ganymede) and $5^m.6$ (Callisto). If it were not for the overpowering light of Jupiter they would all be visible with the unaided eye. Indeed, some people with exceptionally good eyesight have reportedly seen one or two of the satellites alongside Jupiter with no optical aid.

On most nights the Galilean satellites can be seen strung out in a line passing through the equator of Jupiter and extending out to several Jupiter-diameters east and west from it. They all orbit at different distances from their parent planet and so move round with different orbital periods. Hence, the satellites are constantly changing their configurations.

At various times they each pass behind the disk of Jupiter, going west to east, as seen from the Earth. They are then said to be *occulted* by the planet (and sometimes by Jupiter's shadow, as this can extend a little to one or other side of the planet as we see it from Earth). The satellites are said to *transit* Jupiter when they pass from east to west in front of its disk. For an example of a transit of Io across Jupiter's disk please refer back to Figures 8.7 and 8.8. The satellites can even, though rarely, occult and transit one another.

The nightly dance of the satellites and their various occultations, transits and rare mutual events are great fun to watch. Ephemerides and planetarium software animations exist aplenty, so you can always keep track of what is going on within this mini version of the Solar System. These days, though, there is no new science to be obtained from amateur observations and timings of the motions of the Jovian moons.

Telescopes of around 8 inches (203 mm) aperture and above can show the Galilean satellites as definite, though tiny, disks since they all subtend apparent diameters of 1 arcsecond and above as seen from the Earth. A good telescope of as little as 4 to 6 inches (102 to 152 mm) aperture will show the shadows cast by the Galilean moons onto Jupiter's cloud tops (see again Figure 8.7). A few adequately equipped visual observers can just about make out some definite markings on some of Jupiter's satellites. Further, the 'webcam revolution' of just a few years ago allowed convincing albedo features to be recorded in the very best amateur images (see again Figures 8.7 and 8.8 – also Damian Peach's 'Views of the Solar System' website).

In ephemerides, the satellites are often listed as Roman numerals, rather than by name. In the case of the Galilean satellites they are listed in order of increasing orbital radius. Hence we have I (Io), II (Europa), III (Ganymede) and IV (Callisto). Additional, much fainter, satellites were discovered from 1892 onwards and by the mid-twentieth century the total stood at 12. By the late 1990s, the total had increased to 16 and at the time I write these words improvements in detection techniques have led to an avalanche of further discoveries and the total now stands at 63. Please be aware that this total might have further increased by the time you are reading these words.

Most of Jupiter's moons are rather small, insignificant, bodies just a few kilometres across. However, the Galilean satellites are truly world-sized orbs. Indeed the smallest of them, Europa, is only slightly smaller than our Moon while the largest, Ganymede, is a little bigger than the planet Mercury.

The satellites can be divided into three groups, according to their orbital properties. Closest to the planet there is a cluster of satellites that include the Galileans. They all have fairly circular orbits, which lie in the same plane as the planet's equator. This group ranges from the small body discovered by the *Voyager* research scientists in 1980, orbiting at a mean distance of 128 000 km from Jupiter, to Callisto, orbiting at nearly 2 million km from the planet.

The second group consists of bodies orbiting at mean distances on average about 12 million km. Their orbits are much more eccentric than the inner satellites, as well as being steeply inclined to Jupiter's equatorial plane.

The third group of satellites orbit Jupiter at mean distances of 20 to 24 million km. They also have highly eccentric and steeply inclined orbits but are rather odd in that they orbit Jupiter the 'wrong way', technically in the *retrograde*, direction. It seems likely that the outer members of Jupiter's satellite family did not form with the planet but were later captured when they wandered into its gravitational influence.

One of the more unexpected discoveries arising from the *Voyager* missions was that a faint and tenuous ring surrounds Jupiter. The outer edge of the ring, where it is brightest, extends to about 126 000 km from the centre of Jupiter. This is roughly 1.6 times the radius of the planet. The ring seems to be composed of fine rocky particles. Each of the particles orbits Jupiter separately but all are in the equatorial plane of the planet. These give the appearance of a flat, if rather transparent, sheet when seen from a distance.

Forgive me offering such scanty details about Jupiter's extensive satellite system and its faint ring but in this book I must devote the available space to matters which are of relevance to you, the ground-based telescope user, and pretty much ignore all else. The Galilean moons are observable with even the smallest telescope so, of course, I will describe them in some detail in the following notes. Even here, though, I must be brief, despite the fascination of these exotic little worlds and the knowledge we have gained so far. While the best imagers using the best techniques and equipment have managed to just about record the coarsest details on these four largest moons, to most observers and particularly to beginners, they are just four points of light that can sometimes look like the tiniest of disks in good conditions through a moderately large amateur telescope. The space I devote to them in this book has to reflect that fact, even though I would have loved to present many pages of description and space probe photographs instead. For those, can I point you towards the Internet and your favourite search engine. Alternatively, the most recent book about Jupiter's satellites at the time I am writing these words is the large and expensive *Atlas of the Galilean Satellites* by Paul Shenck, published by Cambridge University Press in 2010.

Io

Io orbits Jupiter at a mean distance of 421 600 km, with a period of 1¾ Earth-days. Actually, it goes around Jupiter exactly four times in the time that Europa goes around twice and Ganymede goes around once. So, on every fourth orbit that Io makes it finds itself lined up with Jupiter on one side and both Europa and Ganymede on the other. You can imagine the flexing that Io would experience under the gravitational forces from these other bodies at any time that they pass at their closest to Io and especially at this time of alignment. The same forces also pull Io's orbital path slightly out of shape and this generates a further tidal effect on the body of Io. The internal heat energy liberated within Io has consequences . . .

Io has a diameter of 3642 km and a density of 3530 kg/m^3. This makes it the most dense of the Galilean satellites. From the Earth, Io looks distinctly yellowish but little in the way of surface detail can be seen on its 1.2 arcsecond diameter disk. *Voyager 1* revealed Io to be a spectacular world. Many of the earliest published pictures of the planet display the overall colour of the surface as orange with patches of various shades of gaudy red, yellow and black as well as glistening white deposits. However, these are enhanced colours and the true tones of mostly pinkish- and greenish-yellows and oranges, with mauvish-white deposits covering large areas. The surface is mainly covered in sulphur, traces of the various allotropes of this element producing some of the different shades. Black silicate lava flows are also evident and the greenish colourations are thought to result from areas where the lavas and sulphur mix.

Erupting volcanoes were in evidence at the time of the *Voyager* mission and are seen again from the *Galileo* orbiter, as well as from the *Hubble Space Telescope* and have also been detected from Earth-based telescopes in recent years. The absence of impact craters indicates that the surface of the satellite is very young. Enormous plumes of sulphur dioxide spray from the erupting volcanic vents and flowing lavas (a melt of silicate rocks originating from the mantle, though also rich in sulphur) continually modify the landscape. Our space probes have witnessed many significant alterations to the surface of Io over the past decades.

The *Galileo* orbiter has found that Io has a magnetic field. This fact, and the density of Io, suggests that it is has a large, iron-rich, core. Tidal forces set up by Jupiter and the other satellites cause frictional heating in this core and in the body of the planet. This heat causes the volcanism. The white surface deposits are thought to be frozen sulphur dioxide, and a cloud of sulphur vapour has been detected about Jupiter, concentrated in a toroidal belt which marks the orbit of Io. The bombardment from particles in the radiation zones (Io moves through one of the more intense zones) undoubtedly causes some of the surface deposits to be splattered into space. Sodium has also been detected in the plasma torus.

Io has no appreciable atmosphere and the radiation bombarding its surface makes it one of the most lethal places in the Solar System. With its erupting sulphur and lava volcanoes, Io really is a world like any that might be conceived in the mind of a science-fiction novelist.

Europa

With a diameter of 3130 km, Europa is the smallest of the Galilean satellites. It orbits Jupiter at a mean distance of 670 900 km, taking 3½ days to go once round. The mean density of this satellite is 3010 kg/m^3 and it is thought to have a silicate core. The albedo of Europa is 0.64, slightly greater than that of Io (0.63) and it has a pale brownish surface of ‘dirty ice’ (ice contaminated with rocky materials).

Europa’s surface is incredibly smooth with very little vertical relief. It is also virtually devoid of craters (indicating that the surface we see today is very fresh) but it is covered by a network of crack-like fissures, with each crack filled in with more of the dirty ice. Mostly the infill is of darker ice but sometimes the infill is of lighter-coloured ice.

It seems very likely that the icy surface of Europa floats upon a deep sub-surface ocean of water (and most likely salt water). Magnetic data obtained from the *Galileo* orbiter do lend support to this idea. The in-filled cracks enclose what are effectively huge ice-rafts.

Europa's very slightly elliptical path about Jupiter (and periodic alignments with Jupiter and the other Galilean satellites) are enough to cause frictional/tidal heating of its interior. It is this that will have created the sub-surface ocean on this little body in the otherwise frigid zone of the Solar System. The tidal flexing of the surface produces the cracks that lets some of the liquid water begin to seep to the surface before some of it volatises in the vacuum and the rest freezes over to re-seal the crack.

What are the conditions existing in the sub-surface ocean? Might we expect some geothermal activity on the ocean floor, as is so very common on Earth? Many exotic lifeforms exist around the sites of earthly geothermal vents by virtue of the heat energy released by them, despite the toxic and dark environment. Some biologists even speculate that life on our planet might have originated at these sites. Could there just be a chance that the hydrothermal vents that perhaps exist on Europa's ocean floors might have organisms living around them? If so, might even more advanced marine animals have evolved to populate Europa's sub-surface global oceans? That last speculation is probably one too far, though the presence of microbial life around hydrothermal vents is surely not all that far-fetched. Europa's bland little disk, 1.0 arcsecond in diameter, may appear boring through the telescope but as you look just think about what wonders this little orb may contain.

Ganymede

Ganymede is the largest of the Jovian system of satellites and is the largest satellite in the Solar System, having a diameter of 5268 km. Its disk spans 1.7 arcseconds as seen from Earth. It orbits Jupiter at a mean distance of 1.07 million km. Despite its low surface albedo (0.4) it is the brightest of Jupiter's retinue, as seen from the Earth. This satellite is much less dense than Io or Europa, the mean density being 1940 kg/m^3.

Like Europa, Ganymede's surface is basically icy with darker contaminants. Though its orbital eccentricity is very small, it is thought to be just large enough to generate sufficient tidal heating in its interior to create a sub-surface ocean. Astronomers suspect that it has a large silicate core, overlaid by a mantle of ice, above which is the ocean in turn overlaid by a crust of about 100 km thickness.

Ganymede is extensively cratered and the surface of the satellite bears a superficial resemblance to the surface of our Moon, with many bright craters and 'rays'. However, there are also many differences. On Ganymede there are large plains of strangely lined terrain, and broad bands abound over the surface. Lateral faulting is evident and it may be that in past times an icy form of 'plate tectonics' took place on this frozen globe. Unlike the cases of Io and Europa, Ganymede's surface seems to have been inactive for a very long time, perhaps billions of years.

Callisto

Beyond the orbit of Ganymede lies that of Callisto, 1.88 million km from Jupiter. Callisto is the least dense of all the Galilean satellites, the density being 1830 kg/m^3. It is only slightly smaller than Ganymede, with a diameter of about 4821 km. Its disk subtends 1.6 arcseconds as we Earth-based observers see it. Like Ganymede, Callisto is thought to be composed of rock and ices in the main. It might have a small silicate core, though most planetologists think that Callisto may well be largely undifferentiated. There is a chance it may also possess a sub-surface ocean, though that is far from certain at the time I write these words. Certainly, the characteristics of a weak magnetic field that has been found do lend weight to this idea. The albedo of Callisto is only 0.2, so it appears much fainter than the other Galilean satellites when viewed from the Earth, despite its size.

Callisto's surface has a dirty ice covering and is undoubtably very old. Indeed, its crater-saturated surface speaks of inactivity lasting billions of years. As with Ganymede and Europa, there is little in the way of surface relief on Callisto, aside from the craters, basins and rings – all of which are thought to have been created by impacts long ago.

8.10 COLLISION WITH A COMET

One of the most unusual sights I have ever seen through a telescope eyepiece was the after-effects of the impact of the fragments of the disintegrated comet Shoemaker–Levy 9 on the planet Jupiter in July 1994.

There is much more about comets in Chapter 11, but suffice it to say here that almost the entirety of the volume of a comet is an incredibly tenuous mixture of gas and dust. However, the source of this gas and dust is a small (a couple of kilometres across, or so) 'dirty snowball' of various chemical ices mixed with fine rocky fragments. This *nucleus*, residing in the head of the comet, is the only really substantial part of it.

Eugene and Caroline Shoemaker and David Levy were conducting a photographic search for new asteroids and comets using the 18-inch (0.46 m) Schmidt camera at Mount Palomar when they came across the fateful comet in March 1993. Immediately, it was apparent from the photographic plate that something was odd about this object. Other telescopes were turned towards it and confirmed the initial suspicion that the comet's nucleus had fragmented. Later analysis suggested that it had been tidally disrupted on its previous very close orbital flyby of the planet Jupiter in July 1992. Astronomers soon realised that this time round it would not merely fly by Jupiter. It was going to collide with the planet!

Astronomers watched with mounting excitement as the separate nuclei, appearing like a string of cosmic pearls, headed towards the great planet. Some of the fragments were very small. Indeed, some vanished altogether, seemingly evaporated out of existence, while others were more substantial. Some of the surviving fragments further subdivided, indicating that they were rather flimsy in nature. As the predicted date of the first impact approached more and more telescopes were turned towards Jupiter, and the story made international news.

Then on 16 July 1994 at $20^h\ 12^m$ UT the first of 21 separate fragments impacted with the Jovian upper cloud decks. The bombardment continued for a further 6 days. Although almost all of the impacts occurred just round the limb of the planet, and so out of sight of visual observers, professional infrared telescopes (such as UKIRT in Hawaii) typically saw the flash emerge from behind the limb of the planet as each fragment and its surrounding gases ploughed into Jupiter's upper atmosphere, followed by a great fireball and a plume of atmospheric gases erupting following the vast explosion.

As each impact site rotated into view astronomers were surprised to see enormous black 'scars' on Jupiter's cloudy mantle. At that time Jupiter was only visible very low down in a twilight sky from the UK and was out of reach of my largest telescope. However, the impact scars were very easy to see with even a small telescope, despite the poor observing conditions, as Figure 8.12 shows.

Most of the impact scars lasted more than a month, changing shape and structure all the time, and Jupiter eventually developed a new, temporary, dark cloud belt as the surviving impact scars became stretched around the globe. By 1996, the planet had returned to normal. Though the ill-fated comet Shoemaker–Levy 9 is now gone, it will certainly not be forgotten. This spectacle provided astronomers with the opportunity of studying both a comet and the planet Jupiter in a way never before envisaged, and much complex physics and chemistry was learned about them as a result.

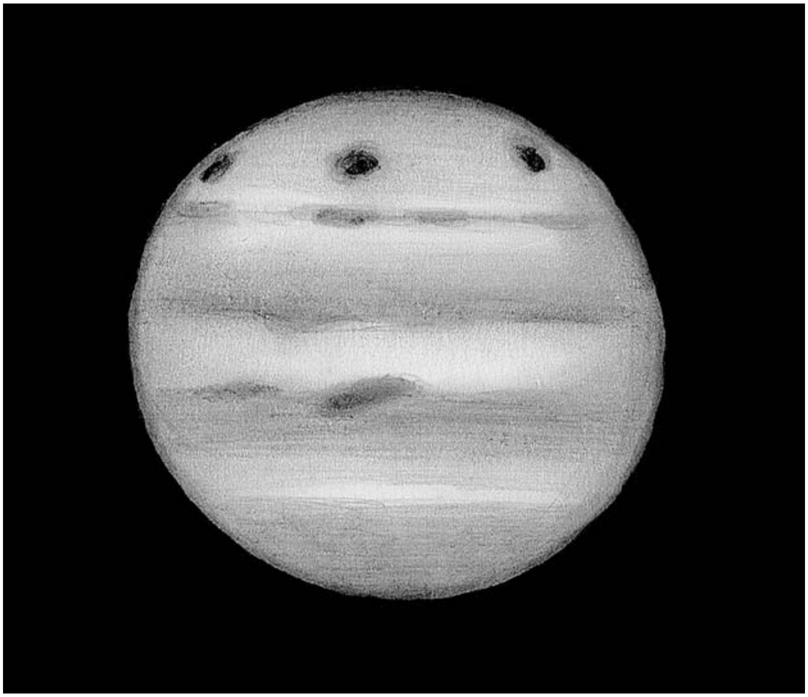


Figure 8.12 The aftermath of the comet Shoemaker–Levy 9 impact on Jupiter. The author made this drawing using his 6¼-inch (158 mm) Newtonian reflector, with a magnification of ×203, on 1994 July 20^{d} 20^{h} 21^{m} UT. Despite the conditions being very poor (ANT. V seeing plus contrast-reducing haze and a brightly twilit sky, with the planet very low over the horizon) the impact scars were very easy to see.

Such impacts were thought to be extremely rare and so it was quite a shock to everybody when Australian amateur astronomer Anthony Wesley discovered a new small black scar at 57°S latitude on Jupiter on 19 July 2009. He was taking images with a CCD video camera attached to his homemade 14½-inch (370 mm) Newtonian reflector from his home not far from Canberra in Australia. Once again the world's professional and amateur telescopes were turned towards Jupiter.

Professional infrared observations confirmed the black feature really was the after-effect of a single small body that must have ploughed into the giant planet's atmosphere just hours before Wesley had recorded his first images of it. The jury is out on whether the impacting body was a very small asteroid or a minor comet.

Not content with surprising the astronomical world once, Anthony Wesley did it again on 3 June 2010 when he video-recorded a bright flash of 2 seconds duration in Jupiter's South Equatorial Belt. At exactly the same time in the Philippines ace planetary imager Christopher Go also recorded the flash on video. This time the impactor that caused the flash left no visible after-effects. Not even the ultrasharp eye of the Hubble Space Telescope could find anything. The Hubble team speculated that the flash was caused by a large meteor that burned up in the Jovian upper atmosphere before reaching denser atmospheric layers.

We had thought that any impacts we could see from Earth were extremely rare. Now we are not so sure. Some historical observations of dark spots seen on the planet might just be previous impact scars. Even though the odds are long, could you be the person to discover the next impact on Jupiter?

8.11 A JOLLY GOOD PLANET TO FOLLOW

I could spend very many pages outlining many of the complex changes that we can observe on Jupiter and yet I would still only scratch the surface. If you get involved in a co-ordinated programme of observation you will soon realise what a wonderful and absorbing target Jupiter is for study through your telescope.

Some of the changes are of almost global proportions. For instance, the occasional fading of the South Equatorial Belt (SEB) occurs when the high-level ammonia clouds cover it. Over a few months it fades and can become almost invisible. The northern component of the SEB (the SEB_n) is most persistent and last to disappear. It stays hidden for a period of a few months to a couple of years during which time Jupiter looks very strange through the telescope. Then it spends a few months reviving itself – but the revival is far from being a passive clearing of the ammonia clouds. It usually starts with what looks like a brilliant white point and which is actually a tremendous upward surge of material from a storm system. That is the kick-off for complex and dramatic activity in the location of the emerging belt accompanied by changes and some activity in various regions of the rest of the planet.

Undoubtedly, photographing Jupiter using the best techniques (taking AVIs and stacking and processing the result) has the potential to give you the best images. Importing your images into a software suite such as *WinJUPOS* will allow you to conduct serious quantitative research on the atmospheric currents and features.

A few particularly dedicated Jupiter watchers have also tried their hand at imaging the planet at a near-infrared wavelength such as 393 nm. This is the central wavelength of a particularly strong methane absorption band. Methane is spread pretty uniformly throughout the main atmospheric layers visible to us and much of the planet appears pretty dark thanks to the strong absorption at that wavelength. However, particularly high-level clouds and hazes over the polar hoods and the tops of white ovals, etc. stand out brightly against the overall darkened planet. Mind you, a suitable filter (with a 5 nm passband centered on 393 nm) is fairly expensive and you need a good-quality monochrome camera and

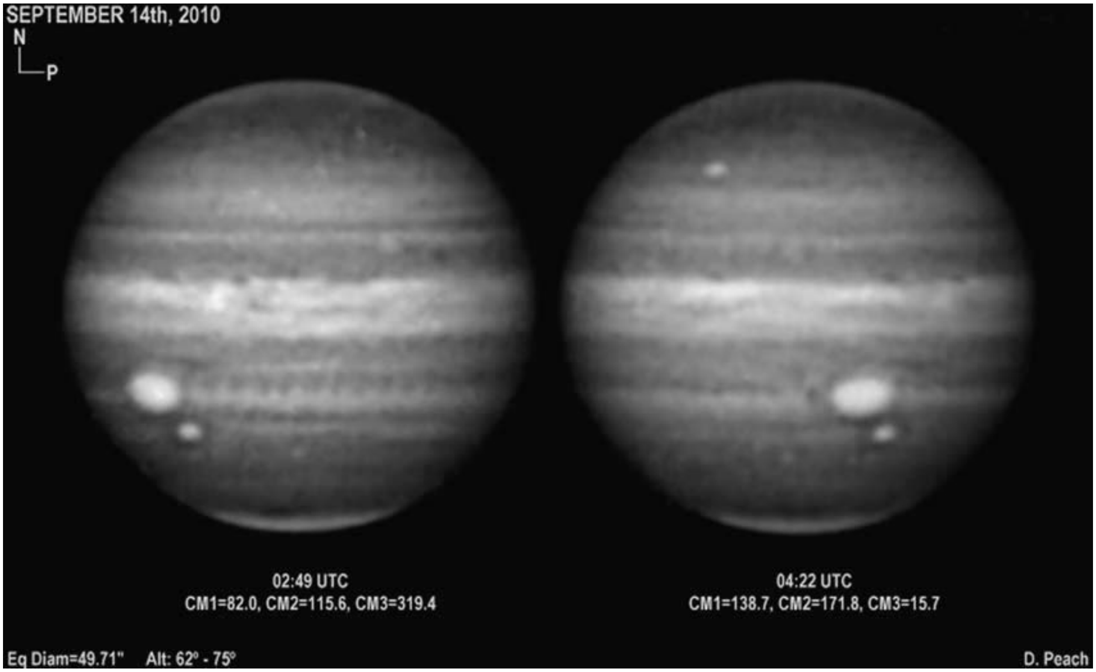


Figure 8.13 Methane-band images of Jupiter taken by Damian Peach at the times indicated on 2010 September 14[d]. The GRS and Oval BA are on show, appearing brilliant against the grey of the southern hemisphere. This illustration was prepared by Damian Peach. North is uppermost.

a fairly large telescope to get a decent image. Even then you are looking at a single exposure of something like 1 to 2 minutes, depending on effective focal ratio and camera. The most successful imagers have produced results that are worthwhile (see Figure 8.13) but I must say I regard methane-band imaging as a project for the already experienced practitioner.

Given that there is a limit to the depth and coverage of the material I can fit into any one chapter in this book, I should mention that there is a book written by John W. McAnnally called *Jupiter and How to Observe It*, which was published by Springer-Verlag in 2009. Surprisingly, at the time I am writing this there are no other books recently published devoted to the amateur observation of this planet.

Two advanced-level, large and very detailed books about Jupiter are: *The Giant Planet Jupiter* by John H. Rogers and the multi-authored *Jupiter: The Planet, Satellites, and Magnetosphere*, which was edited by Fran Bagenal. The first of these is a highly detailed treatise on the observation of the planet up to 1991. It was published in 1995 by Cambridge University Press but second-hand copies can be found (on Amazon, for instance) and it now exists in various electronic formats and as a 'digital paperback'. The second book, published in 2004 by Cambridge University

Press, is still in print. It details the physical and geological natures of the Jovian planet and its moons.

8.12 TUNE IN TO RADIO JUPITER

It was a major surprise in 1965 when intense and fluctuating radio emissions were first detected from Jupiter. This was correctly taken to indicate that Jupiter possesses a magnetosphere. The radio emissions could only be explained in terms of charged particles interacting with a magnetic field.

Apart from the Sun, the planet Jupiter is the strongest emitter of radio waves in the Solar System. The emissions can be divided into three main components, each categorised in terms of wavelength. The first is in the decametric range, having wavelengths of from 7 to 700 metres, and consisting of irregular and sporadic pulses of 'radio noise'. Soon after their discovery, it was realised that these pulses are related to the apparent positions of the moon Io.

The second category is the decimetric range of wavelengths downward from 7 metres, consisting of a steady stream of 'radio noise'. We now know that this radio emission is produced by electrons spiralling along the Jovian magnetic-field lines. These electrons lose energy by a process known as *synchrotron emission*. It is interesting to note that the polarisation of the decimetric radio emission indicates that the polarity of Jupiter's magnetic field is opposite to that of the Earth.

The third category is thermal emission. This is also a steady emission, being due to the temperature of Jupiter's outer layers. The thermal radiation actually peaks in the infrared part of the spectrum (the wavelength being about 25 mm) but tails into the microwave and radiowave portions. There is also some radio emission in the form of 'whistlers' caused by Jovian lightning. However, as far as I am aware this has only ever been detected from space probes in Jupiter's vicinity.

Owing to insufficient space to cover everything, I have generally ignored radio astronomy in this book, though interesting observations of the Sun and meteors can be made using amateur equipment provided the practitioner has at least a modicum of 'radio ham' knowledge. However, it is so very easy to make radio observations of the decametric emissions from Jupiter that I just cannot pass over this one application.

The December 1989 issue of *Sky & Telescope* magazine carries an article written by David Rosenthal about the construction of a radio antenna designed to work with an ordinary analogue radio set of ordinary quality. The one proviso is that the radio set must have a top frequency of reception of at least 18 MHz (a wavelength of 16.7 metres). This arrangement will allow anyone to listen for the decametric radio emissions from

Jupiter. As already indicated, these radio emissions arise from the passage of the satellite Io through the Jovian planet's powerful and complex magnetosphere. The antenna design originates from Rob Sickles, a member of the Society of Radio Astronomers (SARA).

Some years back I constructed a version of this antenna myself, adapting the design to use the scrap materials I had to hand. Figures 8.14(a), (b) and (c) show the result. The diameter of the loop is 21 inches (533 mm) and it is positioned 12 inches (305 mm) above the reflector, which is 23.6 inches (600 mm) across. These dimensions do not have to be precise for the device to work. A sheet of metal or of metal gauze would do as the reflector but I used a sheet of aluminium foil taped onto a flat square piece of plywood. Of course, the fixings of the four wooden posts and the earthing terminal also double as additional anchors for the aluminium foil.

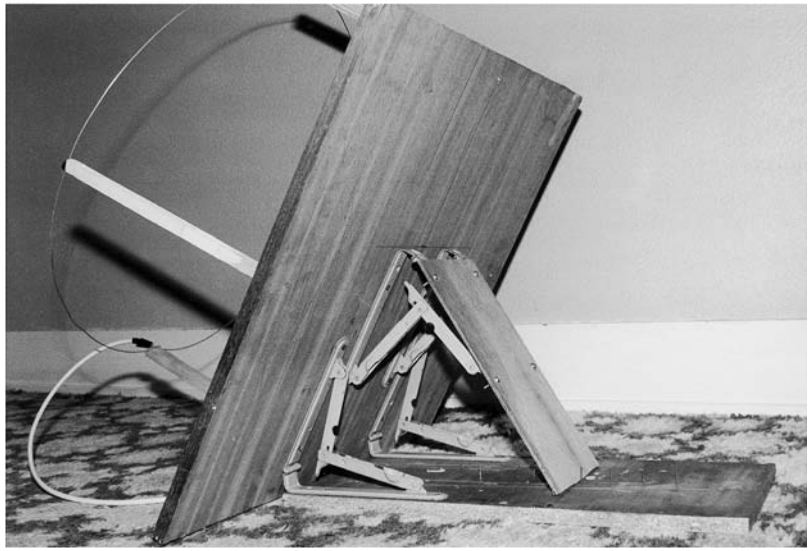
The centre wire of a coaxial cable attaches to one end of the wire loop. The other end of the wire loop is not electrically connected to anything, though it is mechanically anchored to the wooden post as shown in Figure 8.14(c). The other connection of the coaxial cable (to the outer braid) is electrically connected to the reflector as also shown in Figure 8.14(c).

At the other end of the coaxial cable the centre wire is connected to the 'aerial input' (alternately marked 'IN', or 'antenna input') of the radio and the outer braid is connected to the 'earth' terminal (usually marked 'E' or with a downward pointing arrowhead formed from horizontal lines).

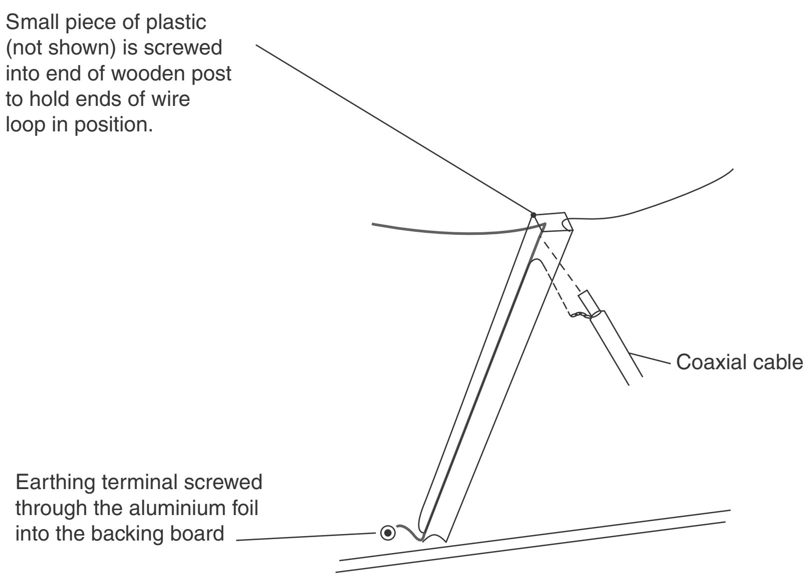
(a)

Figure 8.14 This crude and simple arrangement is good enough to pick up the radio emissions caused by the interaction of the Jovian moon Io with Jupiter's magnetosphere. (a) and (b) show general constructional views and (c) shows the connections to the coaxial aerial (antenna) cable. Please see the main text for more details.

(b)



(c)



I have found that this antenna works well over a wide range of frequencies though it is designed to be most efficient at 21 MHz. In his article, David Rosenthal cautions that there is only about a one in six chance of hearing Jupiter's emissions within any 20 minute listening period. The radio beams have to be both active and sweep across the

Earth in order for us to hear anything. I was lucky when I first tried. I pointed my newly constructed antenna at Jupiter (only a rough accuracy of pointing is required), tuned the radio up to its limit of 15 metres on the short-wave band, turned the volume control up to full and had to wait less than half an hour before I heard the characteristic 'wooshing' noise of the Jupiter–Io interaction.

I found Rosenthal's description of the sound as similar to ocean waves lapping on a shingle beach to be accurate. The wooshes came in at the rate of about one a second. After a few minutes the sound gradually faded away into the general background 'mush'.

I hope that you will feel inclined to give this experiment a go for yourself but do be patient. You may have to wait a while before you hear anything and you may well have to contend with man-made interference. If you find too much interference at the 15 metres position, then tune a little higher or lower until you do find a nearby quiet spot on the dial. The sound is very distinctive when it comes and it is genuinely thrilling to think that one is listening to the result of an interaction involving Jupiter's magnetosphere and vast electrical currents looping between the giant planet and Io far away across the Solar System.

CHAPTER 9

Saturn, Uranus and Neptune

At Jupiter's orbit the light from our Sun is so spread out that it illuminates with a mere one twenty-seventh of its strength at the orbit of our Earth. Of course, even that is nowhere near the outer limits of our Solar System. There are still three mighty worlds and a vast number of very much smaller bodies orbiting much further out where the sunlight is even dimmer. The next major planet is Saturn, where sunlight shines a mere one ninetieth of the brightness we are used to. Beyond that is Uranus and beyond that is Neptune. From these worlds our Sun has very roughly one four hundredth and one nine hundredth of its intensity, respectively. Their great distances also mean that the time light takes to cross from the planet to us is significant, despite the fact that a pulse of light travels three hundred thousand kilometres every second. Whenever we look at Saturn we are actually seeing it as it used to be just over an hour before. Make that two and a half hours in the case of Uranus and fully four hours in the case of Neptune! It is little wonder that these twilit worlds appear wonderfully unearthly and ethereal through our telescopes. In this chapter we will consider each major planet in turn along with what observations we can usefully make of them.

9.1 SATURN IN THE SKY AND THROUGH THE TELESCOPE

One starry winter's evening early in 1971 I was in the garden with the 3-inch (76 mm) reflector my parents had recently bought for me. On a few previous nights I had already had my first close-up views of the Moon's magnificent vistas through it. On this night I remember looking up and seeing an intriguing little group of blue stars twinkling in the sky. Only later did I learn that that group was the Pleiades star cluster. Not far from the cluster was something that immediately struck me as very different – a prominent star that didn't twinkle like the rest. It had a leaden yellow hue that looked totally unlike the colours of any of the other stars in the sky. I wondered if it could be a planet – I very much hoped so as it would be my first sighting of one through my new 'proper' astronomical telescope.

I plugged in the telescope's 20 mm Huygens eyepiece (which gave a magnification of $\times$35). After a few moments of trying to get the telescope pointed to the right spot, a tiny apparition swam into the field of view of its eyepiece. I knew what it was straight away – a minute disk with an encircling bright ring – wonderful Saturn floating in a black sky. Thrilled, I exchanged the 20 mm eyepiece for the 6 mm Huygens (giving $\times$117) and marvelled at Saturn and its magnificent ring system.

The well-displayed rings encircling the planet created a startlingly three-dimensional effect. I could see that the thin outermost section of the ring was blue and the wider, inside, one was snowy white. A thin black line separated the two coloured sections. The inside edge of the white ring section was not sharp but instead faded rapidly to black sky. The planet itself was a little ball, mostly fawn coloured with a dark cap at its top and a thin magenta band just above a lighter zone spanning its middle.

The colours appeared vivid to me at the time despite the small size of my telescope. Now I marvel at how sensitive my colour vision was in my youth. My colour vision is still good but nowhere near as good as it was in those exciting boyhood days of seeing great sights for the first time through a telescope eyepiece. Today the colours appear to me much more muted, even through a larger telescope. However, I am sure that you will see them well enough through a moderately sized telescope. I also guarantee that you will find Saturn exciting to see through any instrument that is good enough to qualify for the term 'telescope'.

Saturn, the second biggest planet of the Solar System, is the next major planet orbiting beyond the mighty Jupiter. Also a gas-giant world, Saturn has an equatorial diameter of 120 536 km and a mass 95 times that of the Earth. The average density of Saturn is a mere 700 kg/m^3, actually less dense than water!

Saturn moves through the Solar System at a mean distance of 1426 million km from the Sun, taking 29½ Earth-years to complete one orbit. Saturn is observable for many months around opposition and the observing season can be extended if you are prepared to venture out with your telescope between midnight and dawn. As compensation for observing in the small hours the atmosphere is then often at its most stable, so providing steady and sharp views.

An ephemeris or planetarium software package may be helpful for you to find Saturn at first. Then, I would expect that with minimal experience you will be able to follow the planet in the sky from one year to the next without any need for additional aids. This is especially so if you become familiar with the patterns of the brightest stars in the constellations. In particular I find that the colour, brightness and lack of twinkling are always a dead giveaway as to which star-like object is really Saturn.

Since Saturn moves relatively slowly about the Sun, oppositions of the planet occur only about a fortnight later each year. The planet then attains a maximum apparent magnitude of $-0^{m}.4$, appearing to the naked eye like a dusky-yellow-hued star. At least it does so when its highly reflective ring system is wide open. At these times two thirds of the light we see comes from sunlight reflected by the rings. At other oppositions Saturn can be somewhat dimmer. When oppositions occur with the rings nearly edgewise the maximum brightness the planet achieves is $+0^{m}.8$. More about the famous system of rings and its apparent variations later.

Seen through the telescope Saturn's globe presents a small, fawn-coloured disk of 19.5 arcseconds apparent diameter at the time of opposition. It then requires a magnifying power of about $\times 98$ to enlarge the disk enough to match the apparent size of the full Moon seen with the unaided eye. Since Saturn's orbit is over nine times the diameter of the Earth's, the percentage variation in the distance between us and Saturn over the course of a year is only about 20 per cent. Consequently, the smallest Saturn's globe ever appears to us (near the time of solar conjunction) is 15.7 arcseconds, when a magnification of $\times 122$ is enough to enlarge its disk to the same apparent size as before.

Through an 8-inch or 10-inch (203 mm or 254 mm) telescope, the body of the planet is seen to be crossed by pinkish-brown equatorial belts with some much fainter belts appearing either greyish or coloured with pale shades of brown, or occasionally pastel greens and blues. There are lighter zones in-between the belts. The colours and intensities of Saturn's markings are somewhat variable. The hemisphere of the planet experiencing winter (and hence its pole tipped away from us) tends to display 'cooler' colours (averaging more towards blues and greens) than those in the summertime hemisphere.

The appearance of the globe of Saturn tends to be reminiscent of Jupiter, though the Saturnian features are usually much less sharply contrasted than their Jovian counterparts. The same nomenclature used for Jupiter is used to describe the belts and zones of Saturn, though only the equatorial belts, temperate belts and polar regions can be said to be permanent features of the planet.

If the main body of the planet appears only a smaller and more pallid version of Jupiter, this is more than made up by Saturn's impressive

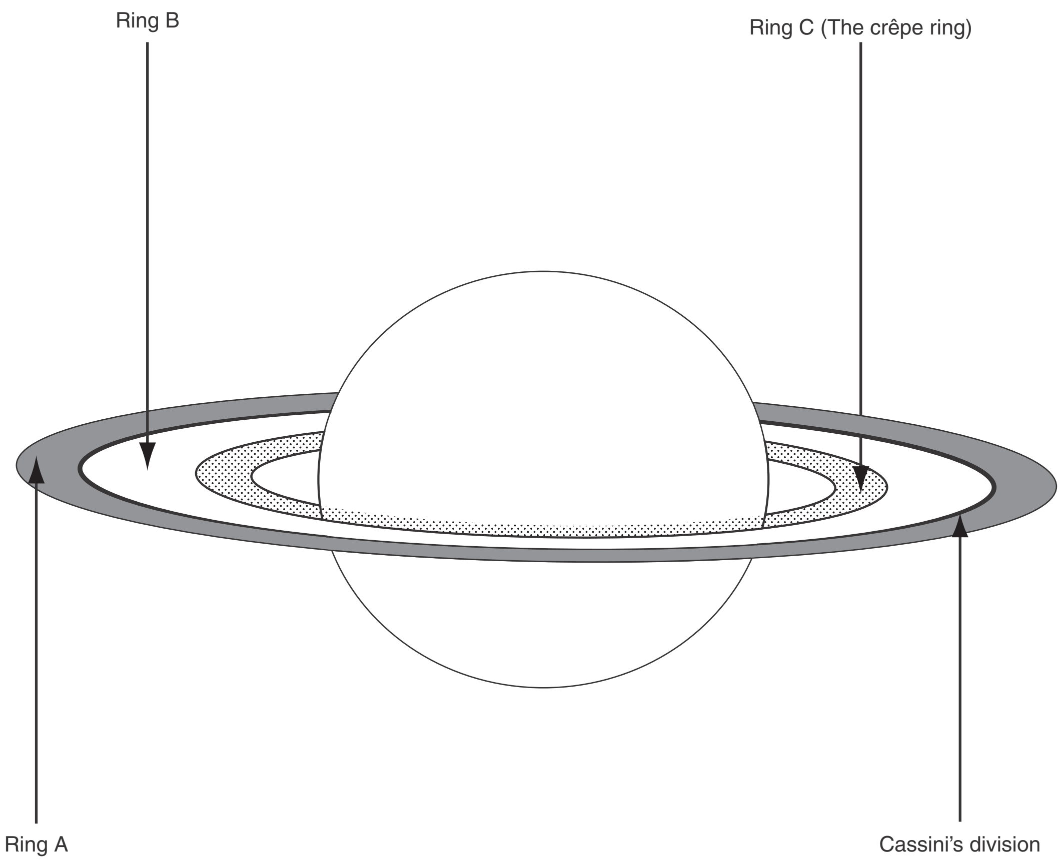


Figure 9.1 The bright rings of Saturn.

system of rings. Galileo was probably the first to observe the rings, though his telescopes were not powerful enough to show them in their true guise and it was Christian Huygens in 1659 who discerned, as he himself wrote: 'a flat ring inclined to the ecliptic which nowhere touches the planet'.

Soon after it was noticed that the rings were divided up concentrically (see Figure 9.1). In 1675, J. D. Cassini discovered a line of darkness that separates the inner and outer components. This line is known as Cassini's Division in his honour. It spans 0.7 arcseconds at the ring *ansae* as seen from Earth (bearing in mind that we see the circular rings as ellipses from our viewpoint, the ring ansae are the apparent 'pointy ends' of the ring system east and west of the planet).

The outermost bright ring component, known as ring A, appears rather less bright than the inner ring, ring B. The rings are also different in colour – to me these days ring A appears bluish-grey while ring B is creamy-white.

In 1850, another much fainter ring component, ring C, was discovered by the British clergyman and amateur astronomer William Dawes and, independently, by George Bond in America. Ring C lies inward of ring B and is not easy to see against the dark-sky background in telescopes smaller than about 150 mm aperture because of the overpowering light from Saturn itself and its adjacent bright rings. It is, however, easily seen even in small telescopes as a dusky band where it crosses Saturn's globe.

Most of the time the sunlight falling on Saturn and its ring system comes from a direction a little different to the direction in which we view the planet. Consequently it is quite usual to see the shadow of the globe of the planet cast onto the rings circling behind it. This appears on just one side of the globe at a time and is pretty much invisible at the time of opposition. Close scrutiny can usually reveal a thin dark band appearing across the equatorial region of the planet, this being the shadow cast onto it by the rings where they pass sunward of Saturn's globe.

Apart from Cassini's, other divisions in Saturn's rings were reported from time to time, but only Encke's Division in the outer part of ring A was taken seriously until the space probes of recent years. Saturn's ring system is vast, spanning a diameter of 274 000 km to the outer edge of ring A. This spans about 46 arcseconds at the time of opposition, about 2¼ times the diameter of the planet's globe.

The rings do not always present the same aspect to us, but rather yaw and tilt over a 29½-year cycle. This is due to our vantage point changing with respect to the planet as Saturn and the Earth move around the Sun. Reference to Figure 9.2 should help to clarify the situation.

Saturn's rotation axis is tilted to the normal of its orbital plane by an angle of slightly less than 27°. Saturn's ring system is accurately aligned with its equatorial plane and hence is always perpendicular to the planet's axis of rotation. Saturn, acting rather like a gyroscope, maintains the direction of its spin axis in space as it revolves around the Sun – along with the orientation of the ring system. Referring to Figure 9.2, when Saturn is at position S_1 it is at opposition when the Earth is at E_1, and so on.

In 1966, the rings of Saturn were presented edgewise to us and they were invisible as seen through small telescopes. Even through large telescopes they appeared no more than a thin line of light. By 1974, the ring system had opened out, so that the south face of the rings was on view and they were opened to their maximum extent (a tilt of 27°). The drawing shown in Figure 9.5, a few pages further on in this chapter, shows the rings still almost fully open a year later. The rings then began to close up, becoming edgewise again in 1980. Continuing the cycle, the rings then began to open once more, presenting their north face to us

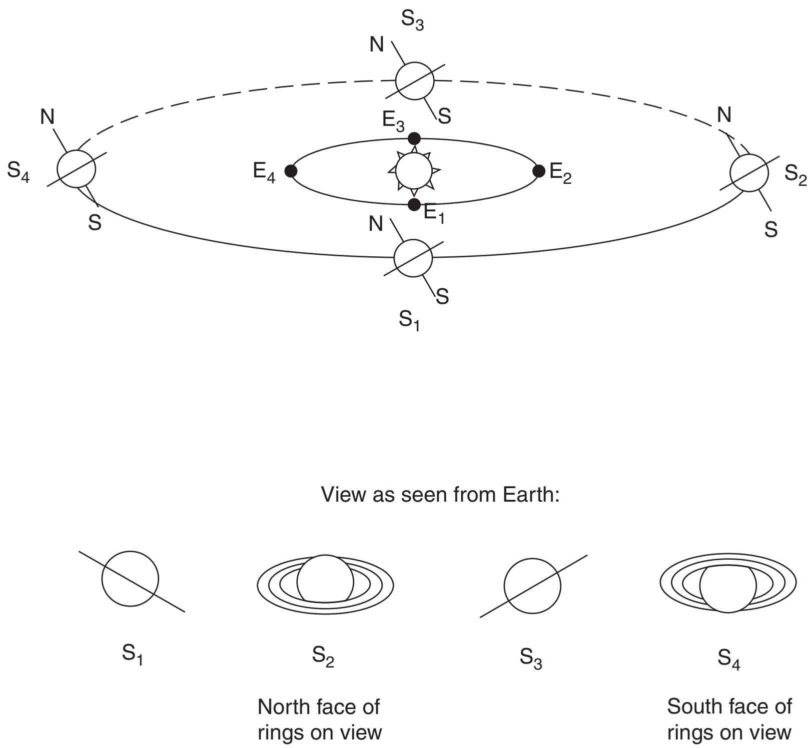


Figure 9.2 The changing aspect of Saturn's rings. When Saturn is at S_1 we see the planet at opposition when the Earth is at E_1. Also the planet then appears as illustrated by the drawing marked S_1 below. The same is true for the other corresponding positions and drawings, S_2, S_3, and S_4.

and becoming fully open in 1987 (again a tilt of 27° but the rings and planet being tipped in the opposite direction to that in 1974), only to become edgewise once again in 1995. Figures 9.3(a), (b), and (c) show the rings closing up towards their edgewise presentation in 1995. The cycle continued with the south face once again fully opened to us in 2003 and the next edgewise presentation happening in 2009. To fully appreciate the year-to-year changing aspect of Saturn's rings please see Figure 9.4, which shows a montage of Saturn images from 1999 to 2010 created by Damian Peach.

Of course the opposition point of Saturn moves through the pattern of stars, taking 29½ years to track once around the sky. The planet also changes its declination during this time. Consequently, when the south pole of the planet and the south face of the rings are best displayed the planet has a northerly declination of *circa* +27° and so it can appear high in the sky as seen from the Earth's northern hemisphere. The deleterious effects of our atmosphere are then minimised and so this is a great time to observe the planet. When the north pole of the planet and northern face of the rings are most prominently displayed observers in the Earth's

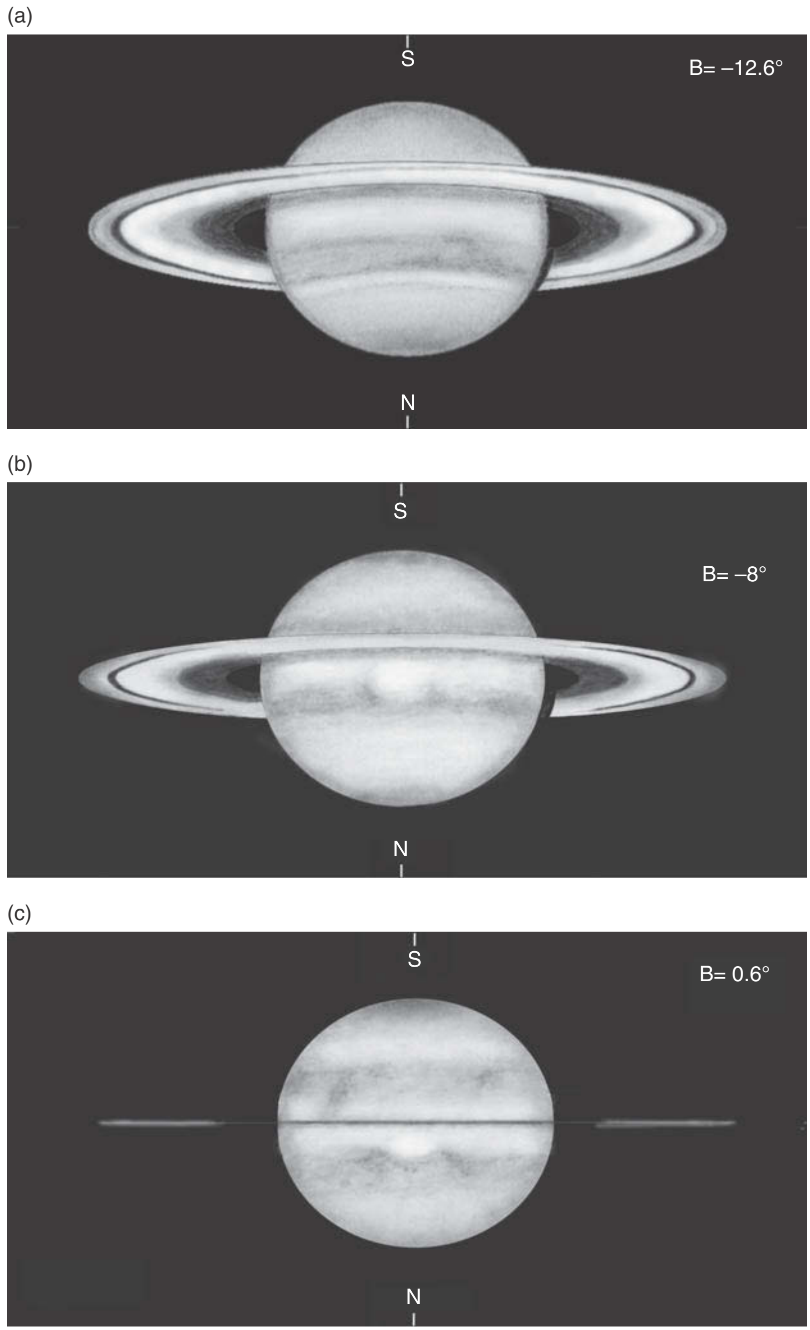


Figure 9.3 Drawing of Saturn by Robert Bullen, using his 8½-inch (216 mm) Newtonian reflector, using a magnification of ×216. During each session he employed yellow, green and orange filters in order to help him detect all the detail that was present on the planet. He recorded the seeing as ANT. III in all three cases.
(a) 1993 September 16^{d};
(b) 1994 October 26^{d};
(c) 1995 August 28^{d}.
The values of B correspond to the tilt angle of the rings in each case.

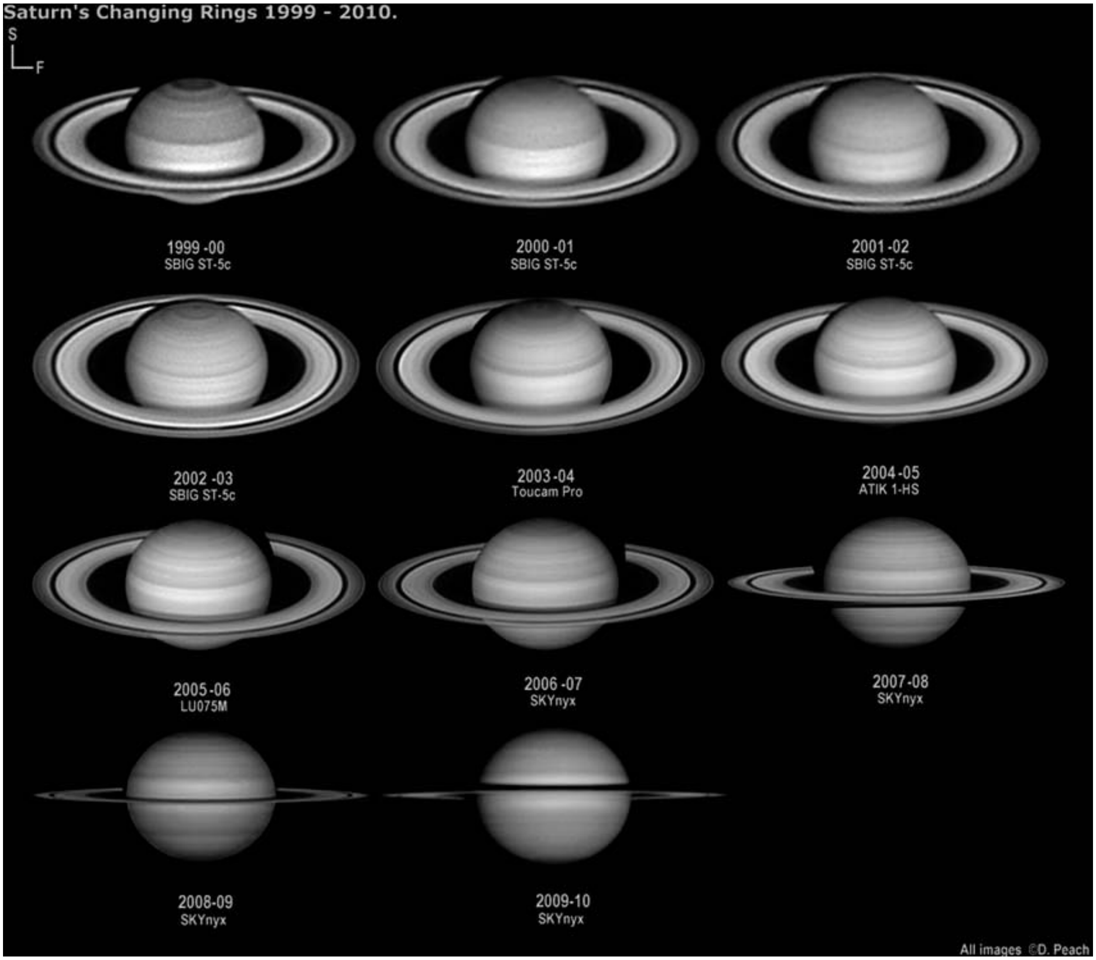


Figure 9.4 Images of Saturn showing the changing ring aspects during the period 1999 to 2010 when the south face of the rings was on view. This montage was prepared by Damian Peach using his own images obtained over those years with a variety of equipment.

northern hemisphere are at a severe disadvantage as the planet can then never achieve a good altitude.

It is a shame to have to note here that Saturn has already crossed the celestial equator heading southwards and will not cross the celestial equator into the northern celestial hemisphere again until 2024. Still, do not despair – the planet will still be an impressive sight and there is plenty of time for you to practice and perfect your techniques to take the best advantage of the best views of the planet when the era of good oppositions returns.

It has long been known that Saturn is a similar type of body to Jupiter, although the cloudy atmosphere appears more quiescent. Very occasionally white spots are seen and large telescopes do reveal irregularities in the belts. Visible cloud-top features, when they occur, have been used to determine the rotation period of the planet. At the equatorial regions Saturn's clouds rotate around the planet with a period of 10 hours 14 minutes. As is the case for Jupiter, the apparent rotation rate is slower at higher latitudes. It is this rapid rate of rotation, coupled with the fluid nature of Saturn, which leads to it presenting a disk even more flattened than Jupiter's (by about 11 per cent of the equatorial diameter, as opposed to about 7 per cent in the case of Jupiter).

9.2 VISUALLY OBSERVING SATURN

Chapter 2 is concerned with the selection and adaptation of equipment and parts of Chapters 6 and 7 (particularly Sections 6.3, 6.5, 6.6, 6.8, 6.9, 7.4, 7.5 and 7.7) are concerned with visually observing planets through a telescope and recording what you see. If you have not already done so, I strongly recommend reading those sections before you continue reading here. I have to be economical with the space in this book, so here I must restrict myself to adding just some additional notes concerned specifically with observing Saturn and assume you are familiar with what has been written earlier.

Observing the globe of Saturn

One reason why Saturn's globe appears more quiescent than Jupiter's is the presence of a substantial haze layer above the major cloud tops. The details below consequently appear with rather muted colours and contrasts. As already noted, the nomenclature of the visible features follows the same general scheme as for Jupiter (please see Figure 8.1, page 231) though I must say that I have ever only seen the equatorial belts, the temperate belts and polar hoods at all regularly. Through a 10-inch (254 mm) or larger telescope the NEB and SEB are normally seen to be double; however, there are variations and at times the two components of either belt can partially or completely merge together. Particularly good seeing conditions can allow the most subtle belts to be observed.

As far as the zones are concerned, the whole of the region south of the SEB and north of the SPR is known as the south tropical zone (STZ). The same is true of the region north of the NEB and south of the NPR – known as the north tropical zone (NTZ). In both cases this is irrespective of whether or not additional belts are visible in these regions.

There are occasional irregularities to be seen in Saturn's belts and zones but Jupiter-type spots are fairly rare events, especially so for purely visual observers. Major white spots have, though, been seen on Saturn in 1903, 1933, 1960 and 1990. On a few other occasions smaller white spots have been detected visually and, as you might expect in the modern era of CCD video imaging, other more minor events are now much more frequently detected than before.

As I write these words (in the spring of 2011 – just as I am about to send my manuscript for this book off to the publisher) a most unusual, and very far from minor, storm has erupted in the high northern latitudes of Saturn and has so far spread more than half way round the globe in longitude. It was first spotted by amateurs in December 2010. Figure 9.7(b) and (c) shows it further on in this chapter. It is very bright and because of its appearance it has been nicknamed 'the Serpent Storm'. There seems to be an electrostatic disturbance associated with it, probably indicating lightning bolts that are of the order of ten thousand times more powerful than earthly lightning strikes! When the analysis is done I feel sure that this storm will turn out to be of unprecedented magnitude and duration in the history of observing Saturn.

Saturn seems to stand the application of fairly high magnifications better than most other planets under identical seeing conditions. Perhaps the vista of the globe surrounded by the sharply defined rings is responsible for this physiological effect. If your telescope and the seeing conditions are both up to it then I recommend a magnifying power of ×200 or more when searching for the smallest details such as belt irregularities. Coloured filters may help by intensifying contrasts; a green or blue filter producing an apparent darkening of the pinkish-brown equatorial belts, for instance.

As is the case for Jupiter, different latitudes on Saturn's visible globe (actually the uppermost levels of Saturn's atmosphere and cloud-decks) circulate round the planet with different periods. In the case of Saturn, a System I circulation has been defined to apply between the southern component of the NEB and the northern component of the SEB. The circulation rate for System I is taken to be 10 hours 13 minutes 59 seconds for a complete rotation of the planet. The situation for the rest of the globe is more complicated but most often a System II circulation is used for the rest (10 hours 39 minutes 24 seconds for a complete rotation of the planet), though a System III is sometimes assigned (based on radio observations, this planetary rotation period is taken as 10 hours 39 minutes 22 seconds). As always, please take guidance from the co-ordinator/director of the observing group to whom you are submitting your observations, as to what is required and what conventions you should follow.

You can calculate the appropriate central meridian longitudes at any given moment from tables published in an ephemeris (such as the annual *Handbook of the British Astronomical Association*) or find it out directly by running a planetarium software package such as *Guide 8*. Timing the transits of any prominent features across the central meridian is still a useful pursuit for the purely visual observer as this allows the circulation rates of various atmospheric currents to be studied.

We have to accept that the CCD/video imager has the advantage of being able to use software such as *WinJUPOS* to obtain instant positional data from any high-quality image. The observer who has prepared a drawing and then scans it into the computer can, in theory at least, use the same software to similarly analyse the latitudes and longitudes of any feature that is recorded. In practice, the same degree of accuracy cannot be expected.

Intensity estimates are valuable and can be carried out with a smaller telescope than the 10-inch or so minimum aperture that is desirable for visually detecting spots and belt irregularities. The standard 0 = brightest to 10 = black scale is the one to adopt, with decimal fractions used where necessary. Colour estimates made by eye are still valuable, even though any colours are difficult to see and visual observations are inescapably subjective. As I indicated in the last section, the colours on Saturn are subject to interesting variations. These can be both seasonal and irregular.

Observing Saturn's ring system

As well as Saturn's globe we have its magnificent ring system to observe. The hardest to see is ring C. At all times when the ring system is fairly widely open, ring C, historically referred to as 'the crêpe ring', should be easy for you to see as a dark band where it crosses in front of the globe of Saturn. This should be the case even through a telescope as small as 60 mm aperture with a magnification of ×80 or above. Seeing it as a ghostly ring shining gently against the dark sky (and hence between the bright B ring and extending part way towards the globe of the planet) is another matter. I have seen it like this through my old 6¼-inch (158 mm) Newtonian reflector on occasions when the sky was particularly dark and haze-free but it can be difficult to see even through a much larger telescope when the conditions are less than ideal.

As you will read further on, there are more rings around Saturn than the bright A and B rings and the ghostly C ring. However, and despite occasional claims to the contrary, these extra rings are not visible to the amateur telescope user's eyeball.

Once in a while, observers report divisions in the rings other than Cassini's. Space probe images reveal that the rings are highly grooved with many fine divisions. However, aside from Cassini's Division, which is easily visible in a 60 mm telescope at ×80 when the rings are fairly wide open, only the much narrower Encke's Division was ever convincingly reported by amateur observers using visual techniques. Even in that case, prior to the space probe images, Encke's Division was usually recorded as running midway through ring A. In fact, it runs close to the outer edge of ring A!

Each of the rings display very slight concentric variations of brightness but I have to say that apart from the significant fading of ring B near its inner edge the variations are not obvious (at least they are not to me!). Ring B is sometimes subdivided into B1, B2 and B3, for instance. B1 is the outermost section and is the brightest. B3 is the innermost section and is the faintest and fades further towards the boundary between it and ring C.

I find the difference in brightness of B1 and B2 very hard to see visually though it is very obvious in properly processed photographic images. However, the boundaries between these or any other regions of differing brightness can sometimes be noticeable to the visual observer. In fact, I am sure that those who reported extra divisions in Saturn's rings were actually recording the boundaries of slightly different brightnesses. As a case in point, the easiest to see of the brightness variations is in ring A. The boundary between the inner, slightly brighter zone and the outer, slightly dimmer one runs midway through the A ring; and right along the position that many observers used to record as the site of Encke's division.

One can usefully keep a watch on the intensity of each of the rings (using the same numbered scale as for recording the intensity estimates of the globe details) and look out for any apparent divisions or irregularities that might occasionally be visible, as well as any colours visible.

A rarer appearance (and something I have never noticed) is an apparent variation of brightness in an east–west direction across the rings. Nor have I ever seen any significant wholesale colour differences extending across the rings in an east–west direction. However, both these effects have been reported from time to time so it is as well to keep a watch out for them.

The times when Saturn's rings are presented edgewise to us are interesting. Generally the rings disappear from view through the smallest telescopes but you will probably be able to see the ring system as an excessively thin line of light through a moderately sized amateur telescope in reasonable observing conditions. Careful scrutiny using high magnifications can be fruitful. Can you see any clumpiness or particular distributions of brightness within the thin line of light? Can you see any sudden brightness changes in the parts that correspond to the positions of Cassini's Division? The dates when Saturn's rings appear edgewise to us can be different from the times they are edgewise to the Sun and any changes of appearance before, after, and during these times should be looked out for and carefully noted.

9.3 DRAWING SATURN

To draw Saturn, a pre-prepared outline is essential. The globe of the planet is very flattened at the poles and there is the obvious difficulty of representing the appearance of the bright rings accurately. The easiest solution is to get pre-prepared blanks from your observing-group co-ordinator/director. Another solution is to make your own blanks. Here, a computer with some elementary graphics facilities and a printer makes for a considerably less arduous job than having to prepare the blanks by hand and pencil. If D is the equatorial diameter of the globe of Saturn and X is the apparent tilt angle of the rings ($0°$ would correspond to an edgewise presentation of the rings) then the following equations will give the other quantities:

approximation (good enough for the purpose of making a drawing) of polar diameter of globe $= D - 0.11\cos X$
diameter to outer edge of ring A (major axis) $= 2.26D$
diameter to outer edge of ring A (minor axis) $= 2.26D\sin X$
diameter to inner edge of ring A (major axis) $= 2.01D$
diameter to inner edge of ring A (minor axis) $= 2.01D\sin X$
diameter to outer edge of ring B (major axis) $= 1.95D$
diameter to outer edge of ring B (minor axis) $= 1.95D\sin X$
diameter to inner edge of ring B (major axis) $= 1.53D$
diameter to inner edge of ring B (minor axis) $= 1.53D\sin X$
(inner edge of ring B is coincident with outer edge of ring C)
diameter to inner edge of ring C (major axis) $= 1.21D$
diameter to inner edge of ring C (minor axis) $= 1.21D\sin X$

Note that the gap between the outer part of ring B and the inner part of ring A is Cassini's Division. The tilt angle of the rings can be found in an ephemeris.

If you need to plot out the ellipses by hand you could do so on graph paper using the following equation:

$$y = b\sqrt{(1 - x^2/a^2)},$$

where a is half the major axis and b is half the minor axis, respectively. I recommend setting the equatorial diameter of the globe of the planet (D in the previous set of equations) as 40 mm on your drawing.

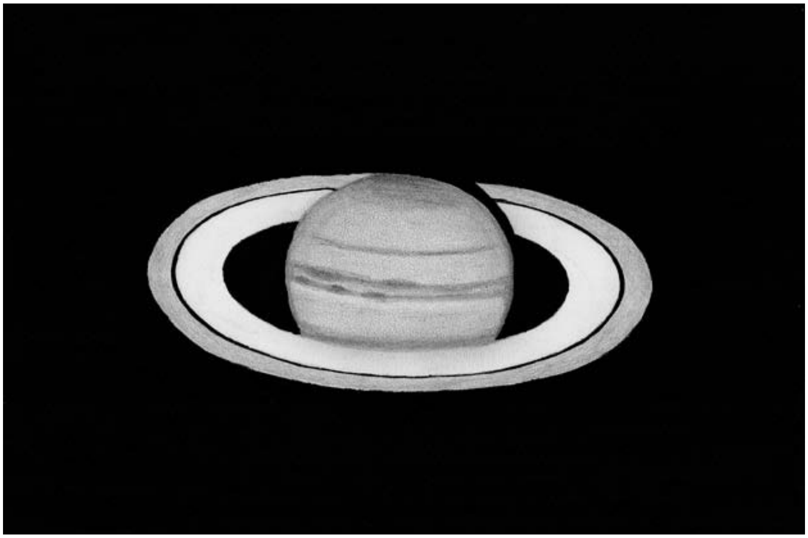


Figure 9.5 Saturn drawn by the author on 1975 March 07^{d} 22^{h} 00^{m} UT, using his 18¼-inch (0.46 m) Newtonian reflector, with a magnification of $\times 260$. Seeing ANT. III. Transparency decreasing from fair to poor during the session.

If you are plotting out ellipses by hand, I would recommend you doing this just once to represent the planet for a number of weeks at a time. After drawing out your freehand curves through the points generating each ellipse you can then ink over them to make the shapes show through for tracing.

Apart from near the times of edgewise presentation, the tilt of the rings does not vary very much from one month to the next. Consequently, you can usually get away with using the same stencil to create your blanks for weeks at a time. You will have to get busy creating new stencils more frequently, though, whenever the rings appear narrowly presented.

Now to the actual drawing made at the telescope. I recommend starting with recording any shadows on the rings cast by the globe, and vice versa. Then continue by adding details in the same way that you would when drawing Jupiter (see the last chapter, Section 8.4). As ever, please do ensure that you record a full set of notes along with your drawing. Without these your drawing will lose most of its value.

As is the case for the other planets, coloured drawings can be instructive, provided you can represent the colours you see with reasonable fidelity on them. Failing that, monochrome drawings made using coloured filters can also be useful. Figure 9.5 shows a drawing of Saturn I made way back in 1975 when the south face of the rings were very well presented to us. Although I used my 18¼-inch (464 mm) Newtonian reflector, the rather average seeing conditions at the time meant that pretty much the same would have been seen through a good telescope of maybe 7 or 8 inches (178 mm or 203 mm) aperture. Of course you have already seen the marvellous drawings of Robert Bullen displayed in Figure 9.3(a), (b) and (c).

9.4 PHOTOGRAPHING SATURN

I love looking at Saturn through the eyepiece of a telescope. To me, photographs of it, or seeing its image on a monitor even in real time, never generates quite the same feeling as seeing the 'real thing'. However, it is undeniable that if you want to record the most subtle of the marking on the planet and reveal it with a level of sharpness, clarity and positional accuracy beyond what is feasible using your eye and drawing board, then carefully processing a good-quality video sequence obtained with adequate equipment is most definitely the way to go.

Though there are very many provisos to this generalisation, I would assert that you could potentially record the same level of detail using a fast-frame-rate camera and a 5-inch (127 mm) telescope as you could using a 10-inch (254 mm) visually and drawing what you see. However, going to as big as a 10-inch to 14-inch (254 mm–356 mm) aperture telescope is still desirable for the best photographic results because the disk of the planet is pallid when compared to the terrestrial planets and Jupiter. Having plenty of light to form the image is always good to improve the signal-to-noise ratio. In turn, this allows one to use the processing tools more aggressively on the captured (and usually stacked) image and hence reveal the most subtle details before processing artefacts start to become visible.

Obviously, a high-end fast-frame-rate camera such as the top-of-the-range models by Lumenera, DMK and Atik can potentially produce the best results but good techniques applied to a good telescope can win out even with a cheaper model of camera. Chapters 3 and 4 detail how to go about photographing the planets. I recommend reading these chapters first and will here only add one or two details pertinent to Saturn.

Firstly, one has to take account of the fast rotation of the planet when planning the lengths of AVIs. Any spot or other feature close to the planet's equator will move at something around 0.1 arcsecond every minute relative to the outline of the planet. Features further north or south on the planet will show a slower relative motion. The speeds of the features vary with the cosine of the latitude – the longer-term differential longitude shifts here being ignored. Assembling AVIs through red, green and blue filters may well show smearing or even colour fringes trailing features in the final stacked result, even if the individual AVIs are themselves short. Changing the filters rapidly will help cut down the total time and so a motor-driven filter wheel would be a useful acquisition.

However, the relative dimness of Saturn compared to the other planets adds a conflicting difficulty. That difficulty becomes quite acute when trying to image the planet in colour (as you will normally want to do). A dim planet will require long AVIs, not short ones, if a good signal-to-noise ratio is to be achieved. This is especially so because of the desirability of longer runs made through the blue filter in order to achieve a sufficiently good signal-to-noise ratio (in most cases the CCD is much less sensitive to blue light than to green or red).

Setting the frame rate of the camera to a fairly low value (maybe 5 frames per second) and setting the individual exposure times to the maximum possible at that frame rate will help, at least for the exposures made through a blue filter. The red and green images could be made with setting something nearer your favourite values and the differences compensated for in the final processing.

Adopting an LRGB sequence may be worth a try. L is a monochrome, usually unfiltered, AVI used to give a good image on which the R, G and B coloured images are subsequently added. However, the length of the complete run still cannot be too long if details such as spots and belt irregularities are to be recorded.

Also, don't push the enlargement factor too much. While an effective focal ratio of f/40 or f/50 may produce a great result when imaging Mars, something nearer f/30 may be a better bet for Saturn. With a low-end camera (for instance a webcam), an even smaller effective focal ratio may produce the best final image you could achieve. After all, the effective focal ratio to theoretically record diffraction-limited detail – as set by the Nyquist theorem – is f/17 for a camera with 5.6 μm pixels.

Even focusing becomes difficult if the image is too dim. This also is a difficulty which is ameliorated by not pushing the enlargement too far. Unless the ring system happens to be quite closed up, Cassini's Division should be easy to see and this feature provides a handy aid to finding the best focus. Even a slight misfocusing reduces the apparent blackness and clarity of the division very significantly. At the times when the aspect of the rings appears too narrow for the Cassini division to be seen, the rings themselves can be used to focus on rather more easily than the planet itself.

All the techniques – one-shot DSLR images, one-shot colour AVIs stacked with a humble colour webcam, RGB individual AVIs stacked, even LRGB AVIs stacked, and any of the other variants you prefer to use – can potentially produce pleasing and often valuable results. Don't be put off by the difficulties. Whatever equipment you have can be put to use to produce a result that I feel sure you will be very pleased with. As always, a little experimentation will point the way for you to produce the best possible results with your own set of equipment. Figures 9.6(a), (b) and (c), and 9.7(a), (b) and (c) show some top-of-the-class results from

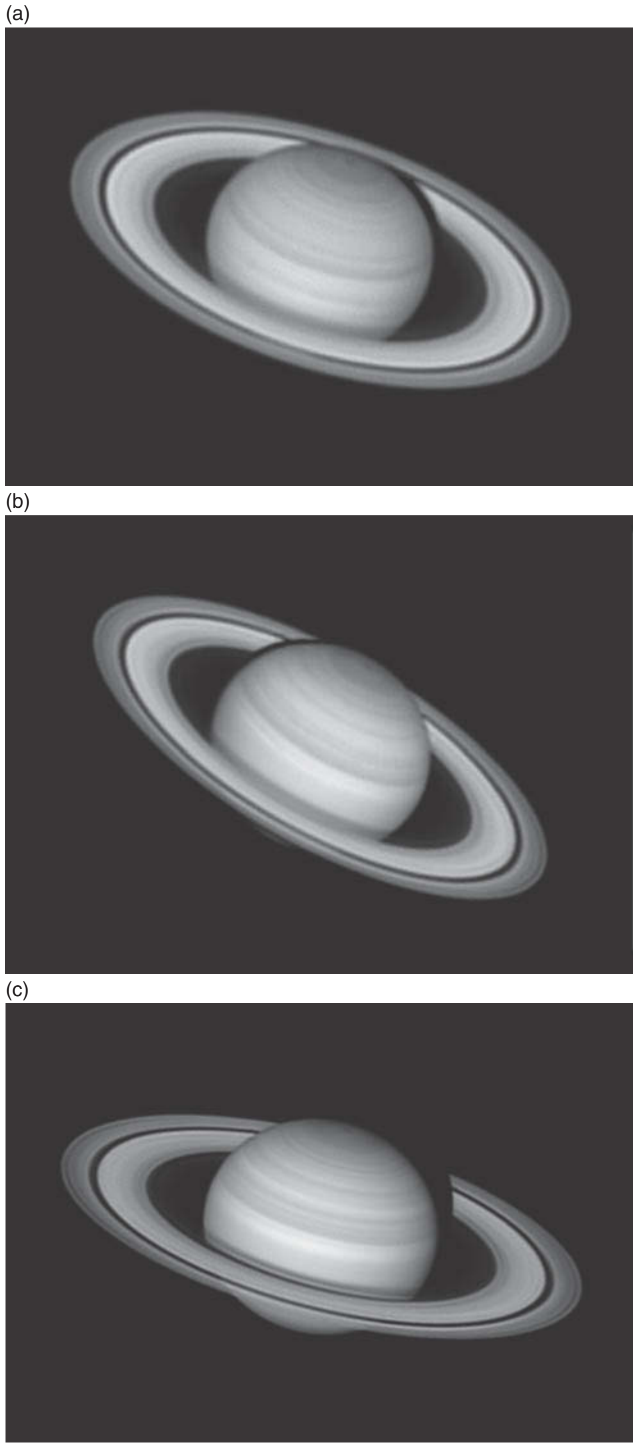


Figure 9.6 Saturn imaged by Damian Peach. (a) 2003 February 19^{d} 19^{h} 48^{m} UT through his 11-inch (280 mm) Schmidt–Cassegrain telescope working at f/31. RGB images taken using a Philiips ToUcan Pro webcam; (b) 2004 December 11^{d} 02^{h} 24^{m} UT through his 9¼-inch (235 mm) Schmidt–Cassegrain telescope working at f/39. RGB image taken using an Atik-1HS camera; (c) 2006 April 11^{d} 23^{h} 48^{m} UT through his 14-inch (356 mm) Schmidt–Cassegrain telescope working at f/42. RGB image using a Lumenera Lu075M camera. Each of these images was captured and processed using *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*. Look at the subtle details in all three rings that Damian has managed to reveal. The difficult and elusive Encke's division is rendered easily seen here! [These figures are also reproduced in colour as Plate V between pages 304 and 305].

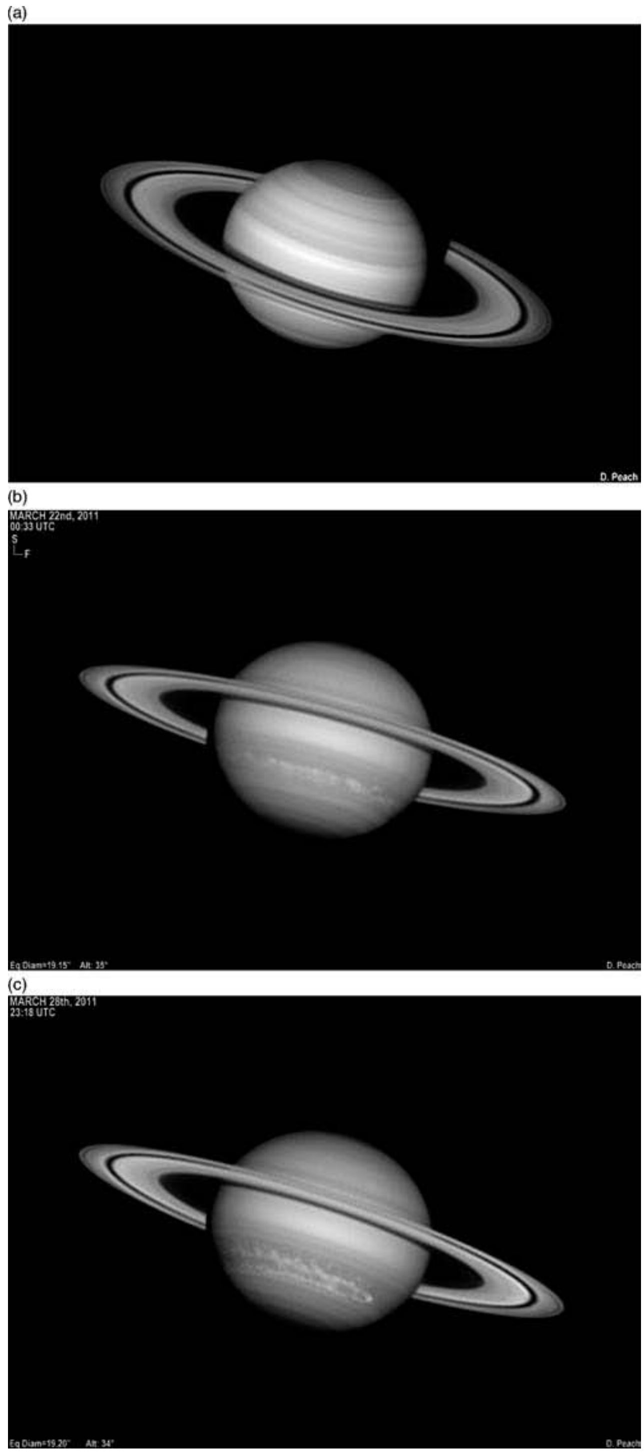


Figure 9.7 More Saturn images by Damian Peach. (a) 2007 May 25^{d} 23^{h} 03^{m} UT using his 14-inch (356 mm) Schmidt–Cassegrain telescope working at f/42. RGB image made using a Lumenera SKYnyx 2.0M camera; (b) 2011 March 22^{d} 00^{h} 33^{m} UT showing the vast and powerful storm stretching around the northern hemisphere of the planet; (c) 2011 March 28^{d} 23^{h} 18^{m} UT showing the 'Serpent Storm' further developed. Images (b) and (c) were each made using Damian's 14-inch (356 mm) Schmidt–Cassegrain telescope working at f/29 and PGR Flea3 camera. All the images were captured and processed in *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*.

Damian Peach. You will find plenty more of them on his 'Images of the Solar System' website.

9.5 SATURN PROBED

After successfully flying past Jupiter late in 1974, the space probe *Pioneer 11* was swung round by the Jovian gravitational field and sent out into space on a course for the planet Saturn, which it passed in September 1979. This probe contributed many interesting results on the magnetic environment about Saturn and the thermal properties of Saturn itself, as well as one of its satellites – Titan. However, the imaging results were disappointing as little detail was seen in the Saturnian cloud belts. Titan looked totally bland.

The ring system provided the most interest; the probe was even scheduled to pass through the ring plane (to the trepidation of many project scientists) and passed through unscathed! Encke's Division was clearly photographed for the first time and an additional ringlet was discovered.

Scientists were completely surprised by the spectacular discoveries made when *Voyager 1* bypassed Saturn in November 1980. These were many and varied. *Voyager 2* followed *Voyager 1* to Saturn, bypassing the planet in August 1981. Since then we have had the ambitious *Cassini–Huygens* dual probe which arrived at the Saturnian environment in 2004. So much has been learned from each of these probes it is best for us to consider each aspect of the planet separately in the following brief summary.

The atmosphere of Saturn

Spectroscopic analysis of the atmospheres of Jupiter and Saturn carried out in the 1930s had indicated that the compositions of the atmospheres of the planets were very similar. The chief constituents are hydrogen and compounds of hydrogen, such as methane and ammonia. More recent infrared measures indicate that the temperature in the upper levels of Saturn's atmosphere is about −180 °C. This is cooler than at Jupiter's cloud tops, but nevertheless warmer than was to be expected if the Sun is the only source of the planet's heat. It seems that Saturn, like Jupiter, radiates more than twice the heat it receives from the Sun.

The computer-enhanced images from the *Voyager* craft confirmed our expectation of a cloud morphology outwardly similar to that of Jupiter. Puffy and chevron-shaped clouds were found, as well as a multitude of white spots and even a small red spot. There are differences between the atmospheres of Jupiter and Saturn, particularly in the distribution of the various wind currents. For instance, a wide band of cloud centered on Saturn's equatorial regions is moving at a remarkable 1800 m/s relative to the 'internal' rotation rate of Saturn (as determined by radio observations of the emissions of Saturn's interior).

Saturn's atmosphere seems more thoroughly mixed, in terms of the different chemical constituents, than is the case with Jupiter's atmosphere. This, together with the high-level haze layer, partly explains the absence of the bright colour-contrasts so characteristic of the Jovian envelope.

The structure of Saturn

Like Jupiter and the Sun, Saturn is essentially composed of about 90% hydrogen and 10% helium. We think that it possesses a 16 000 km diameter core, made of silicates, overlaid by a 8000 km deep layer of ices, over which lies a 14 000 km deep mantle of metallic hydrogen, over which is a planet-wide ocean of liquid hydrogen nearly 30 000 km deep. Over this lies the cloudy atmosphere. The pressure at the surface of the core is thought to be about 10 million atmospheres, while the temperature there is about 14 000 °C.

According to the theorists, gravitational contraction is only responsible for part of the heat energy that Saturn releases into space. They think that the conditions are correct for droplets of helium to form in the upper part of the metallic hydrogen layer. These droplets then make their way down towards the centre of the planet, releasing gravitational potential energy as they do so. In other words, a sort of 'internal rain' of helium is responsible for most of the observed release of the planet's internal heat energy.

A byproduct of this proposed mechanism is that it neatly explains an observed depletion of helium in Saturn's outer layers. The outermost regions of the planet appear to be composed of about 93% hydrogen and about 7% helium, but the average composition of the globe is thought to resemble that of Jupiter, as indicated earlier.

Saturn's magnetosphere

Saturn's magnetosphere, though large by planetary standards, is rather smaller and weaker than Jupiter's vast and intense field. A measure of the overall strength of the magnetic field is given by a quantity known as the *dipole moment*. For Saturn, this is 550 times that of the Earth's field. Jupiter's field has a dipole moment ten times stronger still. However, the magnetic field strength (also known as the *flux density*) at Saturn's cloud tops is roughly equal to the magnetic field strength at the surface of the Earth.

The value of the dipole moment takes into account the physical size of the magnetic field as well as its strength. Saturn's magnetosphere extends to about ten Saturn-diameters in the sunward direction. A long magnetotail extends in the opposite direction, as is the case for Jupiter. Like Jupiter's magnetic field, north and south are in the opposite direction to the Earth's field. Saturn's magnetic field is unique in that the magnetic and rotation axes are aligned to within one degree.

A peculiar radio emission was detected by the *Voyager* craft on their approaches to Saturn. The emission appears to emanate from two sources, one in the northern hemisphere of the planet and one in the southern hemisphere. Neither source rotates with the planet, but both remain aligned to the Sun, though the strength of the radio emission varies with a period of 10 hours 39.4 minutes. We assume that this period reflects the rotation of the inner portions of Saturn's globe. Radiation zones surround Saturn, though these are much less intense than those around Jupiter.

It is the earthly magnetosphere that is responsible for the aurorae seen in our skies. Saturn's extensive magnetosphere is also responsible for capturing solar wind particles and funneling them to create aurorae at Saturn's poles. In the case of Saturn, there is some evidence that particles ejected from one or more of Saturn's moons (Enceladus is a prime suspect) may also contribute.

The rings of Saturn

It has long been realised that Saturn's ring system cannot be made of a solid sheet of matter. In accordance with Kepler's laws, the inner parts of the ring system would 'want' to move round the planet rapidly, while the outer parts would 'want' to move more slowly. If the rings did rotate as a solid sheet then the outer parts would be forced to move more rapidly than the inner zones. The result is that the rings would be torn apart by shearing forces. In 1895, James Keeler turned a spectroscope on Saturn's ring system and measured the Doppler shift of light from various parts of it. In doing so he proved that the rings were indeed composed of innumerable particles, each separately orbiting the planet and obeying Kepler's laws.

Optical studies of Saturn's rings have shown us that most of the particles composing them range in size from a centimetre or so to several metres. The particles are highly reflective and are thought to be composed of ices, though there are differences in colour and reflectivity between the different ring components.

The Saturnian ring system is incredibly thin and flat. Before the space probe encounters we knew that the rings could be no more than a few

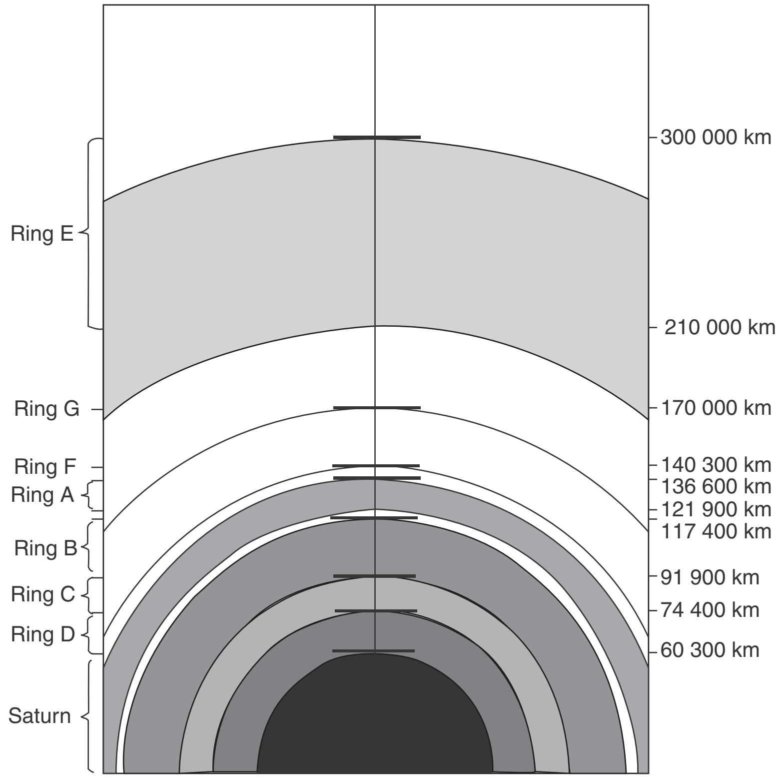


Figure 9.8 Saturn's rings A to G as revealed by the *Voyager* 1 space probe. The labels on the left of this diagram and the figures on its right correspond to the markers on the line drawn down its centre. Recently, a further huge 'doughnut' of dust has been discovered much further out from the planet as detailed in the main text.

kilometres thick. In fact, they have a thickness of no more than about 50 metres! Considering that the bright rings span 274 000 km, this is truly remarkable. From time to time other ring components and divisions in the rings had been reported by Earth-based observers but these features were so elusive that confirmation had to wait until the *Pioneer* and *Voyager* craft arrived in Saturn's vicinity. Four further rings were found, and they have been labelled rings D, F, G and E. In increasing distance from Saturn the rings are: D, C, B, A, F, G and E (see Figure 9.8).

Much more recently, an extremely tenuous but extremely large dusty doughnut, spanning over 36 million kilometres in diameter and something like 2½ million kilometres thick, has been discovered to encircle Saturn. The discovery was made using the Spitzer Space Telescope at infrared wavelengths. The source of the ring material has been identified as meteorite impacts over time knocking some material off the outermost Saturnian moon Phoebe.

As *Voyager 1* approached Saturn in 1980, Cassini's Division and Encke's Division were visible from afar but, surprisingly, other divisions also became visible. When the probe was close to Saturn the rings were seen to be not bland sheets but rather composed of thousands of individual concentric ringlets.

Most of the individual ringlets are circular but some were found that are slightly eccentric. Also, the major divisions, such as Cassini's, are not empty of ring particles but have thinly populated ringlets of their own. One particularly peculiar feature is the F ring. Close-range photographs show this ring to be formed of three components that appear to be 'braided' or 'plaited', together with occasional bright knots along its length.

Another *Voyager* surprise was the existence of radial 'spokes', or dark, finger-like shadings, on the rings. Theoretically, any such features to form in the rings ought to be sheared by differential rotation, but the spokes preserve their identities for one or two rotations, though some shearing does occur in this time. One explanation for their existence is that very fine particles in the rings are electrically charged (by friction – in the same manner as terrestrial thunderstorm clouds) and are levitated above and below the ring plane. The precise mechanism that causes the levitation is uncertain, though Saturn's magnetic field is thought to be a factor. A very small number of amateur observers do seem to be able to faintly see these spokes. The majority do not and I have never seen the slightest hint of them through any telescope I have ever used.

The major divisions in Saturn's rings were formerly attributed to resonance effects with Saturn's extensive family of satellites. For instance, Cassini's Division is situated where a ring particle would have a period half that of one of Saturn's major moons, Mimas. A particle in this zone would experience a gravitational tug from Mimas twice every orbit. Gradually any particles in the zone would be swept into different orbits, leaving it particle-free. The *Voyager* results have not caused us to abandon this explanation, but other processes also occur to produce the thousands of ringlets observed.

The ringlets are caused by small *shepherding satellites*. The mechanism is illustrated in Figure 9.9. In (a) the satellite S_1, which is moving more slowly than the particles in the ringlet, causes the outermost particles to be slowed down and to drop in orbital radius as a consequence. Meanwhile the satellite S_2 causes nearby ring particles to speed up and be driven into higher orbits. In this way the two satellites cause the particles to be confined in a narrow ringlet.

In (b) a satellite lies inside the ringlet and forces particles in higher and lower orbits to exchange momentum when they pass near the satellite. Eventually they settle into the ringlet. Both mechanisms are in operation, in addition to the classical resonance mechanism.

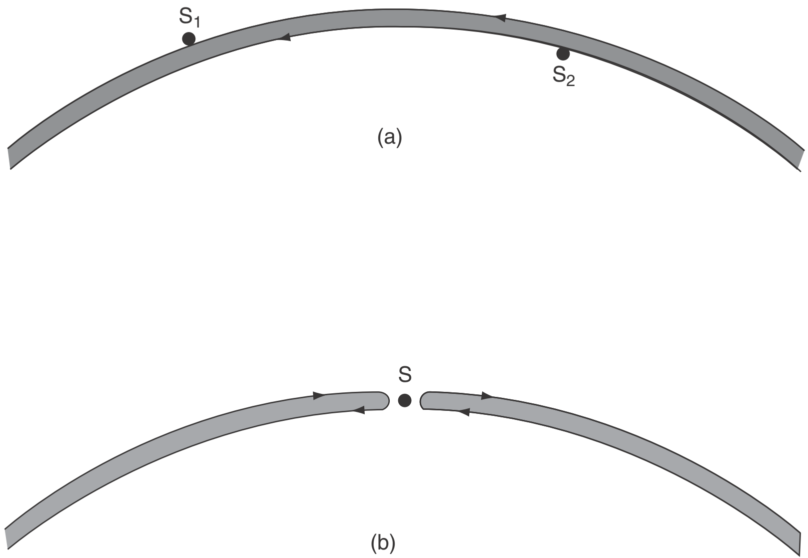


Figure 9.9 Illustrating the mechanisms of ring shepherding by small satellites, as described in the main text.

Seen from afar, Saturn's rings appear like solid sheets. Seen at close range, the rings are seen to be composed of thousands of ringlets. Seen very close up, the ringlets themselves are composed of little groupings of small chunks of ice, with a thinner distribution of icy chunks and material in-between. If they could be watched over a short period the clumps themselves would be seen to change, with some clumps dispersing and new ones forming due to small-scale individual motions of the component icy bodies within the ringlet. As nearby satellites (even the smallest ones) pass, so the ringlet material becomes even more stirred up. Undulating ripples and other minor distortions have been photographed from the *Cassini* probe, for instance. The once-perplexing twisted form of the F ring has now been explained as the result of gravitational interaction with two of the tiny moonlets, called Prometheus and Pandora. So, on the large scale, the rings seem serenely constant and unchanging. On the small scale, you could perhaps describe them as quietly dynamic.

A number of the existing satellites of Saturn are actually the sources of the materials in some of the rings. One example of this is a tiny moonlet, which is actually the sixty-first of the discovered satellites orbiting Saturn. It lies inside a bright arc, which is a local brightening in the extremely tenuous G ring. This is not thought to be a coincidence. In fact, meteorite and micrometeorite impacts on this ring cause particles to leave this moonlet and form the ring. Another instance of a satellite (this time Enceladus) being the source of ring material is described shortly.

9.6 THE SATELLITES OF SATURN

Saturn has the most extensive satellite system of any planet in the Solar System. The first satellite to be discovered and, at magnitude $8^m.3$ the brightest of Saturn's family, is Titan. It was found by Christian Huygens in 1665. In the late seventeenth century Cassini discovered Iapetus (magnitude averages roughly $11^m.0$), Rhea (magnitude $9^m.8$), Dione (magnitude $10^m.4$) and Tethys (magnitude $10^m.3$).

William Herschel, using his 1.2 m aperture telescope, found two more moons in 1789: Mimas (magnitude $12^m.9$) and Enceladus (magnitude $11^m.7$). William Bond added to the list with his discovery of Hyperion (magnitude $13^m.0$) in 1848, while William Pickering found the faint (magnitude $16^m.5$) Phoebe in 1898.

With the possible exception of Titan, all of Saturn's satellites are much less easy to see than one might think, given their magnitudes. This is because they are immersed in the glare from Saturn itself. They are seen at their best when the rings are presented edge-on to us. It was at the edgewise opposition of 1966 that Audouin Dolfus found a new faint satellite – Janus – orbiting close to Saturn. American astronomers found another satellite that shared Janus's orbit and in the edgewise opposition of 1980 a twelfth faint satellite was discovered. The *Voyager* probes increased the tally to more than twenty. At the time of writing the total has been increased to more than sixty. Next we will look at just the chief moons. After that Titan is discussed separately.

Mimas

Mimas orbits Saturn at a mean distance of 185 000 km. It is approximately spherical with a diameter of only 396 km. It is mainly composed of ices, and it has a mean density of 1200 kg/m^3. The surface of the satellite, a pale brown covering of 'dirty ice', is heavily cratered. It sports one massive crater named Herschel that is 130 km across, and so more than a quarter of the diameter of the satellite itself. The impact that caused this crater must have come close to shattering the satellite entirely.

Enceladus

Enceladus orbits at a distance of 238 000 km from Saturn, passing through Saturn's diffuse E ring. Its 498 km diameter globe seems to be mainly composed of ices. Its density is slightly less than Mimas at 1100 kg/m^3. Enceladus has a bright, whitish, surface that is partially cratered but it is the swirling pattern of cracks and gouges that are most striking. Those at the south pole of Enceladus are deepest and the eight most prominent ones are now known as *Tiger Stripes*. A recent discovery has been that these Tiger Stripes are the sites of geysers that spew vast quantities of water vapour mixed with nitrogen, carbon dioxide and some volatile organic compounds into space. Ice crystals condense from the water vapour and go into orbit around Saturn. In fact, it is the geysers of Enceladus that are the source of the material that composes Saturn's E ring! It seems likely that Enceladus has a sub-surface ocean, at the very least under its south pole and maybe it is even more extensive, but theorists are currently still working out just how this little moon can be as active as it clearly is.

Tethys

Tethys orbits beyond Enceladus at a mean distance of 295 000 km from Saturn. It is rather larger than Enceladus, its diameter being 1050 km, but is less dense. The mean density of Tethys is only 1000 kg/m^3, indicating it is also composed of ices. It has a pale brown and heavily cratered surface. One striking feature is an enormous rift valley that splits the surface, which perhaps was created when the sub-surface fluids froze and expanded after the outer crust solidified soon after this satellite formed.

Dione

Dione orbits Saturn at a mean distance of 377 000 km. It is similar in size to Tethys, but obviously has a different composition, since its density is 1400 kg/m^3. Dione's rather greyish surface shows a distinctive pattern of bright radial streaks and areas of heavy cratering. It has an overall diameter of 1120 km.

Rhea

Rhea orbits Saturn at a mean distance of 527 000 km. It is larger than Dione, having a diameter of 1530 km, and is only slightly less dense. Rhea displays a highly reflective, pinkish, surface, which is oddly different in each of its hemispheres. One is heavily cratered but the other is rather bland, save for bright patches and streaks.

Hyperion

Hyperion orbits Saturn at a mean distance of 1 481 000 km. It is a small oblate body, having a mean diameter of only 290 km. It has to be amongst the oddest-looking satellites in the Solar System. It has an icy surface, which is more than just heavily pitted. It actually looks rather like a sponge. This has led some to speculate that Hyperion might be a captured comet nucleus.

Iapetus

Iapetus orbits Saturn at a mean distance of 3 560 000 km. It is much larger than Hyperion, having a diameter of 1440 km and a mean density of 1200 kg/m^3. Iapetus is peculiar in having two distinctly different surface coverings. On its leading hemisphere as it orbits Saturn (it has a captured rotation) Iapetus is covered in a very dark, brownish, material. This causes the apparent magnitude of the satellite to vary from $10^{m}.2$ to $11^{m}.9$ as seen from Earth. The trailing hemisphere sports an icy surface nearly six times brighter.

The recent discovery of the enormous dusty doughnut surrounding Saturn possibly explains the source of the dark material. It seems likely that some of it migrates into the orbit of Iapetus and the little moon sweeps it up onto its leading face. Not everybody agrees with this conjecture. The difference in brightnesses is certainly accentuated by some of the ice vaporising from the dark hemisphere, then migrating to the other and re-freezing there to give a bright frosty covering. Some insist that this is the only mechanism operating to cause the asymmetry.

Phoebe

Phoebe is the outermost known satellite of Saturn's retinue, orbiting at a mean distance of 12 930 000 km from the planet in a retrograde, highly inclined, and very eccentric orbit. Its diameter is only about 140 km, and it is thought to be a captured body, not an original satellite of Saturn.

9.7 TITAN

Orbiting at a mean distance of 1 222 000 km from Saturn (between the orbits of Rhea and Hyperion), Titan is the biggest of Saturn's satellites. In fact it is even bigger than the planet Mercury. Its 5120 km diameter and 1900 kg/m^3 density also makes it the most massive of the Saturnian moons.

Titan is the only satellite known to be surrounded by a substantial atmosphere. Its opaque, cloudy, mantle gives it a distinctly orange colour and a very bland visual appearance. The cloudy covering is so total that no surface details were visible to *Voyager 1*. This is a situation reminiscent of the planet Venus, though we must be careful to realise that the two worlds are totally different. For instance, the temperature on Titan averages a frigid −179 °C, compared with the fiery heat at Venus's surface.

A surprising discovery of the *Voyager* programme was that the atmosphere of Titan is composed of about 90% nitrogen, with methane making up most of the rest. The atmospheric pressure at the surface of Titan is about 50% greater than that at the surface of the Earth.

Nitrogen and methane are both dissociated in Titan's upper atmosphere by solar radiation. As a result of chemical recombination, hydrogen cyanide and other more exotic organic compounds are formed. These compounds are thought to be responsible for the orange colouration. Scientists speculated that the conditions might be correct for a rain of liquid methane and ethane, laced with other organic compounds, to fall on Titan's surface. Some thought that Titan might have substantial oceans of liquid methane and ethane covering its frigid surface.

This enigmatic globe was ripe for a space probe visitation and in October 1997 the ambitious *Cassini/Huygens* mission was launched. This probe is a collaborative effort between NASA, the European Space Agency, and the Italian Space Agency. The space probe entered Saturn's orbit in July 2004. The *Cassini* part of the probe began sending us back pictures and data from a wide variety of instruments about Saturn and its rings and moons.

However, the part of the mission that generated the greatest news coverage and popular interest was the *Huygens* lander. It was separated from *Cassini* on Christmas day 2004 and dispatched on a three week journey towards Titan. On 14 January 2005 it ploughed into Titan's thick atmosphere, a pilot parachute eventually opening to further slow its decent. Then, discarding the pilot parachute, a larger one was deployed to further slow the craft, until this too was jettisoned and a final small stabilising parachute was used for the final drop to landfall. During the entire 2 hours 27 minutes that it descended towards the surface the probe sent us back telemetry of the conditions it encountered as well as photographs.

It thudded onto a hard surface at 5 m/s, breaking through and being finally brought to rest by imbedding itself a further 10–15 centimetres in a type of 'soil' with some plastic give in it. Interestingly, shortly afterwards one of its detectors registered an intensification of methane gas in its local environment. It is tempting to think that *Huygens* landed on a slightly slushy methane snow, perhaps with a hard water-ice top covering.

The pictures it sent back during its descent and once on the surface indicate a terrain of water-ice rocks with indications of an active methane-driven weather system. There was plenty of evidence of dry river beds, and river deltas. Indeed, the landing site – a fairly flat plain littered with smoothed slab-like 'rocks' of ice – showed all the evidence of being a dried-up river bed.

Scientists were surprised at the vaguely Earth-like appearance of the topography. They were also initially surprised by the apparent lack of hydrocarbon liquids and by how little ethane they could detect. However, it must be remembered that *Huygens* only visited one location.

In fact subsequent flybys of Titan made by the *Cassini* probe had revealed (to various of its instruments, in particular its radar-imaging device) indications of vast lakes of liquid hydrocarbon in the north polar regions of the satellite. There were also indications of other large bodies of liquid in the southern polar regions. Other Earth-based long-term observations and theoretical studies have also indicated methane-driven storm systems, complete with flash-floods and hurricanes! The atmospheric pressure and temperature on Titan allows methane to take on a rôle comparable to that of water on the Earth.

The topographic features revealed by subsequent *Cassini* flybys include vast ranges of ice mountains, dry river beds and other fluid-cut channels, and dunes where the 'sand' is composed of ice particles coated in organic matter (please note 'organic' here refers to the purely chemical definition of compounds of carbon). At least one of the features imaged might well be a *cryovolcano* (one that erupts icy materials, rather than high-temperature lavas), though this interpretation is not definite at the time I write these words.

A real oddity is that there seems to be a slight slippage of Titan's axial rotation. Its rotation should be exactly the same as its orbital period (a captured rotation, as is also the case for the Moon orbiting the Earth). Instead, it is very slightly different. There has also been a very tiny change in the rotation rate of Titan in the several years that Cassini has been monitoring it. The only feasible explanation, assuming the observations are correct, is that the crust of Titan floats on a layer of liquid (speculated to be ammoniated water) and is entirely detached from the main body of this little world!

In biochemical terms, some think that the conditions on Titan may one day be suitable for the initiation of life, though probably not for several billions of years. By then the Sun may have increased its temperature sufficiently to allow some form of life to develop on this exotic world. Of course by that time the Earth will be a roasted and dead globe in the fiery inner regions of the Solar System.

9.8 SATURN'S MOONS AND THE AMATEUR ASTRONOMER

Even mighty Titan only spans a mere 0.8 arcseconds at best from our vantage point. Theoretically you could resolve this disk visually though a moderately sized amateur telescope, though processing the image stack created using a fast-frame-rate CCD video camera would give you a better chance in practice. Even with an image showing a well-defined disk there will be no details to see.

Monitoring the brightness of Titan over the longest possible period of time is something which the more advanced amateur can do. At least one American amateur astronomer (who is also a professional physicist), Ralph Lorenz, has monitored its brightness and has detected seasonal reflectivity variations in Titan's upper atmosphere, previously identified by professional studies.

I cover the techniques of photometry in Chapter 10. I recommend that you should especially read Sections 10.8 through to 10.13 if you intend to undertake photometry of planetary moons. In the case of Saturn, the moons other than Titan are even more difficult to follow photometrically because they are so much fainter.

Photographing the moons is easy in theory but you will need to find a balance between the minimum exposure needed to show the moons and the longest you can expose for before the light from Saturn and its rings swamps the image. You can also 'cheat' by artificially creating an unsharp mask, or perhaps trying out any of the available contrast compression filters (such as the one known as 'DDP') during processing in order to suppress the light from the planet whilst allowing the satellites still to shine forth in the final image.

I think it fair to say that most amateur astronomers will be content just to see and correctly identify these moons. Recourse to ephemerides or planetarium software will aid with the identifications. Either resource can also alert you to potentially observable transits of any of the satellites across the disk of the planet. They can occur at times when the rings are near to their most edgewise as seen from Earth.

As well as the satellite appearing to move slowly across the disk of the planet, there is also the accompanying shadow of the satellite cast onto the disk of the planet to be seen. In fact, the shadows are usually easier to see than the satellites casting them, as they appear as black spots. Of course the satellites can also be occulted by the planet as they pass behind it as seen from our viewpoint. Very rarely, planetary satellites can even pass in front of each other. As you would imagine there is always a great deal of enthusiasm for these rare mutual events within the astronomical community.

Before we leave Saturn and head outwards into the twilight zone of the Solar System, I must mention a particularly good book you might find of interest and of real use: *Saturn and How to Observe It*, by Julius Benton (published by Springer-Verlag in 2005).

9.9 THE DISCOVERY OF THE PLANET URANUS

Since the time of the ancient scholars we thought that the Solar System consisted of just the Earth, the Sun, the Moon and the planets Mercury, Venus, Mars, Jupiter and Saturn. That view persisted long after the invention of the telescope. Then, in 1781, the academic world received a rude shock when an amateur astronomer discovered another planet with his homemade reflecting telescope!

Friedrich Wilhelm Herschel was born in Hanover in 1738 and moved to England in 1757. He adopted the name of William Herschel. Later, his sister Caroline joined him in Georgian England. William obtained various musical posts and eventually settled in the spa town of Bath, where he became an organist at the local chapel.

Herschel's fascination with science, and particularly astronomy, was able to prosper amid his settled life in Bath but the high prices of contemporary telescopes were prohibitive and so he set about making them for himself (and for others, in order to boost his income). He was an energetic observer and theorist. In time, he made many valuable contributions to various areas of astronomy.

Quite early in Herschel's astronomical career he made an accidental discovery that was to change his life. It also doubled the known size of the Solar System! It concerned an observation he made in March 1781 using his 6.2-inch (157 mm) Newtonian reflector of 85.2 inches (2.16 m) focal length. He wrote a paper, 'Account of a Comet', which was communicated to the Royal Society by his friend, Dr William Watson. The first part of the account read:

> On Tuesday the 13th of March, between ten and eleven in the evening, while I was examining the small stars in the neighbourhood of H Geminorum, I perceived one that was visibly larger than the rest: being struck by its uncommon magnitude, I compared it to H Geminorum and the small star in the quartile between Auriga and Gemini, and finding it to be so much larger than either of them, suspected it to be a comet.

It soon became apparent to astronomers that Herschel's object did not follow the path of a comet. Its motions revealed it to be a planet orbiting the Sun at twice the distance of Saturn. Instantly famous, Herschel was knighted and appointed astronomer to King George III. The small bursary that went with this position allowed him to devote much more time to his astronomical interests. In gratitude Herschel named his planet 'Georgium Sidus' (George's Star) but the astronomer Lalande suggested the name 'Herschel' and Johannes Bode suggested 'Uranus'. The latter, mythological, name was felt to be in keeping with those of the other planets and came into common use.

Continued observations soon unearthed the main properties of this new world, though refinements to the various measurements and some discoveries had to wait until modern times. Uranus moves in an orbit 2868 million km from the Sun, with a sidereal period of 84.1 years.

Owing to the long orbital period of the planet, it comes into opposition only about 4½ days later each year. Uranus's diameter is 51 118 km and its mass is 14½ times that of the Earth. This gives it a mean density of 1244 kg/m^3.

9.10 URANUS IN DETAIL

Uranus has remained under constant telescopic scrutiny since its discovery. A fair amount was discovered and deduced by Earth-based studies but we had to wait until the arrival of the *Voyager 2* space probe in January 1986 before we could really firm-up our knowledge of the planet. Here follows a necessarily brief summary of the main facts.

Uranus's upper atmosphere is very clear, mainly composed of hydrogen, helium and methane. It is the selective absorption of sunlight by methane that gives rise to the colour of the planet. Infrared measures indicate that the temperature of the lower atmosphere is a frigid −220°C. The planet is thought to have a relatively small rock core overlaid by a deep mantle of ices, thought to be composed of water, ammonia and methane. Over this is the deep atmosphere mostly composed of hydrogen, helium and methane. If you read older books you will find the planet referred to as a 'gas-giant' planet, along with Jupiter, Saturn, and Neptune. More about Neptune shortly, suffice it to say it is now becoming fashionable to refer to Uranus and Neptune as 'ice-giant' planets, thanks to the vast amount of water-ice each are thought to contain.

One major oddity of Uranus is that its rotation axis is much more inclined than any of the other planets. In fact, it is inclined by 98° to the perpendicular to the plane of its orbit. So, Uranus technically spins in the retrograde direction! A consequence is that, despite the 15½-hour rotation rate of the planet, its poles experience continuous periods of sunlight and darkness, each 42 years long. From the Earth we see first the south pole presented to us, then the equator, then the north pole, then the equator and then the south pole again, over a cycle of 84 years.

Astronomers are interested when the motions of a planet cause it to occult a star, since the way the light changes upon immersion and egress gives accurate information on the atmosphere of a planet as well as the planet's diameter. With these objectives in mind, astronomers observed the occultation of the star SAO 158687 in March 1977. Observation groups were set up at various locations all over the world to observe the event. Most of these groups were successful. Indeed, the astronomers received an added bonus. The star was seen to flicker and dim a number of times before the disk of Uranus occulted it. The flickering was repeated some while after the main disk of Uranus cleared the star.

A set of dark rings had been discovered to encircle the planet in its equatorial plane.

Nine ring components were identified from this event, all thin and narrow; the innermost ring having a radius of 38 000 km, the outermost of them having a radius of 51 000 km. Further discoveries were to result from the *Voyager 2* encounter.

As the probe approached Uranus it became apparent that the cyan disk of the planet was extremely uniform and featureless when imaged in visible wavelengths. Subjecting the *Voyager* images to a large amount of computer enhancement revealed some detail. It was found that the sunlit pole (at the time of encounter the planet's south pole was pointed sunward) is very slightly redder and more reflective than the equatorial regions. This was thought to be due to a haze of hydrocarbon molecules, such as acetylene (modern name ethyne, C_2H_2).

Visible at middle latitudes, rotating round the planet with periods of 15½ to 16¼ hours, were a few vague clouds, which scientists thought might have been formed from simple organic compounds, such as acetylene.

Project scientists discovered a further, tenth, ring in the *Voyager* images. This ring is situated between the outermost pair previously known. Fast-forwarding for a moment, other rings have recently been discovered and there are strong indications that further excessively faint ones are awaiting confirmation. At the time I write these words we know of 13 definite rings. The outermost of them has a radius of 97 000 km. Some of the Uranian rings appear to be made of large chunks of dark rock, averaging about 1m in diameter. Others are made of very fine material. All the rings are very narrow and thin. Some vary in particle density around the planet – more like arcs than complete rings.

The *Voyager* probe detectors found that Uranus's magnetic field is dipolar in form, like that of the other planets. The magnetic polarity is in the same sense as Jupiter's and Saturn's fields – in other words, magnetic north and south are inverted by comparison with the Earth's field. The dipole moment of Uranus's magnetic field is roughly a tenth that of Saturn, though the flux density at the surface of Uranus is a little stronger than that at the surface of Saturn. The magnetosphere extends for about nine Uranus diameters in the sunward direction.

One of the biggest surprises of all is that the magnetic axis is inclined at 60° to the rotation axis. In no other planet is the magnetic tilt so large. Remember, also, that the rotation axis is canted over at more than a right angle. Neither does the magnetic axis pass through the center of the planet; it is, instead, offset by thousands of kilometres.

The rotation period of the magnetic field, thought to be the same as that of the planet's interior, was measured at 17¼ hours. This is substantially longer than the rotation of its atmosphere, and means that the winds on the planet always blow from the direction of rotation.

One peculiarity is that Uranus is immersed in a vast cloud of hydrogen gas. This gas appears to be responsible for an aurora-type glow in ultraviolet wavelengths, the *electroglow*, covering just the sunlit hemisphere of the planet. It takes place between about 1000 and 2000 km above the visible atmospheric layers. The glow appears to be caused by high-energy electrons colliding with the hydrogen atoms. Perhaps these electrons result from some of the hydrogen atoms being split into their component electrons and protons by the short-wave radiations from the Sun. This would explain their source, but not how they are accelerated to high kinetic energies.

Recent Hubble Space Telescope (HST) images taken of Uranus in visible light and, especially, Keck telescope images in the infrared have shown white clouds formed at mid-southern latitudes as well as variations in the brightnesses of some light bands parallel to the planet's equator. Clearly the bland appearance at the time of the *Voyager* encounter is not the permanent situation. Uranus has seasons that are very extreme compared to other planets, thanks to its 98° axial tilt. This planet is different from the other gas-giants in that, according to *Voyager* probe measurements, it has no internal supply of heat to invigorate its weather systems.

9.11 THE SATELLITES OF URANUS

Before the *Voyager 2* encounter, five moons were known to orbit Uranus. In increasing distance from the planet they are: Miranda, Ariel, Umbriel, Titania and Oberon. The brightest of these, Titania and Oberon, were discovered by Herschel in 1787. Ariel and Umbriel were discovered by William Lassell in 1851 and the fifth brightest, Miranda, was discovered by Gerard Kuiper in 1948.

Voyager 2 obtained close-up views of Uranus's five major moons, as well as discovering a further ten minor moonlets. Refined techniques have since increased the total number of satellites to 27 at the time I write these words. None of the satellites are larger than 1600 km across and, in the intense cold nearly three billion kilometres from the Sun, little was expected in the way of evidence of geological activity. Yet again the planetary scientists were to be surprised. The group of five major moons all orbit beyond the ring system. Here I offer just the briefest details about them.

Oberon

Oberon's mottled and cratered surface displayed many bright craters surrounded by bright ray systems. Many of the crater floors have dark patches in them, as if 'dirty water' had erupted in an icy form of volcanism. This satellite is the outermost of Uranus's retinue and is the second largest, with a diameter of 1523 km. Its orbital radius is 583 000 km.

Titania

Titania is the largest moon, with a diameter of 1578 km. This satellite orbits at 436 000 km from Uranus. The *Voyager* cameras showed Titania to have a pock-marked surface crossed by great canyons and valleys.

Umbriel

Umbriel, orbiting 266 000 km from Uranus, has a strangely dark covering over its entire 1172 km diameter globe. Ancient-looking craters abound on its surface. At least this satellite seems to have the expected quiescent surface.

Ariel

Ariel produced universal surprise when the first of the *Voyager* pictures arrived after their long journey back to Earth. Its 1158 km diameter globe was seen to be covered in a network of colossal grooves and valleys. There is evidence that warmed ice has been forced up from the interior and flowed over some parts of the surface some time in the past. This satellite moves round Uranus at a distance of 191 000 km.

Miranda

Miranda, 129 300 km from Uranus, is the most astounding of the Uranian satellites. Its bizarre surface looks like a patchwork quilt of different sorts of terrain. Patterns of deep grooves swirl across its surface in several places. In others there are no grooves but just rough and hummocky ground covered in craters. Enormous, jagged cliffs soar up from its surface in the borders between the different types of terrain. Miranda is a small body, only about 472 km across, but its surface speaks of past activity on a fantastic scale.

Most scientists think that Miranda has been smashed into several large pieces by a collision, perhaps with another moon or an asteroid, and has later reassembled into its present form. Maybe some past cataclysmic event is responsible for the appearances of Miranda and Ariel (and perhaps also the other moons), as well as the strange axial tilt of

Uranus and the inclination of its magnetic field. *Voyager 2* may have told us much about Uranus but we still have a great deal to learn.

9.12 URANUS AND THE AMATEUR ASTRONOMER

Uranus appears in our sky as a star-like object of the sixth magnitude (around $5^{m}.6$ at opposition) so it can be seen with the naked eye on a really clear night. Only very rarely do I ever see stars of that magnitude midway up in the sky and I have never even tried to pick out the planet amongst the stars with my unaided eye.

You will require an ephemeris or a planetarium programme in order to identify Uranus against a starfield if your telescope needs to be set manually onto its target. A GOTO mounted telescope would obviously be a great convenience, provided it is set up accurately. I have much more to say about techniques for tracking down targets too faint to see with the naked eye in Chapter 10 (Section 10.7).

Seen through a telescope, Uranus sports a cyan-coloured disk which is a mere 3.9 arcseconds in diameter at the time of opposition. Its distance from us, and therefore its apparent size, varies by only 10 per cent during the course of the year. You will need a magnification of around $\times 500$ in order to enlarge the disk of the planet to the same apparent size as our Moon seen with the unaided eye. Of course, you will need a big telescope and unusually good seeing conditions to get a sharp image with that sort of magnification. Even then, any disk detail that might be present is going to be extremely hard to see.

As already mentioned, a couple of decades ago Uranus was presented with its south pole facing the Sun (and us) and the planet displayed a very blank visage. The southern hemisphere was uniformly bathed in weak sunlight and the northern hemisphere was in constant darkness. Now the planet is more equator-on to the Sun and us and things on the planet have changed. Both hemispheres are now getting their daily dose of daylight and night and the Uranian weather systems have come out of hibernation, so-to-speak. The sharpest optical eyes (particularly the Hubble Space Telescope and the largest Earth-based telescopes fitted with adaptive optics) have shown us that the atmosphere has come alive, and banding, clouds and spots have become prevalent.

Uranus's equator became edge-on to the Sun in December 2007 and it will not be until 2028 that the north pole will be entirely facing the Sun and we might expect the planet to present a blank visage to us once more. Also, the declination of the planet is improving from year to year from the point of view of observers stationed in the Earth's northern hemisphere. So, now and for the next decade and a half the time is particularly ripe to study the planet.

PLATE I (upper) The great auroral storm of 1989 March 13^{d}. (lower) The garden-friendly colour scheme of the author's observatory dome.

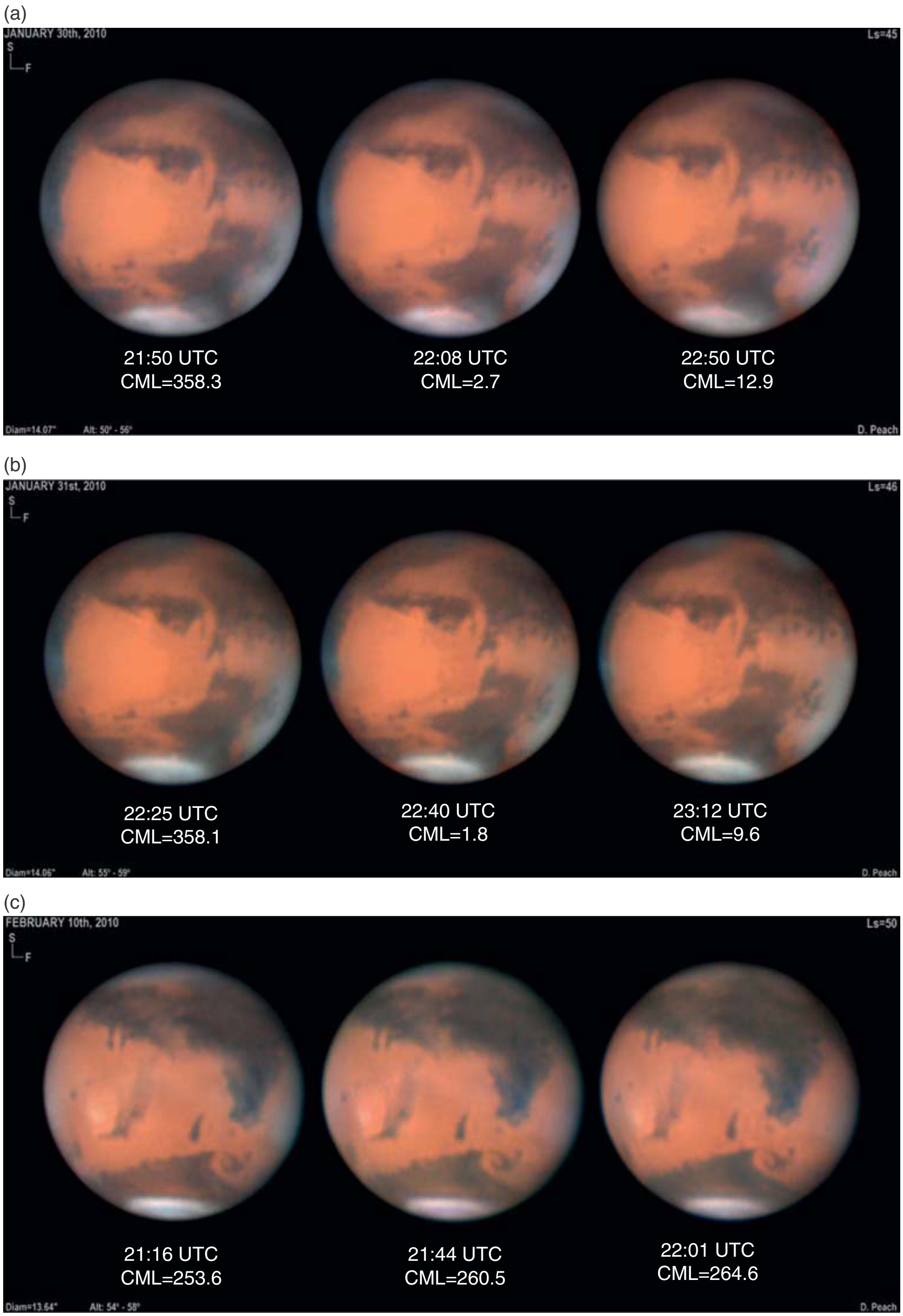


PLATE II Mars images by Damian Peach. See the captions to Figure 7.6(a), (b) and (c) on page 218 for details.

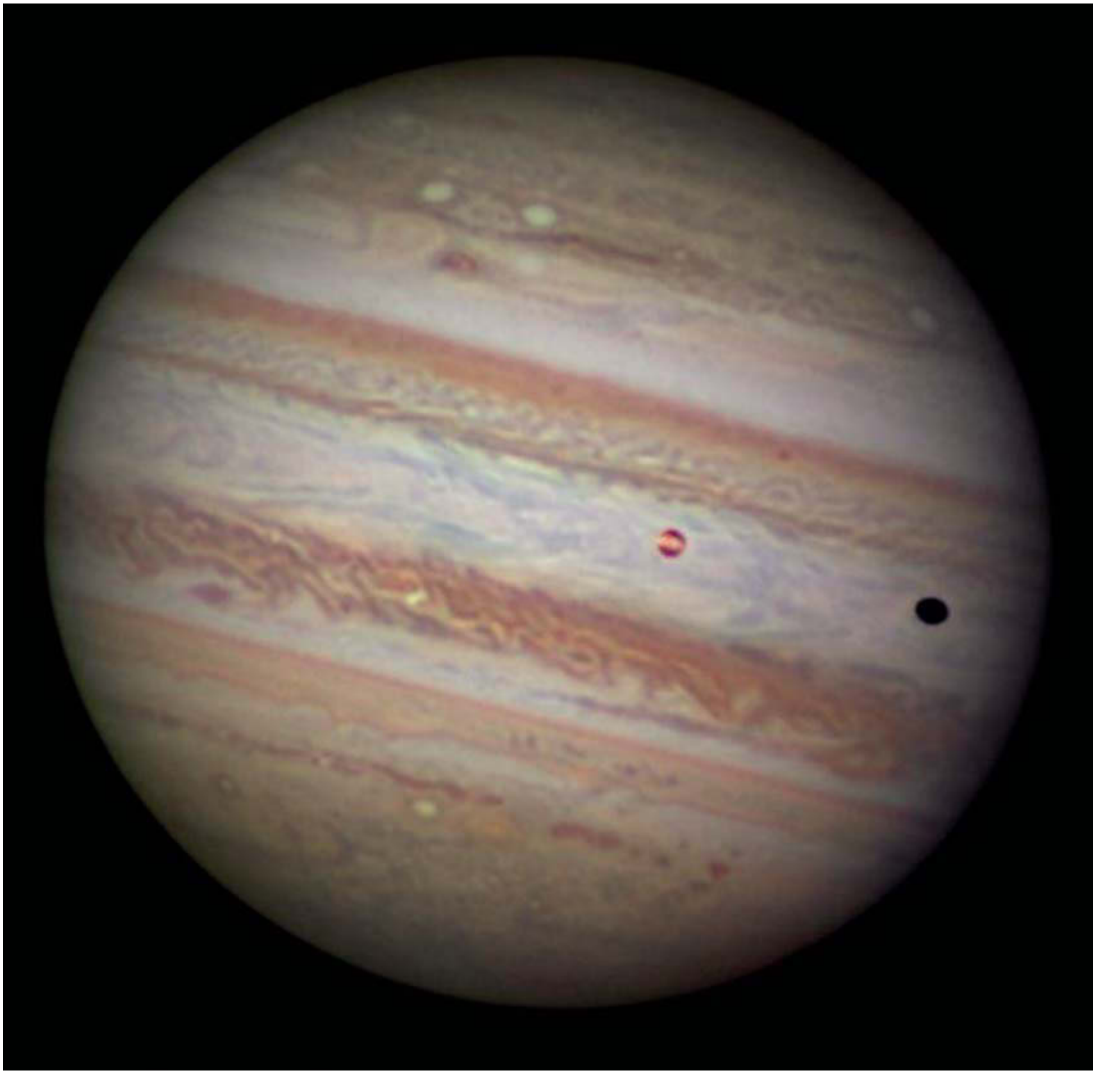


PLATE III Jupiter with its satellite Io transiting imaged by Damian Peach. See the caption to Figure 8.7 on page 246 for details.

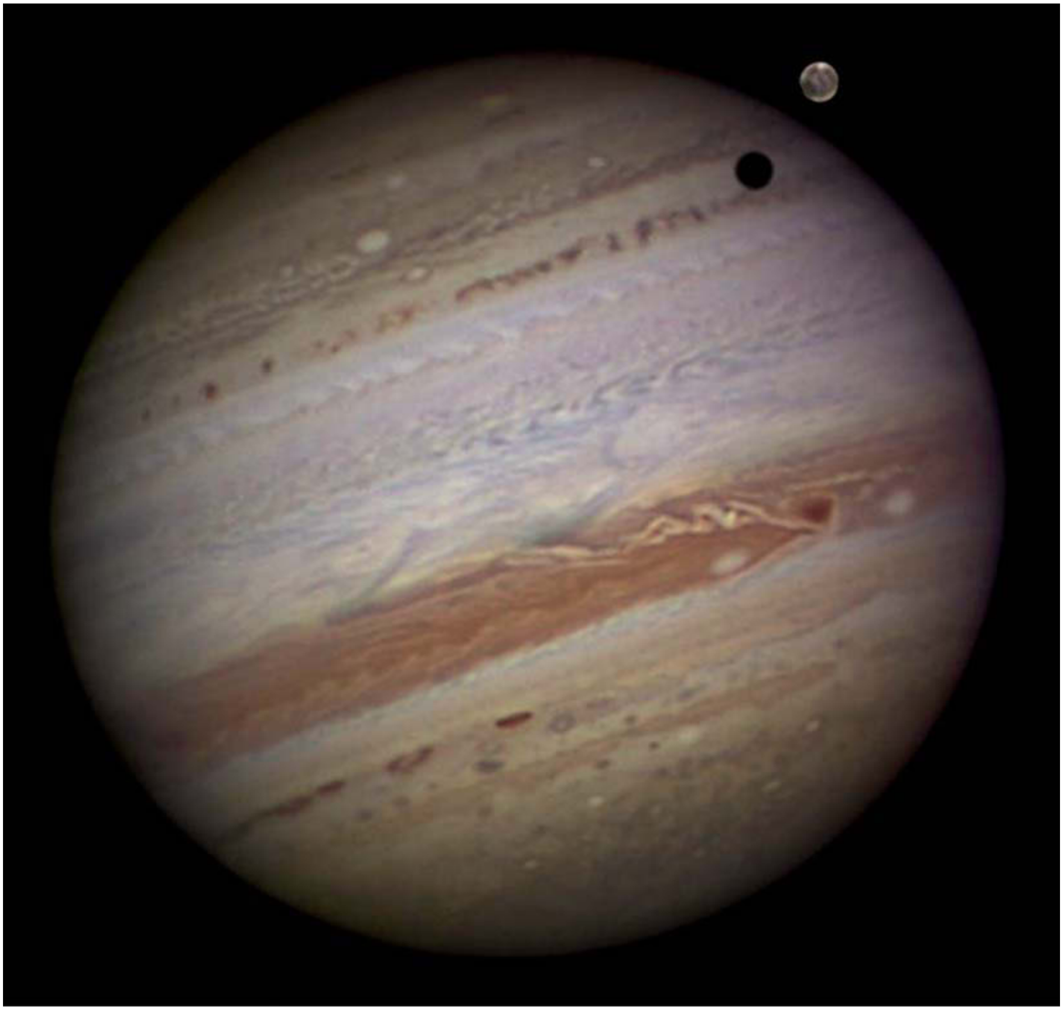


PLATE IV Jupiter with its satellite Ganymede transiting imaged by Damian Peach. See the caption to Figure 8.8(a) on page 247 for details.

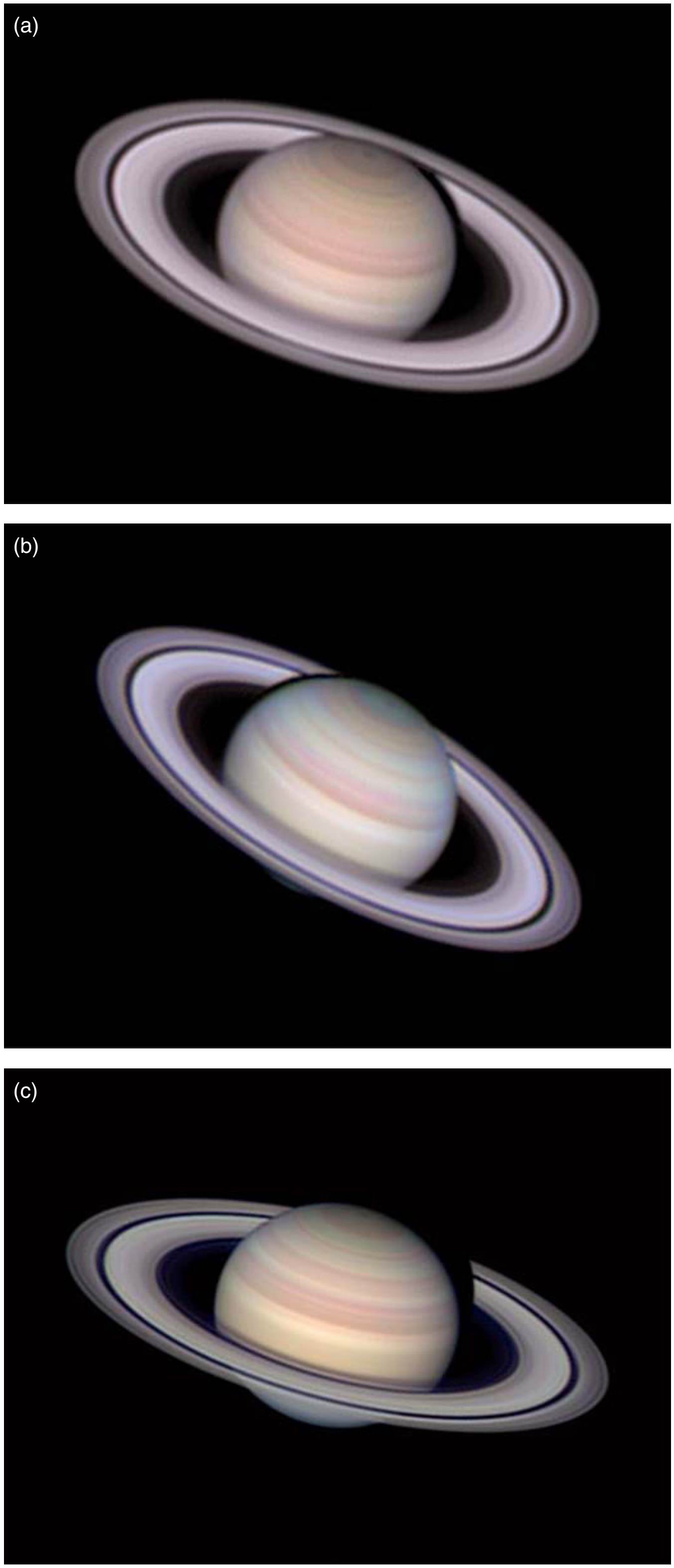
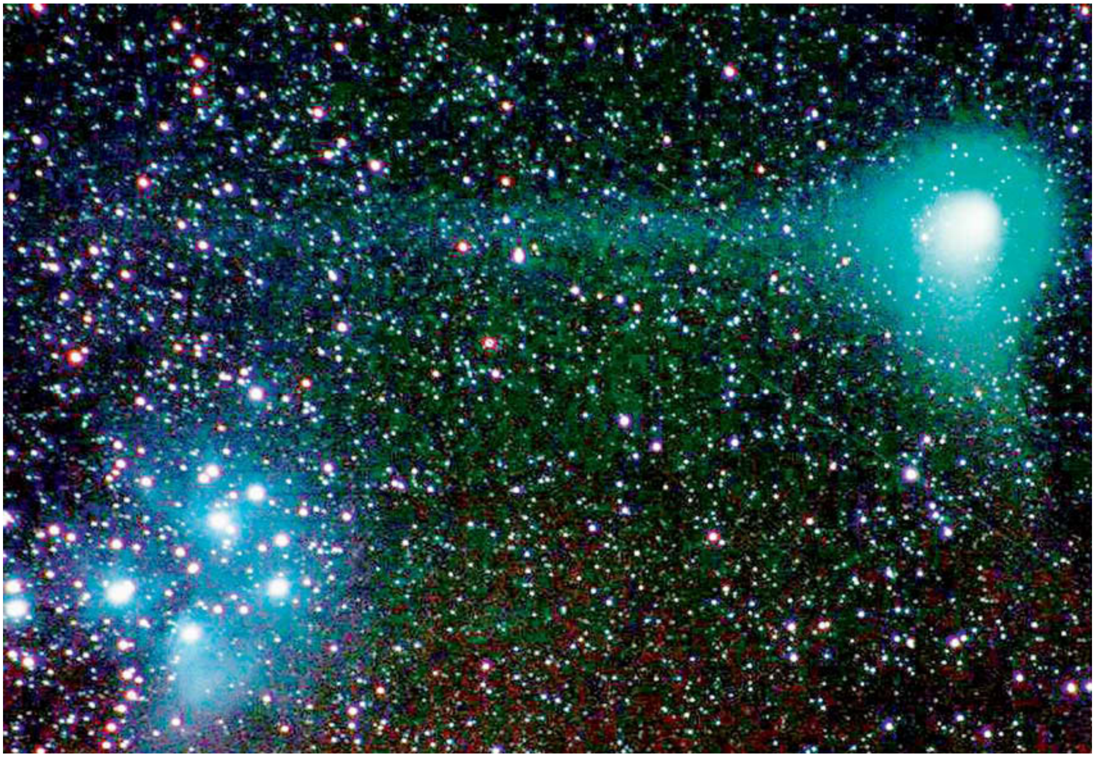


PLATE V Saturn images by Damian Peach. See the captions to Figure 9.6(a), (b) and (c) on page 285 for more details.

PLATE VI (upper) Comet C/1996 B2 Hyakutake photographed by the author. See the caption to Figure 11.5(a) on page 364 for details. (lower) Comet C/1995 O1 Hale–Bopp photographed by Martin Mobberley. See the caption to Figure 11.9 on page 371 for details.



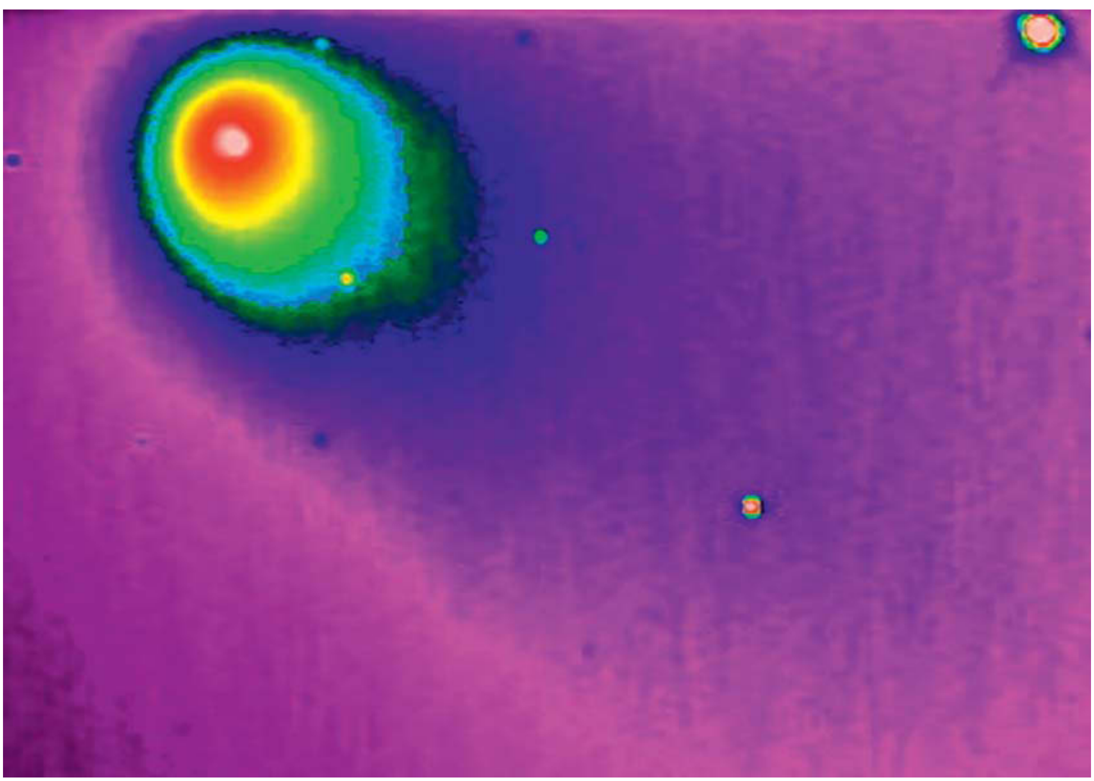


PLATE VII (upper) Comet C/2004 Q2 Machholz passing the Pleiades star cluster photographed by Bob Samuel. See the caption to Figure 11.10 on page 372 for details. (lower) Isophotal image of the Comet C/2001 Q4 Neat by Ian Bennett and the author. See the caption to Figure 11.16(d) on page 395 for details.

(a)

(b)

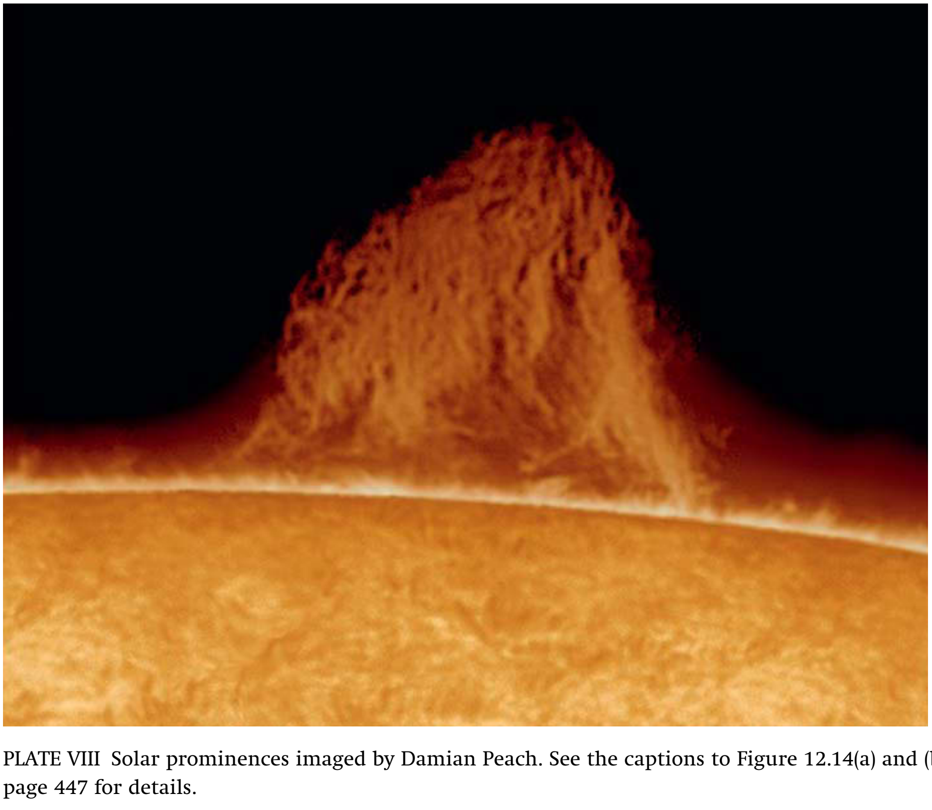


PLATE VIII Solar prominences imaged by Damian Peach. See the captions to Figure 12.14(a) and (b) on page 447 for details.

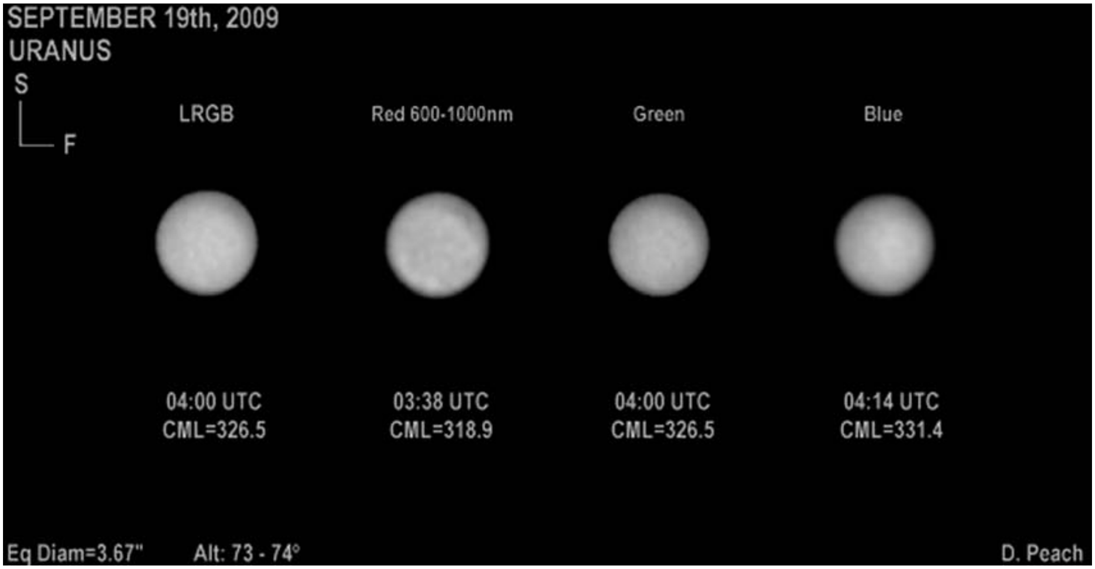


Figure 9.10 This panel of images of Uranus was created by Damian Peach from images he took through different filters as shown. The images were all made using Damian's 14-inch (356 mm) Schmidt–Cassegrain telescope working at f/29 and PGR Flea3 camera. All the images were captured and processed in *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*. Further details as shown. Just showing a fairly sharp image of the disk of the planet, let alone showing any hint of disk details (most apparent in the red to near infrared image), is a very considerable achievement.

Of course its small apparent size and relative faintness still poses a significant challenge. A small telescope with an eyepiece delivering a magnification of $\times 60$ is enough to show Uranus as a definite disk. Showing any details on that disk is quite another matter. Personally, I would be suspicious of any observers turning in visual observations showing disk details if they used anything smaller than a 250 mm reflector. In the case of Uranus, bigger is usually better provided the telescope's optical quality has not been sacrificed to provide size within a limited budget. Also, its design and construction must allow for acceptable thermal acclimatisation. Even then, unusually stable atmospheric conditions are needed to allow a large telescope to deliver anywhere near its full performance.

Perhaps multi-frame photography – stacking a number of reasonably long exposures and carefully processing the result – will give you the best chance of recording any details on the planet. As always, experiment to find out what works best with your particular suite of equipment. To be honest, though, you will be doing extremely well just to record the planet as a blurry disk! Figure 9.10 shows a superlative result from Damian Peach.

One line of research an amateur can do is to monitor Uranus for subtle changes in brightness. If you are practised at making visual estimates of variable stars then you can monitor Uranus with the aid of nothing more powerful than a small pair of binoculars. I describe how to go about making visual magnitude estimates in my book *Observing*

Variable Stars, Novae and Supernovae (Cambridge University Press, 2004). Potentially your visual estimates might approach $\pm 0^{m}.1$ accuracy. Of course, greater sensitivity and objectivity would be achieved using CCD–based photometry. That is also described in that book – and a potted version of the technique is covered in the next chapter here (you will need to read Sections 10.9–10.13). You probably will not be able to resolve even the largest dark or light spots in Uranus's atmosphere but these might be revealed photometrically, as would larger-scale atmospheric brightness changes, both short-term and seasonal.

As far as the Uranian moons go, Titania is slightly brighter than Ariel and Oberon but all three are of fourteenth magnitude and so will be hard to see even through a 9- or 10-inch (228 mm or 254 mm) telescope. Umbriel is 15th magnitude and Miranda is 16th magnitude. An 18-inch (457 mm) reflector ought to show Umbriel as a faint point but even that size of telescope will probably not be sufficient to glimpse Miranda unless your eyesight and the observing conditions are both exceptionally good.

Photographing the moons is eminently possible. Of course they will only appear as faint starlight points. The only real problem is suppressing the swamping effect of the much brighter planet. This can be dealt with in the same way as for photography of Saturn's satellite system.

9.13 NEPTUNE EMERGES FROM THE DEEP

Positional observations of the planet Uranus soon after its discovery revealed unaccountable perturbations. Uranus seemed to drift off its predicted position. Some astronomers began to wonder if another large body, as yet unseen, was pulling Uranus off course.

A chemist-turned-astronomer, Urbain Jean Joseph Le Verrier, worked on the problem and eventually arrived at a prediction of where in the sky the unknown planet might be found. Le Verrier wrote to astronomers at the Paris Observatory but, getting no positive response from them, he wrote to Johann Galle at the Berlin Observatory. On 23 September 1846, Galle and a student, Heinrich d'Arrest, found Neptune with the Observatory's 9-inch (228 mm) refractor. This was the first night of their search and Neptune was found less than a degree away from its predicted position! Uranus had been a chance discovery, but Neptune was tracked down using the power of mathematics.

If you read many accounts of the discovery of Neptune you will most often find equal credit given to a young Englishman, John Couch Adams, for calculating the position of Neptune plus a tale of professional obstinacy and inertia involving the Astronomer Royal of the time, George Biddell Airy. However, certain papers that have come to light only in recent years throw new light on the events in England. It seems that Adams did not do so well after all. Historians now think that the compromise story was a diplomatic expedient. Certainly Adams deserves credit for his painstaking research but it no longer seems justifiable to give him equal credit. Le Verrier's results were more certain and more accurate and led directly to Neptune's optical identification.

Neptune moves at a mean distance of 4494 million km from the Sun, taking 164.8 years to complete one orbit. In many ways Neptune and Uranus are rather similar. Neptune's diameter is 50 538 km, which is only slightly less than that of Uranus, but its mass is larger, at 17 times that of the Earth. Thus, the average density of Neptune is rather higher than that of Uranus, being 1660 kg/m^3.

9.14 NEPTUNE PROBED

Right from its discovery, it was obvious that Neptune is a similar sort of body to Uranus. However, it presents such a small disk to us that only a small percentage of the drawings made by past visual observers have recorded anything even approximating to genuine surface features. Once again we remained largely in ignorance of the fine details concerning Neptune until *Voyager 2* had its encounter with it in August 1989. This was the probe's last encounter with a Solar System object and to this day it continues on its way leaving our planetary family ever further behind as it heads into the loneliness of deep space.

Infrared measurements have indicated that the atmosphere of Neptune has a similar temperature to that of Uranus. Again like Uranus, its blue colour is chiefly due to the absorption of red light by methane gas. In common with Jupiter and Saturn (but unlike Uranus), Neptune radiates away into space more heat than it receives from the Sun. In fact, it radiates more than 2½ times the received solar heat energy, more than that of either Jupiter or Saturn.

It is unlikely that the heat output is supplied by an internal rain of helium, as is the main agency at work in Jupiter and Saturn. Instead, the slow release of its primordial heat of formation is thought to be the sole source (remember Neptune is much further out from the Sun, and so we are considering a much smaller heat exchange). However, the fact that Neptune pours out so much heat reinforces the puzzle concerning the absence of a net heat outflow from Uranus. Presumably the answer must lie in profound differences in the internal structures of the planets.

Until relatively recent times, no atmospheric features had ever been reliably observed from Earth in visible wavelengths, owing to the difficulty of observing Neptune's tiny disk through our unsteady atmosphere. However, infrared studies of the planet did show that its atmosphere is not clear but clouded. Although poorly resolved, the clouds were seen just about well enough to enable determinations of the rotation period of the planet to be made (at least for a limited range of latitudes). At a latitude of 30°S the rotation period was found to be 17.7 hours. Our vision of the planet was to sharpen considerably once *Voyager 2* arrived on the scene.

Far from being like the bland Uranus, Neptune surprised everybody by displaying a much more dynamic visage as *Voyager 2* swept in for its encounter in August 1989. The globe was seen to be streaked with white clouds of methane crystals, which float in the clear atmosphere well above a layer of chemical haze (possibly a mixture of hydrogen sulphide and ammonia), which defines the visible 'surface'.

Particularly striking were the dark spots, especially the Great Dark Spot at a low southerly latitude (about 20°S), which though dark blue was strangely reminiscent of Jupiter's famous Great Red Spot. A smaller dark spot at a high southerly latitude sported a bright white central region. The dark spots are thought to be clearings in Neptune's atmosphere, which allow us to see to deeper levels. The circulating motions of clouds round the spots reveal vast wind-shear forces, like those around Jupiter's GRS. Recent HST images are well enough resolved to show that the Great Dark Spot has now disappeared. However, another giant dark spot has materialised in Neptune's northern hemisphere. This certainly was not expected.

Winds speeds proved to be very high compared with the basic rotation period of the main bulk of the planet, as is the case for the other gas-giants. Wind speeds of up to 300 m/s are typical, blowing in a direction opposite to the rotation of the planet but can top twice this speed. As evident from the clouds and spots, regions of shear between wind streams abound. Owing to Neptune's outpouring of heat, the temperatures in its lower atmosphere are broadly similar to those of Uranus, despite Neptune's greater distance from the Sun.

The preliminary Earth-based radio observations plus the results from the *Voyager* probe have enabled scientists to build up a picture of the planet's magnetosphere. Neptune, like Uranus, has a broadly dipolar magnetic field (though rather more chaotic near the surface of the planet), the axis of which is both heavily inclined (at 47° to its rotation axis) and offset from the centre of the planet. The magnetic field is a little larger than that of Uranus and is orientated in the same sense as for the other gas-giant planets – yet again the opposite of that of the Earth.

From the radio waves generated by the magnetic field as it rotates, it was determined that the field (and hence the inner region of the planet) turns with a period of 16 hours 7 minutes. Neptune's rotation axis is inclined at 28°.3 to the perpendicular to its orbital plane.

The *Voyager* encounter revealed that Neptune has a very faint, six-component ring system (first indications of them were observed from Earth in 1980). The rings span a radius of about 40 000 km to about 70 000 km, and are thought to be composed of fragments of one or more disintegrated satellites. Some of the rings are reasonably uniform around the planet and the others vary in density, being better described as ring-arcs than rings.

Voyager discovered six tiny (less than 420 km across) moonlets, most orbiting within the ring system. Beyond them are the two major moons, Triton (discovered by Lassell in 1846) and Nereid (discovered by Kuiper in 1949).

Triton moves around Neptune at a distance of 353 000 km, with a nearly circular retrograde orbit. It seems certain that Triton was a captured Kuiper Belt Object and not an original satellite of Neptune. Triton's orbit appears to be decaying, so that it will cross the Roche Limit in about 100 million years. The Roche Limit is the distance where tidal forces would disrupt any sizable body that approaches a major planet. If the ring system is faint at the moment, it certainly will not be after Triton has been broken up and the fragments disseminated around Neptune!

Voyager 2 showed that Triton is a strange globe (diameter about 2600 km) of pinkish and bluish areas. It has an extremely rarified nitrogen atmosphere (with some methane), and great nitrogen-driven geysers of dark material erupt onto its patchwork surface of bluish- and pinkish-tinted ices. Triton is thus the third orb in the Solar System discovered definitely to sport active volcanism (the jury being out on Titan at the time I write these words).

The other satellite, Nereid, moves in a direct but highly eccentric orbit, with a mean distance of 5.6 million km from Neptune. Nereid is an irregular lump of dirty ice, about 170 km across its longest diameter. It has an albedo of about 0.12.

Apart from the bright but bland Titan, all the planetary satellites described in this chapter appear as no more than faint sparks of light. Consequently I have given them a very terse treatment here. You will find a great deal more information and a large number of the magnificent space probe images of them online. Please just use your favourite search engine and enjoy what appears.

9.15 NEPTUNE AND THE AMATEUR ASTRONOMER

Neptune normally appears with a brightness of around $7^{m}.9$ and so a pair of binoculars is the minimum optical aid you will need to see it.

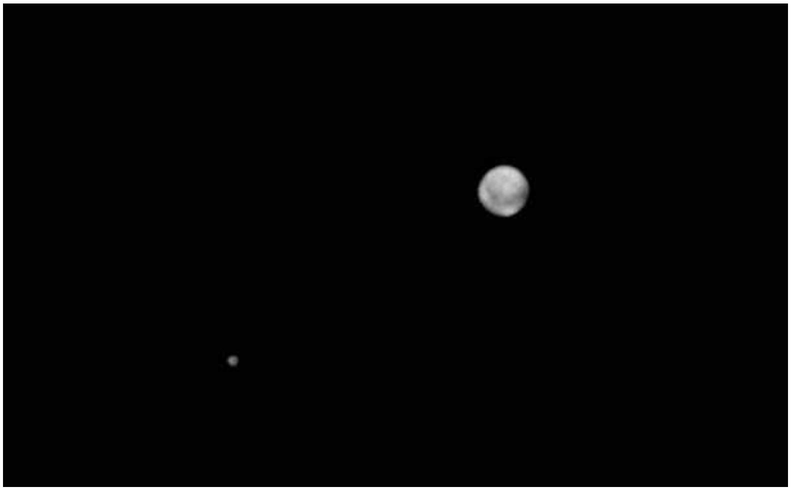


Figure 9.11 Neptune with Triton imaged by Damian Peach on 2010 September 25^{d} 00^{h} 37^{m}–52^{m} UT using his 14-inch (356 mm) Schmidt–Cassegrain telescope working at f/29 and PGR Flea3 camera. All the images were captured and processed in *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*. Triton is also in the frame but Damian has separately increased its brightness to show it up more clearly. Also, its image seems very large compared to Neptune because the (albeit excellent) seeing conditions and the diffraction limit of the telescope have conspired to expand its image beyond the sub-pixel size it should have at this image scale. It is extremely difficult to achieve anything more than a fuzzball when trying to image Neptune. This is an outstandingly good image.

It shows a pale-blue disk spanning a meagre 2.4 arcseconds across and so a magnification of around $\times$770 would be needed to show this blue orb as big as the Moon looks to the unaided eye. I have never seen Neptune as anything better than a small, bland, soft-edged blue disk in any telescope I have ever turned towards this planet. Most times I have looked I have only seen it as a pale greyish-blue fuzzball! You will receive deserved acclimation if you manage to convincingly image any details on this most difficult planet – good luck!

The long-term monitoring of Neptune's brightness is something an amateur could quite usefully do. This could be done visually but CCD-based photometry would produce much more valuable results in the same way as for Uranus. Of Neptune's two major moons, only 13th-magnitude Triton is bright enough to be seen visually through an amateur's telescope. Eighteenth-magnitude Neried will only be revealed by photography with an exposure of a few minutes or maybe more, depending on the size of the telescope. Figure 9.11 shows a Damian Peach image of the disk of Neptune and Triton. Believe me, you will be doing marvellously well if you turn out anything approaching as good as that one!

9.16 PLANETARY OCCULTATIONS

Sometimes the Moon passes across a planet as seen from Earth. Such lunar observations are always spectacular to watch even if no really useful scientific data can arise from them these days.

Watching a planet or planetary satellite passing in front of a star can also be an exciting affair. Sometimes it can provide information of real scientific value. Accurate timings and descriptions of the change in appearance of the star can be made, perhaps using an audio recording device to leave the observer free to watch the event uninterrupted.

Those with CCD equipment can make a valuable contribution by taking images and even more so by making brightness measurements throughout the event. I cover the main details of timing occultations in Chapter 10, Section 10.15. In the same chapter I also describe how to go about photometry (Sections 10.10 to 10.13) – though I must say that you should gain some experience first before thinking about sending in your results to any observing group. Erroneous results can do real harm to any analysis.

I well remember a particular event way back on 3 July 1989. This was an occultation of the fifth-magnitude star 28 Sagittarii, first by Saturn's rings and then, 15 hours later, by Titan. It was still daylight in the UK at the time of the ring and planet passages but by the accounts of those in suitable locations it was spectacular. The star was seen to wink and flash as it traversed behind the multitude of ring grooves and divisions (or perhaps it is more accurate to say the planet's rings moved across the background star). Exactly what was seen and the durations of each stage was highly dependent on the location of the observer.

The Titan event was visible from the UK in mid evening and this also turned out to be a great spectacle. Individual cloud layers in Titan's atmosphere caused the star to flash and fade and apparently change colour a number of times during immersion and egress, which took about a minute from start to finish. From the UK, the star was completely hidden by Titan for about 4 minutes. Hundreds of amateur and professional observers worldwide contributed their observations to this joint effort. Accounts of this event can be found in October 1989 issues of *Sky & Telescope* magazine and the *Journal of the British Astronomical Association*.

I will finish this chapter by noting a book that you might find interesting and useful to have: *Uranus, Neptune and Pluto and How to Observe Them*, by Richard Schmude (Published by Springer-Verlag in 2010). Pluto used to be regarded as a major planet, albeit a very small one, but a few years ago it was demoted. More about that and the myriad of diminutive rocky and icy bodies of our Solar System in the next chapter.

CHAPTER 10

Small worlds

On the evening of 1 January 1801 Guiseppi Piazzi was engaged in the observational work necessary for the compilation of a new star catalogue when he found an unfamiliar object in the constellation of Taurus. The object looked like a star of the eighth magnitude. When Piazzi observed on the following night he found that it had shifted against the pattern of fixed stars. Clearly this was not a star. It turned out to be a previously unknown member of the Solar System.

10.1 THE MAIN BELT ASTEROIDS

The mathematician Karl Gauss found that the new body, which Piazzi named Ceres, orbited the Sun at a distance of 27.7 AU (about 430 million km). It was obviously small. We now know that its diameter averages about 950 km (it is slightly oblate).

As discussed in Chapter 1, a group of astronomers known as the 'Celestial Police' had already begun searching for new members of the Solar System. They carried on searching. On 28 March 1802, Celestial Policeman Heinrich Olbers found a second small body, Pallas, which moves at roughly the same distance from the Sun but in a much more eccentric and highly inclined orbit than Ceres. Then in September 1804 another Celestial Policemen Karl Harding discovered a third, Juno, and in March 1807 Olbers found a fourth, Vesta. All these bodies turned out to be smaller than Ceres (of the order of half Ceres's diameter).

The four bodies became known as *minor planets*. Owing to their telescopic appearances they were also called *asteroids*, a term coined by William Herschel literally meaning 'star-like'. Nowadays, it is the term asteroid which is in fashion.

After a period without further discoveries the Celestial Police disbanded but a fifth body, Astraea, was found by Karl Hencke in 1845

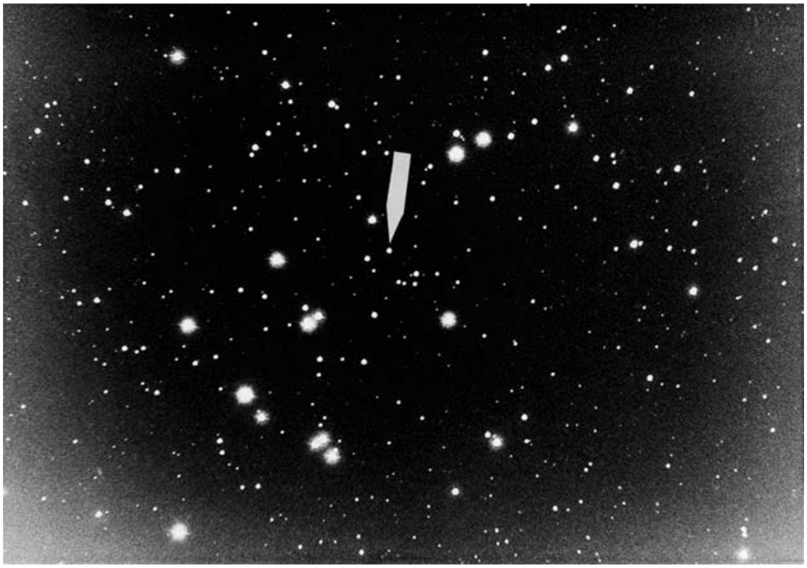


Figure 10.1 Main Belt asteroid (5) Astraea (arrowed) transiting the Beehive star cluster. This 10-minute exposure was made on Tri-X photographic film by Martin Mobberley on 1987 March 29^{d} 20^{h} 31^{m} UT using his 14-inch (356 mm) reflector at its f/5 Newtonian focus.

(see Figure 10.1). Soon after more asteroids were discovered – and then more – and then still more. As technology improved the rate of discoveries increased, explosively so in very recent times. Now something like sixty thousand new asteroids are being discovered every year! By the beginning of 2011 the tally had grown to well over half a million known asteroids, with about a third of them having reasonably well-determined orbits.

As to the question of their nature and what they are made of, some idea can be gained by examining the spectra of sunlight reflected from their surfaces. So, careful analysis of their spectra can tell us a lot about them. Asteroids have been classified into the following types, each type having certain spectral characteristics: A, B, C, D, E, F, G, M, P, Q, R, S, T, V. Though this list is presented in alphabetical order, do note that not all the letters of the alphabet are used. The types S, C and M are by far the most common and these also match laboratory spectra of common meteorites. Other asteroidal spectra correspond to rarer meteorite types.

We now know that the vast bulk of the asteroids orbiting between Mars and Jupiter are small, irregularly shaped bodies made of rock. In the main they are composed of varying amounts of metallic-rich and non-metallic-rich rocky minerals, though there does seem to be a significant water-ice content to some of them. The reflectance spectra of some even contain evidence of clays. Clays are significant in that liquid water is needed to produce them – though that water must have existed underground as no liquid water can exist on the surface of any airless body.

In recent years several asteroids have been visited and photographed by passing spacecraft and one, Eros, has even been landed upon. The smaller examples seem to be highly irregular in shape – really just potato-shaped, or even peanut-shaped, lumps of rock. Some of them are known to be double or multiple systems orbiting around their barycentres.

Most asteroids that populate the inner regions of the Solar System orbit between 2 and 4 AU from the Sun. These are the *Main Belt* asteroids. Ceres remains the largest Main Belt asteroid so far discovered. We only know of seven definitely larger than 300 km across. Various families of asteroids exist, being classified in terms of their orbits. As far as the number of Main Belt asteroids goes, there is likely to be more than a million of them larger than a kilometre in size but many more years of work will be needed before we can be sure of the true number.

The mighty planet Jupiter is responsible for a large number of zones of avoidance in the Solar System, known as *Kirkwood gaps*. These are mostly at radii from the Sun where any object would have an orbital period that is a simple ratio of Jupiter's. This is because the repeated tidal tugging of Jupiter on any asteroid in that zone tends to pull it out of orbit. Closer to Jupiter, however, the situation is reversed and instead the asteroid orbits are concentrated into those that have orbital periods which are simple ratios of Jupiter's orbital period.

A detailed statistical analysis of the asteroids' numbers and orbits have shown that the Main Belt asteroids are themselves subdivided into groupings separated from each other by Kirkwood gaps. Hence we have the *Hungaria*, *Flora*, *Phocaea*, *Koronis*, *Eos*, *Themis*, *Cybele* and *Hilda* groupings, just to name the most prominent of them. There are many others. The fact that the members of each group also share other similarities, such as surface composition, orbital inclination, etc. – these characteristics being distinct from the members of other groups – suggests that each group resulted from the splitting up of a particular separate former parent body.

We now think that the presence of Jupiter was responsible for inhibiting the formation of a planet-sized body but that several Ceres-sized planetoids were formed, together with much left-over debris. Mutual collisions then fragmented theses planetoids to form the groups of asteroids we see today. The gravitational resonance effect of Jupiter operated to clear out the zones of avoidance, throw out many asteroids, and herd the rest into their present orbits.

I have already remarked on the similarities between the reflectance spectra of asteroids and of meteorites. Please refer back to Chapter 1 for more about meteors and meteorites. The most common asteroids, those with S-type spectra, seem to be made of the same stuff as the most common meteorites – the ordinary chondrites, and some of the stony irons. The dark-hued C-type asteroids seem to be compositionally similar to the dark-hued carbonaceous chondrites. To take a final example, the fairly common M-type asteroids share the same compositions as the irons and enstatite chondrite meteorites.

As far as we can tell from asteroid spectra and meteorites, it seems the precursor planetoids existed for long enough to become *chemically differentiated*. This means that the lighter minerals migrated to the outermost parts and the heaviest materials sank towards the core of the planetoid in each case. Ceres and a few of the largest asteroids that we see today are undoubtedly chemically differentiated. In the case of Ceres, there is most probably a water-ice layer under a thin outer crust of rock and ice, though most of the interior is reckoned to be composed of rocky materials.

10.2 PLUTO AND THE LITTLE ICE WORLDS

Clyde Tombaugh was hired to conduct a photographic search for a planet orbiting beyond Neptune using a specially built photographic telescope at the Lowell Observatory in Arizona, USA. He eventually tracked down the body we now know as Pluto and its discovery was announced in March 1930.

The discovery of Pluto raised a number of problems. It was much fainter and smaller than expected, appearing only as a star-like point of the 14th magnitude. Its orbit is also highly irregular, being inclined at 17°.2 to the plane of the ecliptic. Pluto moves at a mean distance of 5900 million km (39.3 AU) from the Sun but this distance can vary from 4500 million km (29.7 AU) to 7400 million km (49.3 AU). At certain times in Pluto's 248-year orbit it comes nearer to the Sun than does the planet Neptune.

Pluto's diameter is 2300 km and spectra indicate that its surface is covered in frozen methane. Any astronaut on Pluto would see the Sun appearing like a brilliant star and the temperature on the surface of the planet is certainly no higher than −220°C. A tenuous atmosphere, largely made of nitrogen but with some methane, was detected in 2009. Interestingly, the presence of methane causes the temperature of the atmosphere to rise with height above the surface, reaching a maximum of −170°C. The density of the atmosphere varies as the planet orbits the Sun, most of it freezing out when the planet is at aphelion.

In 1978, James Christy, using the 1.54 m reflector of the US Naval Observatory at its Flagstaff station in Arizona, photographed the planet in order to try to measure its diameter. The very best photographs showed a 'bump' attached to the image of Pluto – an attendant satellite had been found. This satellite, named Charon, is about a third of the size of Pluto itself and orbits at about 17 000 km from it with a period of 6.3 days. Pluto also rotates on its axis with this same period. Thus, the satellite Charon appears fixed in the sky when viewed from one hemisphere of Pluto and is always invisible from the other hemisphere. The motions of this satellite allowed a calculation of Pluto's mass. It proves to be about 1.3×10^{22} kg, or about $^1\!/_{460}$ of the Earth's mass.

The *Hubble Space Telescope* (*HST*) has turned its sharp vision towards Pluto and images have been obtained which show light and dark markings on the globe of the planet, as well as showing Charon very clearly separated from Pluto. Long-term observations carried out from the HST have revealed significant changes in the surface over time. Perhaps Pluto has a similar surface to the Neptunian satellite Triton? Certainly, astronomers think that the surface methane-ice is 'dirtied' with organic compounds. The density of Triton and Pluto are similar at about 2000 to 2100 kg/m^3. Two further attendant satellites of Pluto have been found. They are each of the order of a hundred kilometres in diameter and are named Nix and Hydra [Stop Press: while this book was going through production, a further two small satellites were discovered]. NASA's *New Horizons* spacecraft is currently on its way to the Pluto system. In 2015, when it gets there, we will at long last know much about this historically significant little world and its satellites.

Despite its small size, most astronomers had rated Pluto as the ninth major planet in the Solar System. However, a few years ago, an infamous meeting of the International Astronomical Union resulted in a set of contentious definitions of what constitutes a major planet with the result that Pluto is now officially known as a *dwarf planet*. So the number of 'planets' in Solar System has now officially returned to its pre-1930 total of eight!

Actually, I must say that by the end of the twentieth century there really were indications that Pluto was indeed not a major planet but rather just one of a whole new family of icy worlds – numbering in the millions if we count those larger than a kilometre across, and maybe billions if we count all those larger than a metre – that populate the outermost limits of the Solar System.

Even early in the twentieth century asteroids were being discovered, which proved in each case to be just the first-found members of asteroid families that orbited elsewhere than in the Main Belt. For instance, there was Achilles, found by Max Wolf in 1906, the first-discovered member of the two *Trojan* groups of asteroids that shared an orbit with the planet Jupiter. These are locked into the two *Lagrangian* positions of gravitational stability; one is always 60° in front of Jupiter, the other always 60° behind it. Then there was *Apollo* discovered by Karl Reinmuth in 1932 that turned out to be the first of a new family of asteroids that crossed the orbits of Venus and the Earth. The Apollo asteroids are a subset whose orbits bring them close to the Earth once during each orbit of the Sun. These we call the *Near-Earth Asteroids*, or *NEA*s. Two other NEA groups are the *Aten* and *Amor* asteroids. We know of a few hundred NEAs so far but we think there may well be a couple of thousand still awaiting discovery. Still other asteroids were found orbiting elsewhere outside the Main Belt.

It was only late in the twentieth century, though, that discoveries were made that indicated that there were huge numbers of asteroidal bodies populating the realms of the outer planets and even beyond. In 1977, Charles Kowal discovered Chiron, whose orbit ranges from 8.4 AU (further out than Jupiter) to 18.8 AU (almost as far out as Uranus). This was the first discovered member of the *Centaur* group of asteroids which have mean orbital radii between that of Jupiter and Neptune. They have highly elliptical, and somewhat chaotic, orbits thanks to gravitational pulls and tugs from the major planets. Some have perihelia inside the orbit of Mars. Some have aphelia further out than Neptune.

In 1992 came the discovery of the first *Trans-Neptunian Object* (*TNO*) – objects which never, or only just, approach the Sun closer than Neptune – and many others followed. At present we know of more than a thousand TNOs. Quaoar, discovered in 2002, was the first really large example, with a diameter about three quarters of that of Pluto. Four more large ones were discovered between 2002 and 2005 and another has been found more recently. This tally stands at the time of writing, though other large TNOs are sure to be discovered – maybe even before you are reading these words.

The largest of them is Eris, orbiting at 97 AU. It was discovered in 2003 and initially named ‘Xena’. Eris is similar in size to Pluto and it has a satellite of its own, called Dysnomia. Eris’s density and composition are also similar to Pluto. At the present time Eris is the furthest known substantial object in our Solar System, at nearly 97 AU from the Sun. This is more than three times the distance of Neptune from the Sun (and Pluto at perihelion) and at Eris the sunlight is only about one ten thousandth as bright as it is in our region of space. From the Earth, Eris appears as a star-like speck of magnitude $18^{m}.7$, a challenge for amateur imagers with moderate-sized telescopes.

Evidence from spectra suggests that while the innermost asteroids are basically rocky in composition those in the outermost regions of the Solar System are mostly icy. This is in full accord with the theoretical models of the formation of our Solar System.

Referring again to Chiron (not to be confused with Pluto's satellite Charon), it is an icy body with a diameter of a few hundred kilometres. Traces of a gaseous mantle have been detected and this would put it in the class of the comets (comets are described in the next chapter). Indeed, we now know that there is a doughnut-shaped region well beyond the main planets populated by a vast number of icy worlds. This is the *Kuiper Belt.* So far we have discovered over five hundred definite *Kuiper Belt Objects* (*KBO*s) but this is undoubtedly the tip of the iceberg. The Kuiper Belt also seems to be a repository for short-period comets. Well beyond that we have the spherical *Oort Cloud* – the repository of long-period comets – but more about comets in the next chapter.

It seems that the characteristics distinguishing many types of asteroids, including those of asteroid families such as the Centaurs and TNOs from each other, and from comets, is far from clear cut. Frankly, I think the IAU committee members with their somewhat woolly definitions of what constitutes this or that class of object, along with the sheer number of classes introduced, have made life unnecessarily complicated. As a case in point, for an object to be classed as a dwarf planet it has to be: (i) in orbit around the Sun, (ii) not in orbit around a major planet, (iii) have sufficient mass for its gravity to make it roughly spherical but (iv) not massive enough that its gravitational field will have cleared its orbital path of debris. I could spend many pages picking the IAU definitions to pieces.

If it is really necessary to have a class of object defined as a 'dwarf planet', then I would have much rather had the definition based on a size range. As it is, not all large asteroids are dwarf planets. To the time of writing, the new class of dwarf planets include just five members: Ceres (the largest Main Belt asteroid), Pluto (the first TNO), plus the KBOs Haumea, Makemake and Eris.

Oh, and just when you thought we had finished, we have another official label to stick on Pluto. As well as its status as a dwarf planet and one of the larger TNOs, the IAU has introduced an orbitally defined sub-class known as *Plutino*. By definition, this label applies to any small body having an orbit similar to that of Pluto! I don't blame you if at this point you feel like taking a headache pill and lying down in a darkened room. Of course the characteristics of the families of the different types of objects are important for the whole picture to be revealed but try not to get too bogged down with the etymology. Merit each Solar System object on its own and enjoy your study and observations of it for what it physically is.

There are a large number of books covering all aspects of the study of asteroids currently in print. An Internet search will soon uncover them, though perhaps I could mention here four that may be of particular interest to you:

Asteroids III, edited by William F. Bottle Jnr. *et al.*, was published by University of Arizona Press in 2003. This 785-page book has 150 contributing authors and is authoritative, accurate and up-to-date on all aspects of asteroid research up to 2002. Also, there is *Pluto and Charon: Ice Worlds on the Rugged Edge of the Solar System* by Alan Stern and Jacqueline Mitton. The second edition of this book was published in 2005 by Wiley-VCH. Another book about Pluto is *Pluto – Sentinel of the Outer Solar System* by Barrie W. Jones, published by Cambridge University Press in 2010. Finally there is *Asteroids and Dwarf Planets – And How to Observe Them* by Roger Dymock, until recently the BAA's Asteroid and Remote Planet Observing Director, published by Springer Verlag in 2010.

10.3 ASTEROID DESIGNATIONS

On first discovery a suspected asteroid may be given a provisional designation by its discoverer. After confirmation it is given an official four-part designation. The first part is the year of discovery, say 2007. After that is a space, followed by a letter. The letter denotes the half-month of the discovery according to the following:

A January 1–15	B January 16–31
C February 1–15	D February 16–29
E March 1–15	F March 16–31
G April 1–15	H April 16–30
J May 1–15	K May 16–31
L June 1–15	M June 16–30
N July 1–15	O July 16–31
P August 1–15	Q August 16–31
R September 1–15	S September 16–30
T October 1–15	U October 16–31
V November 1–15	W November 16–30
X December 1–15	Y December 16–31

The letter I is not used in case it is confused with the number 1 and, as you can see, the letter Z is not needed.

The next letter denotes the order of discovery within the given half month. It starts off with A for the first discovery and runs in alphabetical order, through Z for the 25th (once again I is not used, so H denotes the 8th discovery, J denotes the 9th, etc.). For the 26th discovery in a given half month, a number 1 is added to the end of the designation and the 'order of discovery' letter is re-run. The procedure is continued: the 1 becomes a 2 for the 51st to the 75th discovery, the sequence of letters preceding the number being re-run once again, and so on.

For example, if an asteroid discovered on 2007 May 9^d was the tenth to be discovered in that half month, its designation would be: 2007 JK. If an asteroid discovered on 2008 December 22^d is the 53rd to be discovered in the half month beginning 16 December, then its designation would be 2008 YC2.

Asteroid discoverers, or sometimes those responsible for establishing the orbit of a newly discovered asteroid, are usually given the privilege of assigning a personal name to their discovery.

When the newly discovered asteroid has been observed enough for its orbit to be established with fair accuracy it is then assigned a number which reflects its order of discovery, with the sequence beginning at 1 with Ceres. From then on the asteroid is identified by that number in parenthesis in front of its name, or its IAU standard designation if it is unnamed. So we have: (1) Ceres; (2) Pallas; (3) Juno; ... (5) Astraea; ... (2060) Chiron; ... (5145) Pholus; ... (99942) Apophis ..., and so on.

10.4 SOME USEFUL WEBSITES

You might come across some details about asteroids, including asteroid ephemera, in magazines and other periodicals but you will need frequent and up-to-date information on all things asteroidal if you really wish to take the subject seriously. As a starting point I can do no better than recommend the asteroid observing section websites of the various national astronomical associations. There you will find everything you really need including, ephemerides, 'calls to arms' to observe particular asteroids, advice and information on observing practice and available resources, links to other websites such as the Lowell Observatory, the European Asteroid Occultations Network and many others, and very much more besides.

The BAA's Asteroids and Remote Planets observing section can be found via the link on the BAA homepage (www.britastro.org) and ALPO's Minor Planet Section can be accessed via link on the ALPO homepage (www.alpo-astronomy.org).

Another useful website is that of the Minor Planet Observer and Palmer Divide Observatory (www.minorplanetobserver.com). As well as being the source of the *MPO* software suites I shall be detailing later, this site does have other useful links, including 'Minor Planet Bulletin Downloads'.

There is also the related Collaborative Asteroid Lightcurve Link (CALL) webpage (www.minorplanetcenter.info) which is packed with useful

Figure 10.2 The bright image of the primary mirror of the author's 18¼-inch (0.46 m) reflecting telescope can be clearly seen against the eyelens of the eyepiece. This image is the exit pupil, the best position for the observer's eye in order to see all the celestial light collected by the mirror. The image is actually centred on the optical axis but is formed a short distance in front of the eyelens, which is why it appears displaced to the upper-left in this oblique view.

current information and links to co-ordinated programmes of observational work on specific target asteroids. It also provides information about and links to the important publication the *Minor Planet Bulletin*, including information and templates for submitting observations and articles/papers.

10.5 TELESCOPES FOR VISUALLY OBSERVING ASTEROIDS

Any telescope that gives a sharp image of a star will be fine for observing asteroids. Obviously an equatorial mount and a sidereal drive is a great help – and a good GOTO facility even more so – but even a humble Dobsonian-mounted Newtonian reflector will do if you are prepared to expend more effort in finding the asteroid and then keeping it in the field of view.

When using a telescope visually, beware using a magnification much less than the aperture in millimetres divided by 5. If you do, the image of the primary mirror or object glass the telescope produces in front of the eyelens (see Figure 10.2) will be larger than 5 millimetres across. This image, known as the *exit pupil* has to be smaller than your eye pupil otherwise not all of the celestial light collected by the telescope can enter your eye.

To find the diameter, in millimetres, of the exit pupil produced divide the aperture of the telescope, again in millimetres, by the magnification the eyepiece produces with it. A 5 mm exit pupil will be fine for most people when dark-adapted. On average, a youngster's eye pupils can expand more than an older person's when fully dark-adapted and this 5 mm limit ought to be reduced by about 0.5 mm per decade after about 60 years of age. Thus, a 70-year-old man ought not to use a magnification less than the aperture of his telescope in millimetres divided by 4.5 if he is not to waste some of the celestial light collected by it.

Obviously the larger the aperture of the telescope, the fainter the asteroids that can be seen through it. Here is a predictive formula which I developed from the results of a practical investigation conducted by Bradley E. Schaefer of the NASA–Goddard Space Flight Center:

$$\text{practical limit } m_v \text{ (5 mm exit pupil)} = 2.6 + 4.7 \text{ Log } D,$$

where D is the aperture of the telescope in millimetres. Actually, the faintest stars or asteroids that can be seen through a given telescope depend to some extent on magnification because they are seen against the not-completely-black sky background. Increasing the magnification makes the sky background appear darker The greater contrast between the darkened image of the sky and the little-affected pinpoint image of the object makes the object easier to see. I discuss this much more fully in my book *Observing Variable Stars, Novae and Supernovae* (published by Cambridge University Press in 2004).

The formula given here is for a magnification equal to the aperture of the telescope in millimetres divided by 5, for instance $\times 50$ used on a 250 mm (approximately 10-inch) aperture telescope. Table 10.1 includes a column of faintest magnitudes predicted from the foregoing formula, as well as a column of figures for the limiting magnitudes obtainable when using a high magnification under really excellent conditions. These are also derived from a formula I developed from Bradley Schaefer's results.

Of course, any predictive formula can only ever be a rough guide because there are many factors which will affect the final result: atmospheric transparency, unsteady seeing, moonlight or other sources of light pollution, the efficiency of the telescope, etc. The formula and table given here, though, provide a better guide than others you may find in print.

10.6 BINOCULARS FOR OBSERVING ASTEROIDS

There is one oft-given piece of advice concerning binoculars that I would always dispute. Many authorities recommend 7×50 binoculars

Table 10.1 *Telescopic limiting magnitudes*

Telescope aperture (inches/mm)	Limiting magnitude – high magnification	Limiting magnitude – 5 mm exit pupil
1.4/ 35	11.3	9.9
2 / 51	12.0	10.6
2.4/ 60	12.3	11.0
3 / 76	12.8	11.4
4 / 102	13.3	12.0
5 / 127	13.8	12.5
6 / 152	14.1	12.9
8 / 203	14.7	13.4
10 / 254	15.1	13.9
12 / 305	15.4	14.3
14 / 356	15.7	14.6
16 / 406	16.0	14.9
18 / 457	16.2	15.1
20 / 508	16.4	15.3

(magnification factor 7, 50 mm diameter object glasses) as the best size you can choose for astronomy. However, this produces an exit pupil of 7 mm diameter at each of the eyepieces. That may be fine if you are in your teens but is wasteful of light if you are much older than that. For example, if your eye pupils will only expand to 5 mm when fully dark adapted, then you might just as well have chosen the equally common 7×35 binoculars. Your views through either will be indistinguishable and the 7×35 binoculars will be much cheaper, as well as more compact and lighter to carry and handle. The binoculars that **I** recommend as best are the 10×50 size. Their 5 mm exit pupils will suit the eyes of people aged from 16 to 60.

What about higher magnifications, though, and perhaps binoculars with bigger objective lenses? The main advantage of binoculars over telescopes is their inherent wide field of view. Typical mid-priced binoculars will have eyepieces fitted that have apparent field diameters of about 50°, or maybe just a little larger. A magnification of ×10 will result in a real field diameter of 5°. That is, for instance, just enough to squeeze all the main stars of the Hyades star cluster into the field of view in one go. Binoculars in the same price range giving higher magnifications necessarily have smaller fields of view. The prices of binoculars fitted with eyepieces of much wider apparent fields really start to rocket upwards.

There is another disadvantage to binoculars of higher magnification. You will find that holding them steady enough is not at all easy. A few moments of trying to fix your eye on the subject while it jitters and swims erratically about in your vision will make you feel queasy. Not only that, your eye and brain will have precious little opportunity to actually study the subject. You will find you can actually perceive remarkably little in the way of detail, despite your best efforts. You might wish you had chosen the lower-power binoculars (and saved some money), instead.

There are also considerations of weight. How long will you be able to hold a hefty pair of binoculars in position before the ache in your arms and shoulders, soon spreading to your neck, gets too much to ignore? Not very long. All-in-all you will find 10×50 to be the best category of hand-held binoculars for your general observing.

Even with 10×50 binoculars, you will soon see the advantage of resting your elbows on a suitable platform when using them for long periods. The top ledge of a fence or anything else you can press into service will increase your comfort – and hence the detail you will be able to appreciate and observe – when using such a rest to ease your muscle load.

Of course, the situation is a little different if the binoculars themselves are on some sort of stand. Then they can be heavier and even have more magnification, and still be a joy to use. As is the case when you are choosing telescope mountings, beware anything too light and spindly. A number of different mountings for binoculars are commercially available.

There are also now available other mountings for binoculars that work on the same general principle as the table-lamps of the famous 'Anglepoise' tradename. Some have counterweights, others have springs to do the same job. In some cases you can attach these units to the arms or frames of deck-chairs, making for very comfortable viewing! I recommend you scan the adverts if one of these appeals to you.

Of course, big mounted binoculars are extremely expensive. At the multi-thousand dollar end of the market, Fujinon's 25×150 binoculars come on a sturdy tripod and tilt-and-pan head. They also have extra prisms incorporated in the optical train in order to have the eyepieces angled upwards by 45°. There are some others angled upwards to 90°. This feature affords a great relief on the neck muscles when viewing any object at high altitude.

Binoculars, large and small, can be found second-hand but please do examine them closely (particularly looking for scratches in the lenses and checking that the focusing action is smooth and slop-free) and thoroughly check them out in use before you part with any money.

Image-stabilised binoculars give a jitter-free view at higher magnifications without the need for a tripod. The image still moves in response to hand movements when the stabilisation button is pressed but the motion is silky smooth. Observers report a significant improvement in visual limiting magnitudes and perceived details over non-stabilised binoculars of the same aperture. The downside is that image-stabilised binoculars are expensive. An article written by Gary Seronik about binoculars and binocular mounts, titled 'How to choose binoculars for stargazing', can be found in the October 2007 issue of *Sky & Telescope* magazine.

10.7 SETTING YOUR TELESCOPE ONTO A CHOSEN ASTEROID

You want to observe a particular asteroid. How do you go about locating it in the field of view of your telescope? Asteroids are very much needles in the celestial haystack. They are indistinguishable from the stars that vastly outnumber them.

To start with you will need an ephemeris for the asteroid in question. For a few notable asteroids this might come from a current magazine but you will normally have to look in a more specialised source. There are publications such as the annual *Handbook of the British Astronomical Association*, issued free to members, which contain asteroid ephemerides. Much more comprehensive information can be obtained from the director of the asteroid observing section of any of the national societies via the section websites and/or hard-copy publications, as I outlined in Section 10.4.

Let us say that you have obtained the asteroid's position at a particular time (you might have to interpolate the figures given in the ephemeris to obtain the position at any specific time that you desire). Your next job is to create a *finder-chart* for the asteroid. This is a chart which shows the field of view of your eyepiece, with the asteroid (preferably at the centre) and all the stars that you can see that are as bright or brighter than the asteroid. You will need this chart in order to recognise the star pattern and identify which one of the 'stars' is actually the asteroid.

Creating your own finder-chart

You will probably find it most convenient to select and print a relevant section of a map using planetarium software that shows stars at least as faint as that of the asteroid (the ephemeris should give you an approximate magnitude for the asteroid).

New planetarium software is coming onto the market, or appearing as freeware, all the time, so I will have to leave you to research what is available at the time you intend going shopping. However, I will give the popular *Starry Night Pro* a mention as it contains stars down to 16th magnitude (you can manually select the magnitude limit – but the faintest stars only appear when you zoom in on a small area of sky). It also contains ephemerides of all the planets and many asteroids and comets. You can also keep it updated by downloading further ephemerides into the program.

When you move the cursor to a star, some data for that star appear next to it – including the magnitude and the source catalogue for that star. The magnitudes from the *Tycho* star catalogue can be relied on to be accurate. On that subject, beware using magnitudes from the popular *Guide Star Catalogue* as these may well be in error by up to ± 0.3 magnitude.

In Section 10.17 I give details of the extremely useful *Minor Planet Observer* (*MPO*) software suite. One of its components is the *MPO Asteroid Viewing Guide*. This is effectively a piece of planetarium software especially for asteroids and it can even directly generate finder-charts for you.

If you are working from a computer-generated printout, mark on it the position of the asteroid as best as you can judge it from the scale of the printout and the grid lines. Then draw a circle on it which, at the scale of the printout, represents the field of view of the low-power wide-field eyepiece you will use for locating the asteroid.

You can find the diameter of the field of view roughly by dividing the manufacturer's stated value of the apparent field of the eyepiece by the magnification. Otherwise, time a star's passage across the middle of the field of view, from one side to the other, with the telescope drive switched off. Simply multiply that time in seconds by $15 \cos \delta$ to get the field diameter in arcseconds, where δ is the declination of the star in degrees. Ignore the negative signs of northerly declinations. Divide the field diameter in arcseconds by 60 to get the figure in arcminutes. Divide by 60 again if you want the field diameter in degrees. You should print your chart at sufficient scale in order to produce a circle of at least a few centimetres across. This is your finder-chart.

However, the current practice amongst most asteroid observers (at least in the UK) is to use planetarium programs such as *Guide* or *Megastar* and download orbital elements from the Minor Planet Centre (www.minorplanetcenter.net/iau/mpc.html), or the Lowell Observatory (asteroid.lowell.edu) and plot the positions or tracks direct on a laptop. I, though, prefer paper charts illuminated by a dim red-filtered torch to having a bright laptop screen at the telescope. The choice is yours.

GOTO telescopes

If you own a telescope with a GOTO facility that really does (and never mind the advertising hype!) allow it to set on a target to an accuracy of within a few arcminutes, then life will be very easy for you. If it really ought to work this accurately but doesn't in practice then you will need to give some attention to setting it up more accurately. Perhaps the notes I offer in Appendix 3 may be of help.

If the telescope is provided with unusually accurate setting circles then these might do in getting the telescope aligned to the correct starfield. Otherwise you will have to find the correct patch of sky by *star-hopping*.

Star-hopping

Using a computer printout will also prove useful for star-hopping. On this, draw a set of nearly (or slightly) overlapping circles, each circle representing the telescope field of view, that links an easy-to-find object (such as a bright star or recognisable asterism) to the position of the asteroid. This gives you a set of 'visual stepping-stones'. You proceed by moving the telescope until the next pattern of stars enclosed by the next circle comes into view. After several of these controlled 'hops' you arrive at the field of the asteroid. Once you have identified the pattern of stars in the field of view you can decide which of them is actually the asteroid. In the most difficult cases you might want to prepare two finder-charts: one for your finder-scope, and one for the main telescope. As before, you could use a laptop at the telescope but I find looking from the eyepiece to the bright screen and back again often rather difficult, even unpleasant, and certainly rather tiring.

Beware of precession

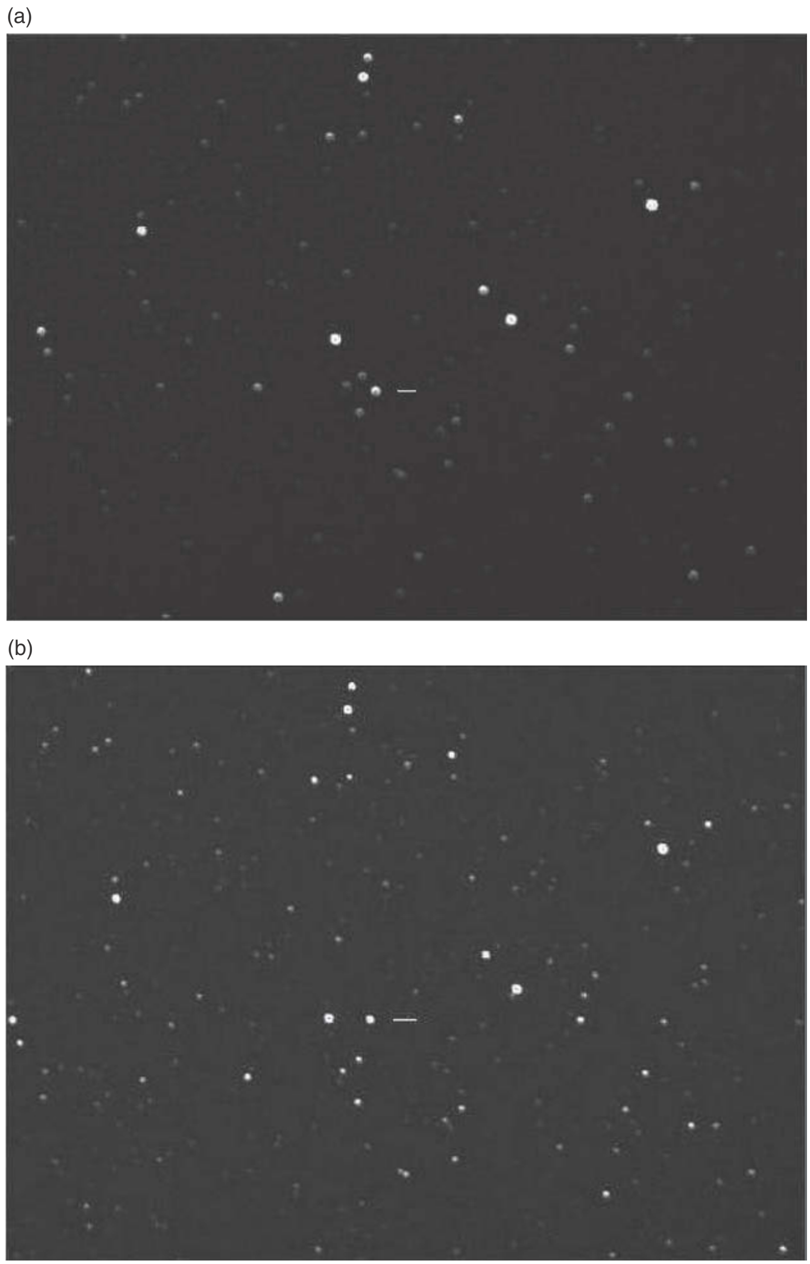
Thanks to long-term cyclical motions of the Earth's axis of rotation, called *nutation* and *precession*, the co-ordinates of stars change a little with time. Fortunately, ephemerides give positions of objects such as asteroids and comets in epoch 2000.0 co-ordinates, just the same as that provided by modern star atlases and catalogues. The last standard epoch was 1950.0 and you should only come across that in editions of catalogues and atlases published well before the beginning of this century. I describe how to calculate corrections for precession in my book *Advanced Amateur Astronomy* – but there should be no need to get involved in that if you stick to using modern publications.

10.8 PHOTOGRAPHING ASTEROIDS I – CAMERA AND TELESCOPE

You can photograph a starfield with a conventional camera and telephoto lens, though exposures long enough to show asteroids of the tenth magnitude and fainter will also show a lot of stars, making identification difficult. Normally you will want an image scale that comes with a focal length of at least a metre – and that means using a telescope.

A DSLR camera or a CCD astrocamera can be attached to the telescope in order to record images at the principle focus in the manner described

Figure 10.3 Images of Main Belt asteroid (44) Nysa (indicated by the short horizontal line immediately right of the asteroid in each case) made by Mike Clarke using his 80 mm f/7 refractor and Canon 350 camera. Image (a) was made on 2007 February 06^{d} 21^{h} 30^{m} UT and (b) was made on 2007 February 07^{d} 20^{h} 30^{m} UT.



in Chapter 3. Many asteroids are bright enough to be imaged using exposures as short as 30 seconds even through a small telescope (see Figure 10.3). Of course, if longer exposures are needed then this increases the demand for a good sidereal drive and a properly set-up telescope mount.

The first problem, though, is to have the telescope pointing at the target starfield. A good finder-scope, preferably one with illuminated crosshairs, will be a great help. Even so, getting an image of the asteroid onto the CCD is easy only if the CCD is at least a centimetre and a half square. If your telescope has an accurate GOTO function then that is a great help in getting the asteroid image onto a small CCD. A GOTO that places an object within an arcminute or two of the centre of the field of view probably is good enough if the CCD imaging area is at least a few arcminutes wide and tall (see Chapter 3, Section 3.3 for how to calculate image scales and sizes). Then you can use your finder-chart to identify the object on your computer monitor and fine-adjust to centre on it.

There is an accessory which can make acquiring the target on a small CCD very much easier: a *flip-mirror system*. Various companies such as Meade offer them. They cost in the range of $150 to $300. This small unit is inserted into the telescope drawtube just before the CCD camera. A small lever actuates a mirror. With the mirror 'up' it directs the light at right angles into a viewing eyepiece. The telescope can be moved to place the subject at the centre of the wide field which is visible. Then the mirror is flipped 'down'. The light from the telescope is then free to pass into the CCD camera. The selected target will then appear somewhere on the computer monitor ready for centring.

One pitfall with the flip-mirror system is that it takes up several centimetres of focus. Will your telescope drawtube rack inwards far enough with the unit plugged into it to allow a focused image to form on the CCD? If not, you might have to be prepared to make alterations to the optical assembly (or maybe just install a new low-profile focuser) to suit.

With a manually operated telescope probably the best procedure is to plug in a wide-field eyepiece and find the required field using star-hopping, as I describe in Section 10.6. Centre on the target as carefully as you can. Next, put in the flip-mirror system with the already attached CCD camera, trying to disturb the telescope as little as possible. Focus the image as seen in the eyepiece. With the flip-mirror 'up', centre on the target and then gently move the lever to lower the mirror and view the results on the computer monitor.

With the camera plugged into the telescope and it trained on the target the next task is to focus the image precisely on the CCD. This is achieved by tweaking the focuser between exposures and monitoring the results on the camera viewscreen or (for the astrocamera) the computer monitor. After doing this for the first time a mark made using a felt 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?

Most astrocamera systems have a special 'focusing mode' whereby only a small area near the middle of the frame is imaged in order to speed up downloading the images. It produces a rapid sequence of images, allowing one to quickly achieve the sharpest possible focus.

We next require that the image stays centred while we get everything ready for the exposure and we especially need the image to remain fixed in position on the CCD while the exposure is taking place. If your telescope refuses to track on its target to an accuracy of better than about 3 arcseconds during the exposure then your photographs will show the asteroid and stars elongated into trails, rather than appearing as points. An exposure of about a minute ought to be enough to show stars and asteroids down to the 17th magnitude, after processing, for a telescope of around 8 inches (203 mm) aperture.

If you find that the telescope mount does cause trailing of the images, first consider if there is anything you can do to improve matters mechanical. If the telescope drive suffers from slop or backlash you might try adjusting the counterweighting, or adding new weights, in order to take up the slack in the system. An east–west jittery motion in the image, or even an erratic drift-back then lurch-forward effect, may well be cured this way. Many authorities recommend deliberately unbalancing the telescope in right ascension so that the drive motor has to work harder in order to push the telescope round. I would add a note of caution, though. Most amateur-telescope drive motors are rather feeble. An overloaded synchronous motor might run half speed. It might even draw too much current and be permanently damaged. Stepper motor drives will also run hot and may burn out, often damaging the associated electronics as well.

Personally I think that unless the drive motor is unusually powerful it is better to unbalance the telescope so that it would slew to the west on its own if the drive gear was disengaged. In that case the drive would be acting as an escapement more than as a source of motive power. Even so, you could still overload the motor if you overdo the unbalancing to the point that the gear-train starts to bind up.

If you cannot improve your existing telescope's tracking, one solution is to remount its optical tube assembly. Consult the current manufacturers and suppliers adverts in magazines, brochures and websites and take time in making your choice. Be prepared, though, to spend a lot of money if you want a truly excellent mount such as those made by Losmandy (www.losmandy.com), Software Bisque (www.bisque.com/sc/media), or Takahashi (please find using search engine – different addresses depending on region).

In many cases a cheaper telescope mounting can be made to track almost as well as one of the most expensive models by using a separate guiding unit, such as Celestron's NexGuide. This unit plugs into a small-aperture short-focus telescope rigidly mounted on your main telescope. Full instructions come with this or any other commercial autoguider but the main requirement is that your telescope mount must be sophisticated enough to have an electrical port to accept tracking correction commands from a separate autoguider. The cheapest telescope mounts will not have this facility.

Another alternative is to install an *adaptive optics* unit, such as that made by SBIG for use with several of their cameras. The current model for smaller-sized CCDs is the AO-7 and it costs about $1300. The SBIG cameras have a second small CCD set next to the main one. The small CCD is for monitoring the tracking and results in signals sent to the adaptive optics unit. These cause tiny changes in the tilt of a mirror, which results in the image remaining stationary on the main CCD despite any small tracking errors of the telescope. The system can correct up to about 2 arcminutes of tracking error when used with an effective focal length of 2 metres. SBIG also do a more expensive adaptive optics unit for their very much more expensive large-format CCD astrocameras.

As with the flip-mirror system, the disadvantage of an adaptive optics unit is that several centimetres of focus are used up. In fact, with a flip-mirror system, an adaptive optics unit and, finally, the CCD stacked and plugged into the telescope, you can be pretty sure that you will have to make a major adjustment to the positions of the telescope optics. Exceptions to this are the range of commercial Schmidt–Cassegrain and Schmidt–Newtonian telescopes, as the primary mirror moves to affect focusing and there will be enough focusing latitude available.

Undoubtedly the easiest solution one can use to correct for the effects of poor tracking is to *track-and-accumulate* exposures. Most astrocamera camera systems come with software which has a track-and-accumulate option that operates while taking the photograph. This involves taking not just one exposure of the desired length but lots of short exposures. You will not have this option if using a DSLR. In that case you will have to resort to taking multiple exposures and manually stacking them into one composite using appropriate image-processing software. I described how to go about this in Chapter 4 (Section 4.3).

Even if only twelve 5-second exposures are well enough tracked for subsequent stacking from a run of a couple of dozen or more, then that

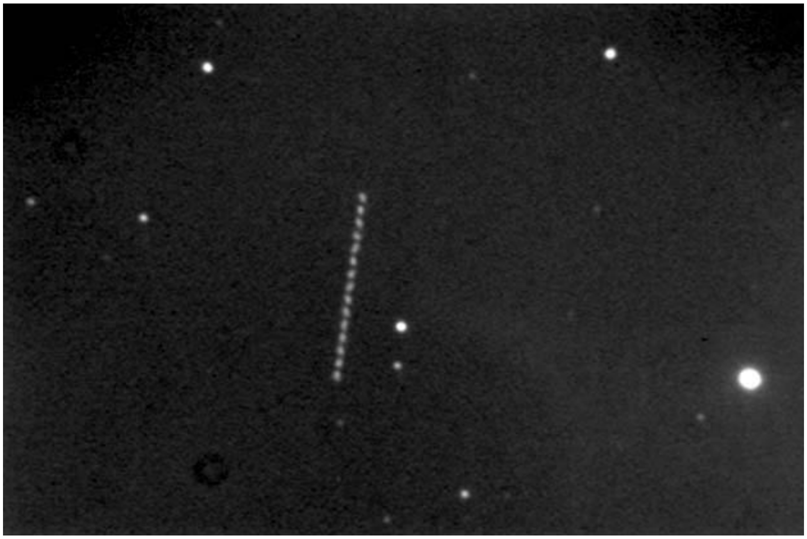


Figure 10.4 The NEA 2006 VV2 imaged by Bob Neville on 2007 April 01^{d} 20^{h} 14^{m} UT. This is a set of fifteen 10-second exposures showing the rapid motion of the asteroid which, at its point of closest approach the day before, came within 3.4 million km of the Earth. This image is a composite, aligned using the background stars. The field is 8 × 13 arcminutes. The individual exposures were made with a 12-inch (0.3 m) Meade LX200 Schmidt–Cassegrain telescope and a Rockingham Instruments CCD plus RG610 filter.

is sufficient. When stacked they would synthesise a 1-minute exposure, though with a signal-to-noise ratio inferior to that of a genuine 1-minute exposure.

Even if your telescope tracks well at the sidereal rate there can still be problems tracking fast-moving asteroids, such as NEAs. Star images might be pinpoints but the asteroid image will be a trail, or a series of points if there is a gap between each in a series of exposures (see Figure 10.4). If the asteroid is faint and fast-moving it may well move on to the next pixel before sufficient image has built up to show it clearly – or for the camera-control software to lock onto for a standard track-and-accumulate exposure.

To solve that problem use a program such as *Astrometrica*. You can download this from www.astrometrica.at. After a 90-day trial period you will be required to pay a registration fee of about 25 euro (roughly £17/$34). It is also a marvellously easy program to use for astrometry, as described in Section 10.14. It is its 'track and stack' function we will find of most use here. The program asks you to input the predicted rate and position angle (direction of motion) of the asteroid. It then stacks the image of the asteroid, leaving the stars as trails or lines of dots and the asteroid as a single image (see Figure 10.5).

Taking images of asteroids in a digital format (the way it is almost always done these days) allows the possibility of making some very useful precise measures. One of these measures is *astrometry*, a precision measurement of the asteroid's position with respect to the background

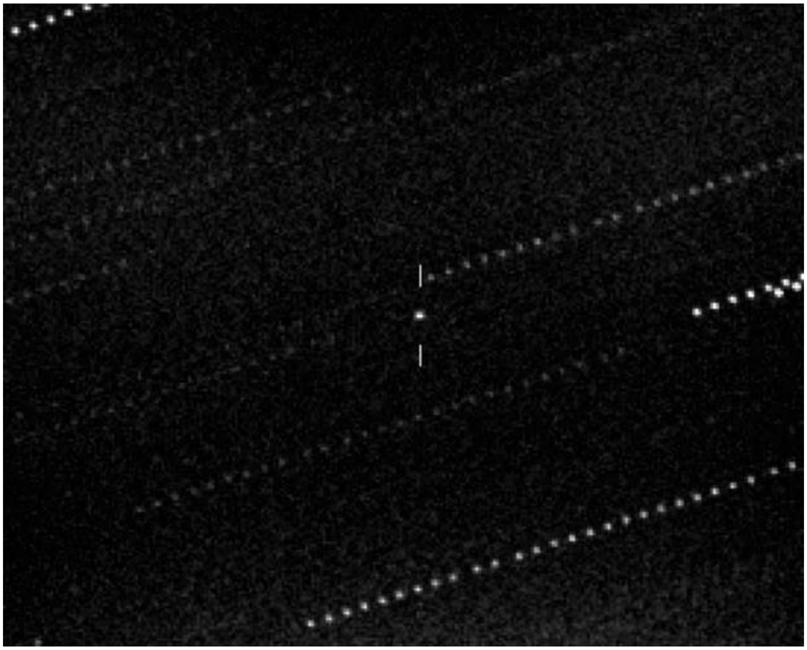


Figure 10.5 The NEA 2006 BV39 imaged by Peter Birtwhistle. This photograph is a composite of twenty-seven 2-second exposures taken on 2006 January 28^{d} 05^{h} 13^{m} UT. They were stacked to compensate for this body's rapid motion (277 arcseconds per minute at a position angle of 109°) using the *Astrometrica* software suite. At the time this asteroid was two and a quarter hours from closest approach from Earth and was just closer to us than our Moon! The field size is 8×10 arcminutes. The telescope used was a Meade 16-inch (0.4 m) Schmidt–Cassegrain used with a telecompressor lens giving f/6.

stars at a given instant. Another is *photometry*, a precise measure of its brightness at the instant of the photographic exposure (again by comparison with selected nearby background stars). The latter technique demands that the image be prepared in a specific way for the measurement. This involved the use of *calibration frames* . . .

10.9 PHOTOGRAPHING ASTEROIDS II – CALIBRATION FRAMES

The picture you will get from your digital camera, probably the result of several stacked 15- or 30-second exposures, may be cosmetically good enough as it stands. Of course you can always do a bit of image enhancement using tools such as 'Curves' in *Adobe PhotoShop* in order to darken the sky background and stretch the contrast enough to make the faintest stars visible.

The output of the proper CCD astrocamera will probably be less 'pretty', being peppered with white spots caused by hot pixels and with dust rings visible and a variety of other non-uniformities. Any attempt at contrast stretching in this case will make the imperfections leap to the fore. In this case the image can be made 'prettier' by the application of *calibration frames*.

If you wish to do some real science with your images, particularly photometry, then these calibration frames become essential. In the following notes I will describe the full procedure necessary for making calibration frames of the necessary quality required for photometry. If you are going to use a DSLR camera for your photometric work you will need to work with images in RAW format, as you do not want the onboard cosmetic manipulations that the camera will impose when it outputs images in other formats.

Flat field

A flat field is a short exposure of an evenly illuminated field of view. Its purpose is to eliminate the variations of image brightness that occur due to imperfections in the optical system. Specks of dust on the window will cast shadows on the CCD, for instance. Also, vignetting will progressively darken the field of view towards the corners of the image. These imperfections, and more, can be accounted for in the processing that is done after a flat field is created and applied.

Ideally, a flat field is created by making an exposure of the twilight sky at the beginning of the evening's work. If working with a CCD astrocamera, do make sure that the camera cooling has been on long enough for the temperature to have stabilised before you begin. Fifteen minutes is probably long enough. The sky ought to be sufficiently bright at the time so that the correct exposure is less than a second while most of the pixels are approaching half-full capacity (a brightness count of about 32 000, for instance, for 16-bit imaging – how to monitor this will be explained in the instruction book you obtained with the astrocamera). Do not exceed that half-full level, though, because a few of the pixels will then be filled to saturation. The number of saturated pixels will increase with further exposure. Having any significant number of pixels saturated is undesirable in a flat field.

In the real world, most amateur astronomers have to contend with the vagaries of the weather and the myriad of other things in everyday life which mean that a twilight shoot before the main session is seldom achievable.

An alternative is to set up a flat white screen in front of your telescope and illuminate it as evenly as possible. Do this just before you embark on the evening's programme. You could (and probably should) add a further screen of white perspex or some other suitable material to the end of your telescope to further diffuse the light. Clearly you will need to be prepared to do some experimenting before you can settle on your preferred method for creating a flat field.

I mentioned that the exposure for creating a flat field ought to be less than a second. This is to reduce the effects of the sources of 'noise' (particularly thermal noise) that would afflict a longer exposure. Noise shows up as graininess in an image and it represents an uncontrolled pixel-by-pixel variation that is highly detrimental to photometry. This is also the reason for having the light source bright enough such that most of the pixels are filled to the better part of half capacity (so that the ratio of signal to noise is favourable).

Even so, it is a very good idea to actually take a run of at least 10 (20 would be ideal) flat-field exposures and later average the result of them (again, this is something that the supplied software will allow you to do). The final result will be a flat field with very little ‘noise’. In other words the final flat field will be smooth (as opposed to grainy) and accurately mirror the variations in the optical illumination of the CCD by the telescope.

Bias frame

This is only necessary for photometry. Many measuring instruments have a *non-zero offset*. In other words, when the quantity being measured is actually zero the measuring device does not show zero but instead indicates a small positive or negative reading. To get accurate brightness measures one must always add or subtract this quantity, the *zero offset*, as appropriate from all the readings. CCD astrocameras also have a small non-zero offset inherent in the readout electronics. This can be taken care of in the subsequent processing by utilising a bias frame.

To take a bias frame the telescope is capped (and/or the camera shutter is closed if there is one fitted) and the shortest possible exposure is given. This is probably one hundredth of a second, though a few camera operating systems do have provision for a ‘zero’ exposure length. As before take a series of at least 10 bias frames to get an average. Do this just after you have completed the flat-field run.

Dark frame

Dark frames are, like bias frames, taken with the camera or telescope shuttered against any light entering. This time, though, the exposures given are the same duration as those for taking the images. Hence, raw dark frames are chiefly afflicted by thermal noise. When viewed, such a frame gives a slight snowstorm appearance of ‘hot’ pixels against a grey background. As before, it is a good idea to take at least 10 dark frames and use the average of them in the final processing. Mind you, this is time consuming if you need to image the chosen starfield with an exposure time of more than a couple of minutes. Fortunately, exposures lasting no longer than a minute will usually prove sufficient.

Applying the calibration frames to the starfield image

The raw star image is afflicted with all the blemishes and faults that we have isolated in the calibration frames. The image-processing software that will come with your camera (or which you can obtain separately if you do not wish to use the camera manufacturer's software) will have a number of functions, or operations, it can perform on the images you obtain with the camera. You will be able to subtract one frame from another, or add one frame to another, or you will be able to average frames, and even 'divide' one frame by another.

There are many other functions possible and commonly included in imaging software. I can only provide general notes here. It is down to you to study the literature supplied with the camera/software package and learn how to carry out these operations. In most cases this will involve nothing more frightening than clicking on options displayed in menus. You must spend the time and effort you will need to get to know the software package you are using.

For photometric purposes we will only need to average, subtract and divide frames. Indeed, all the wonderful functions that can be carried out for image processing, such as contrast stretching, applying processing 'filters', image sharpening, etc. are most definitely to be left untouched as using them would render our images useless for photometry. Please, though, do feel free to use them for making portraits of asteroids against starfields.

The procedure is to bring up the raw starfield image and then subtract the averaged bias frame and then the averaged dark frame. The result of this is then divided by the averaged flat field. The resulting image is the one you should use for your photometry. For this to work well does require the temperature of the CCD be kept constant during the observing run. You should always keep an eye on the temperature indicator and discard the images if it varies by more than a degree during the photometric session.

Let me here restate a very important point: if your aim is to perform photometry do not be tempted to improve the cosmetic appearance of the image beyond the application of the calibration frames. **Do anything further to the image and you will render it useless for photometry**.

It is difficult for me to show you an illustration of the calibration process necessary to render a raw image suitable for photometry because the on-screen visual effects are rather subtle. However, I can show you pretty much the same process in operation on an image to prepare it for **visual display**. See Figure 10.6(a)–(d). Here the contrast levels are much exaggerated and so these do show the effect of the dark frame and flat field well.

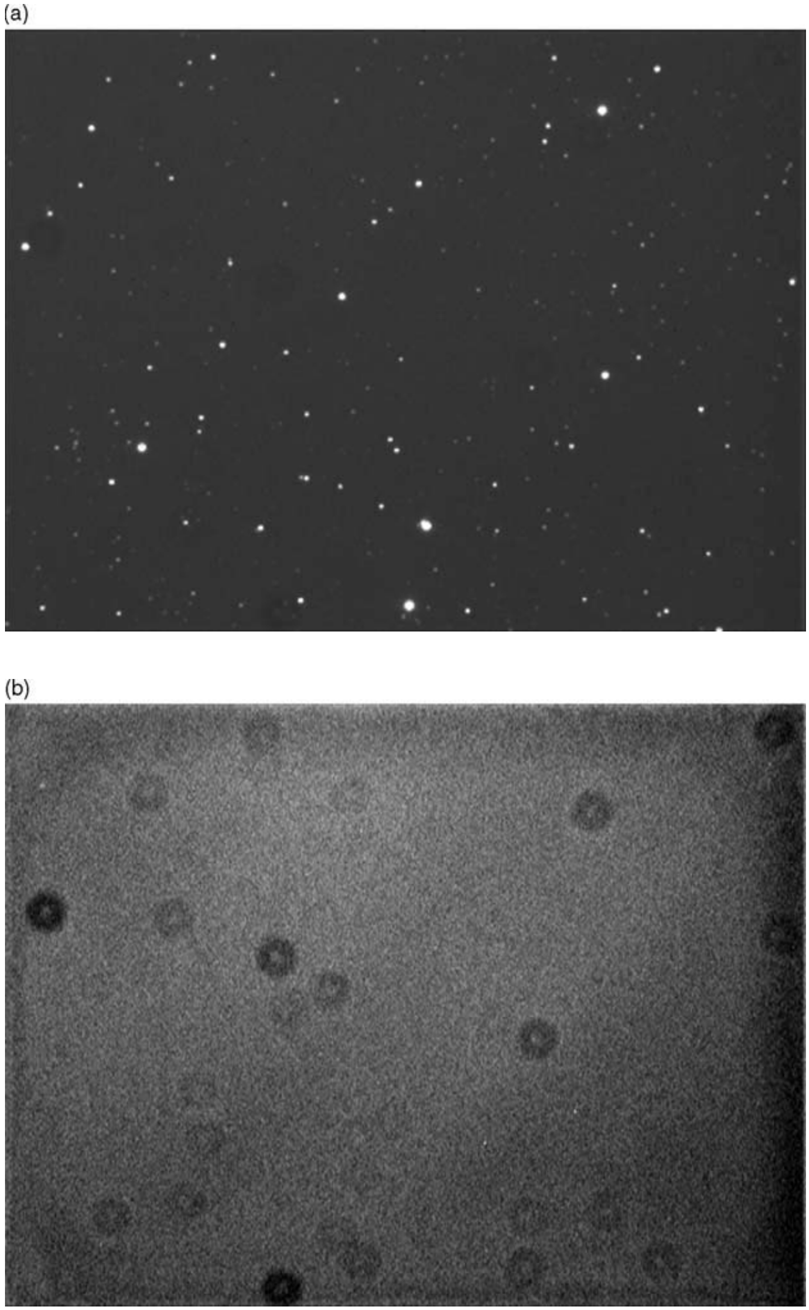


Figure 10.6 Calibration frames applied to a starfield photographed by Nick James using his 12-inch (0.3 m) Newtonian reflector and Starlight Xpress CCD astrocamera. (a) The raw image. (b) The flat field.

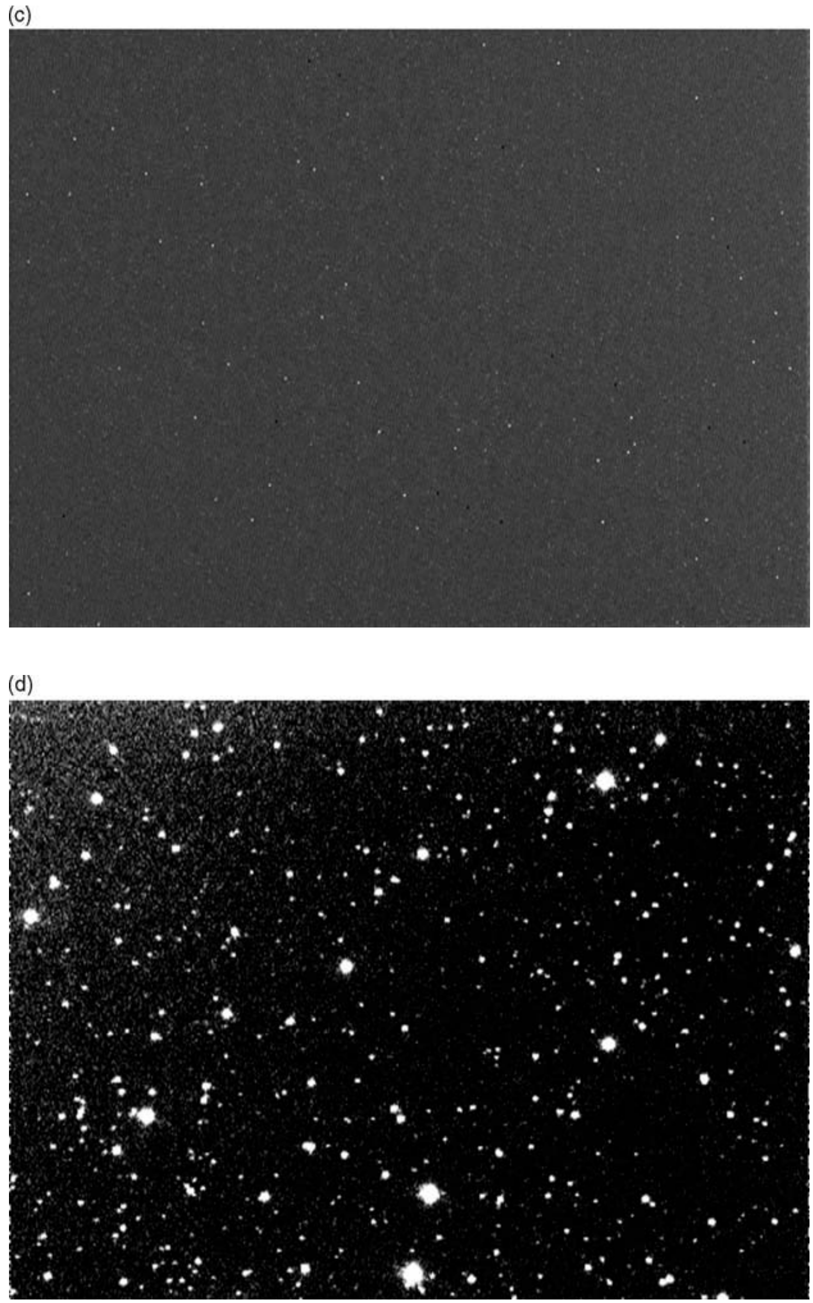


Figure 10.6 (*cont.*) (c) The dark frame.
(d) This image is the result of subtracting the dark frame from the raw image and dividing the result by the flat field. This image is contrast stretched and has the background level set to zero in order to show the faintest stars – but neither operation must be done on any image that is to be used for photometry.

Figure 10.6(a) shows the unprocessed image as it appeared straight from the CCD astrocamera. On it the sky background count is around 20 000 units on a scale of 0–65 353 (this is what you get with 16-bit imaging – preferred for photometry). Figure 10.6(b) is the flat field. It is the average of a number of short exposures of the twilight sky. Dust shadows are evident, as is a general variation of intensity across the CCD. Figure 10.6(c) is the dark frame. Even though the CCD is cooled it still suffers from thermal noise as can be seen by the white specks on this image. Figure 10.6(d) shows the image after processing (the dark frame subtracted from the raw image and the result divided by the flat field). However, the image has been here processed for visual display so contrast stretching has been used and the background level has been set to zero. These latter operations are **not** to be performed when preparing an image for photometry.

10.10 PHOTOMETRY I – TAKING THE PICTURE

The way the brightness of an asteroid varies with time can be used to derive a probable rotation rate for it, as well as giving a first clue as to its shape, and even giving some clues about the reflective properties of its surface.

An experienced variable-star observer can make visual brightness estimates with an accuracy of about $\pm 0.^{m}1$. He or she does this by comparing the brightness of the variable star with one or more *comparison stars*. These are stars, preferably of similar brightness to the variable, whose magnitudes are precisely known. They are usually shown on a finder-chart with the variable star located at the centre, and the comparison stars marked with their known magnitudes.

In principle you can estimate the brightness of asteroids by using the same technique. In truth, though, visual methods of brightness determination have become obsolete in the asteroid observing scene. Now CCD-based *photometry* is the way to do it. Using that technique you can make a genuinely useful contribution, especially where your results are combined with those of others to create a meaningful graph of brightness versus time, termed a *light-curve*.

Here, working with the asteroid observing section of the BAA, or of ALPO, or other national astronomical society, is invaluable. The director of the observing section can advise you of what asteroids are currently available in the sky and are suitable and of interest for this type of research. The director will also, usually via the section website, supply you with an up-to-date ephemeris for any chosen asteroids.

This ephemeris will include an asteroid's positions at particular times along with rough values of brightness. The latter will be helpful to you when trying to identify the object in a starfield. You might even be supplied with one or more suitable finder-charts showing the position of the asteroid with suitable comparison stars also marked with their magnitudes. Maybe, though, you will have to create your own finder-chart marked up with comparison star magnitudes.

We begin by taking a photograph of the asteroid with its surrounding starfield. The procedure is broadly the same as I described in Section 10.7 but there are just one or two considerations we have to be mindful of if the image is to be useful for subsequent photometric analysis.

We will assume that at this point we have taken our calibration frames and we now have the focused image of the starfield, with the asteroid centred, on the CCD. We switch from focus mode to normal imaging mode and so we next have to decide on the exposure.

The ideal result would be to have the pixels illuminated by the asteroid, or the brightest comparison star, whichever is the brighter, about one half full of liberated charges (in technical jargon, these pixels are full to half of their *full-well capacity*).

The higher the 'count', the less it is afflicted by random 'noise'. Statistically, the uncertainty in the reading is inversely proportional to the square root of the count. So a count of 100 units of brightness has a 10 per cent uncertainty, while one of 10 000 units has an uncertainty of 1 per cent. This corresponds to about $\pm 0^{m}.01$ for that one brightness reading. For a count of 32 000 units, statistics predict an uncertainty of 0.56 per cent. It is desirable for each of the measures to have an uncertainty of **less** than 1 per cent if the final calculated magnitude is going to be accurate to $\pm 0^{m}.01$. Having the fullest pixels not much more than half full (say 35 000 units out of a possible 65 535 units) is desirable to avoid any inherent non-linearity in the CCD.

When in doubt take a series of images, bracketing your best guess at the correct exposure. In fact, I would recommend taking multiple images every time. The longest exposure times you will need will probably be no more than a minute. As a very rough idea, a 1-minute exposure will quite likely correctly expose a 10th magnitude asteroid for photometry using a typical amateur telescope and CCD camera. However, a great deal depends on the precise details of the equipment, the seeing conditions and the sampling (how many arcseconds per pixel) on the CCD. The colours of the asteroid and the comparison star must also be taken into account. In connection with that I should mention that you will need one or more filters in the optical train – but that is something I will return to in Section 10.13.

The best advice I can give about determining the correct exposure is to get some practice with your system. Learn what exposures you require to produce images suitable for photometry with different integration times. You can predict that, for every magnitude dimmer the star or asteroid image is, you will have to increase the exposure by 2.5 times. Conversely, reduce the integration time to 0.4 (1/2.5) of the previous exposure for every one magnitude increase in star/asteroid brightness.

10.11 PHOTOMETRY II – OBTAINING MAGNITUDE MEASURES FROM A CCD IMAGE

Thus far we have completed all of the really difficult tasks. We have our properly focused, properly exposed, and calibrated image on the computer screen. We save it in whatever format is compatible with the software package(s) we are using (commonly TIFF or FITS).

To finish the job (in all likelihood a day or so after our observing run) we have to bring up the image and apply the photometric functions contained in the software package we are using (probably the one supplied with the astrocamera).

The details of operation vary greatly from software package to software package. Most astrocameras come with software that includes the provisions for photometry. Other stand-alone photometric software packages also exist. At the time I write these words, the Windows-based *AIP4WIN* is very popular. It comes on a CD-ROM with Richard Berry's *Handbook of Image Processing* (published in 2000 by Willmann-Bell). Another stand-alone package is *IRIS* by Christian Buil. This one is currently free for download from his website at www.astrosurf.com/buil.

Both of these programs are very powerful and can even automate most or all of the procedure. Whatever the software we are using, we will be carrying out a procedure that is classified as both *aperture photometry* and *comparative photometry*. It is 'aperture photometry' because we use the software to define a small circle or square, the so-called 'aperture', around the asteroid and each comparison star we are to measure. The software then reads the total amount of light recorded by the CCD within this small aperture. It is also 'comparative photometry' because the final determination of the brightness of the asteroid is made by direct comparison with the brightnesses of the nearby stars of already known brightness.

At the sophisticated end of the software market, so to speak, programs such as *IRIS* will automate most of the process and make all the calculations for you. In other, simpler, programs you manually select the size of the photometric aperture, position it over the asteroid and take a brightness reading, then position the aperture over each comparison star and record those brightness readings in turn. Next, you position the same aperture over one or more parts of the image which are obviously free of stars and again record the brightness levels. You then have to use a set of equations and use your pocket calculator in order to get the final answer you want: the magnitude of the asteroid.

As ever, it is for you to read and follow the instructions that go with the software package you are using. Here I can only highlight a few general matters that are important if your photometry is to be accurate.

To start with, here is the master equation you will need if you are using a manual photometry program:

$$\Delta m = -2.5 \text{ Log} \frac{(C_{star} - C_{sky})}{(C_{comp} - C_{sky})},$$

where Δm is the difference in magnitude between the comparison star and the asteroid (remember that the dimmer object has the larger magnitude number), C_{star}, C_{comp}, and C_{sky} are the counts within the same-sized apertures around the asteroid, the comparison star and the sample of empty sky, respectively. You should sample several areas of blank sky to check for consistency and take the average count as the true background reading.

Finally, knowing the magnitude of the comparison star and the value of Δm allows you to find the magnitude value of the asteroid. You should repeat this procedure using at least one more comparison star. Better still, use a third, or even a fourth comparison star. If any of the magnitude values you derive disagree keep going until you are sure where the error is. It is just within the realms of possibility that one of the assigned comparison stars is actually variable in brightness!

What size 'aperture' should you use?

Owing to the seeing and instrumental defects (including errors in tracking), star images will be larger than simple optical theory would predict. In fact, each star image in the field of view will be a 'blob' spanning several arcseconds, with a much fainter halo extending further out. The ideal size of the aperture you select to surround each star image should be enough to encompass almost all of the light from this 'halo' but not so much as to dilute the count with an over-large contribution of light from the sky background.

You will have to make the judgement by eye. Try momentarily turning up the brightness of your monitor to full (but **do not** use the image processing software to make any changes) and increase the size of the aperture until it looks to you that you have included all the light from the star within it. It is crucial that you use this same size of aperture to make each of the other counts. If a small amount of the light from the star does fall outside the aperture, then you can be fairly sure that this will also be the case for all the other stars you measure. Hopefully the ratios of brightnesses will not be skewed as long as you ensure that the aperture contains almost all of the light from each object.

A refinement to the sky background reading

It is best practice to use a *median* function on the aperture you use to sample the sky background. The median count is a bit like an average count. In effect, though, a given cluster of pixels are all brought to the same level of brightness. The presence of any faint stars that might lurk in the aperture then have a lesser effect on the final figure than they would for a simple summation of brightness. It is highly likely that your software package will sport a median function for you to use.

Use only counts from 'clean' apertures

Even after our calibrations, some images will contain flaws. Believe it or not, even random cosmic-ray hits can fire individual pixels or lines of pixels in the CCD during an integration. If you see any such sources of pollution make sure that you do not place the sampling apertures to include counts from them. If any such blemishes are so awkwardly placed that you cannot avoid them, then it is best to discard the image and use another. This is a good reason for taking a series of images during your observing run. Failing that, the only remedy is to replace the affected pixels with the median level – in effect to paste out the blemishes. Such tinkering should really only be a last resort and the observation report you submit should include a note to that effect.

Consistency and calibration

Can you rely on the software to give you accurate magnitude values? I recommend testing this assertion out on several fields containing comparison stars. In any field make one of the comparison stars your 'asteroid'. Perform the observing run and reduction procedure using the other comparison stars as known standards. Does your chosen star come out at the correct magnitude?

Repeat this procedure on fields containing stars to cover a range of known brightnesses. It is worth spending several evenings doing just this before embarking on your asteroid photometry programme. From your results, make a graphical plot of the true magnitudes of the stars against your own determinations of their magnitudes. Ideally, all these magnitudes will perfectly agree. Even if they do not, the graph should show either a smooth curve or a straight line. If so, you can use this graph to calibrate your final results of star and asteroid brightnesses and in this way produce a correct final value from the result of each observation.

Any scatter in the graphical points will give you an indication of the likely uncertainty in any subsequent brightness measurement you do obtain. **Don't forget to include this uncertainty value in the report you send to your observing co-ordinator**. Your results are worthwhile provided the uncertainties are no more than $\pm 0^{m}.1$. Potentially, though, they could be as good as $\pm 0^{m}.01$.

Up to the time I am writing these words, it is still true that some of the automated photometry programs that manufacturers supply with astrocameras cannot be relied upon to give very accurate results. I cannot overemphasise the importance of investigating (and calibrating if necessary) your entire system in the field before you routinely begin submitting your observations to your co-ordinator. As a bonus you will get valuable practice while working with stars of known brightness before you embark on your work with asteroids.

10.12 PHOTOMETRY III – FILTERS

Before the mid-nineteenth century, the only detector available to astronomers was the human eye and brightness determinations had to be made by eye estimates alone. Then came photography and brightness measures made from photographs. Much later came photoelectric detectors. Now we have CCDs. In each case the *spectral response*, the way the detectors respond to different wavelengths, differs and so special filters have to be used to ensure that the brightness measures obtained from one method are comparable with those obtained from another.

If you are only interested in producing a light-curve from which an asteroid's rotation can be found then you do not need a filter. If, however, you do wish to record an asteroid's magnitude on the modern photometric scale then you must use a filter fitted to your astrocamera when taking comparison-star and asteroid images. Since CCDs vary in their precise spectral responses from model to model, your best course of action is to consult the manufacturer's literature (or even consult the manufacturer directly if you need to) and obtain the recommended filter for your photometric work.

This standard filter will be *V-band* meaning 'visual'. The filter–CCD combination will roughly match the response of the eye. The peak response will actually coincide with the yellow part of the spectrum. You could also obtain filters for other standard photometric bands. For instance, there is a *B-band* that has its peak of transmission in the blue–violet part of the spectrum. Making magnitude determinations in two or more bands allows you to obtain data on the colour of the asteroid. Only undertake such *colorimetry* after you have become well practised in V-band photometry.

A book that may be of particular use to you is *A Practical Guide to Light-curve Photometry and Analysis*. It is authored by the creator of the *Minor Planet Observer* suite of software, Brian Warner, and was published by his company Bdw Publishing in 2003. It is available through the company website (www.minorplanetobserver.com), Amazon.com, or BarnesandNoble.com.

10.13 PHOTOMETRY IV – LIGHT-CURVES AND ANALYSIS

If you can submit accurate values of a given asteroid's magnitude at accurately recorded times then your asteroid section co-ordinator/director may be able to use your results to generate a light-curve for the asteroid and in the process calculate its rotation period. Normally the co-ordinator/director will combine your results with those of other observers to get a reliable and meaningful result. Maybe another experienced 'team leader' will do the same job and you can become a contributing member of that team. The team-generated results could be sent directly to such repositories as Geneva Observatory or the Collaborative Asteroid Lightcurve Link (CALL), and even papers prepared for *The Minor Planet Bulletin*, ALPO or the BAA, etc. In time you may even wish to head specific projects of asteroid research yourself.

Software suites such as Brian Warner's *Canopus* can be used to generate asteroid light-curves and derive probable rotation periods. Here, though, I will just show examples of results derived from collaborative 'calls to arms' for three asteroids: (218) Bianca, (554) Peraga and asteroid 2006 XD2.

During 2005, Martin Crow and Roger Dymock submitted photometry on two Main Belt asteroids – one of which was (218) Bianca – to Dr Mikko Kaasainen of the University of Helsinki for use in his Shape Modelling Programme.

Figure 10.7 shows the light-curve derived from the observers' results. You will notice that the brightnesses are presented in relative units and the analysis software has looked for a repeating shape in the light-curve and has used this to generate a phase-angle plot of the light-curve. In this, zero-phase angle corresponds to a particular orientation of the asteroid and the increasing phase angle corresponds to a progressive rotation of the asteroid until a phase angle of 1.0 which corresponds to one complete rotation. In the process the software determines the rotation period. In the case of asteroid (218) Bianca this is 6.33 hours $\pm$ 0.01 hour. This work is included in a paper entitled 'Physical models of ten asteroids from observers' collaboration network', published in *Astronomy and Astrophysics*, Volume 465, No.1 (April 2007).

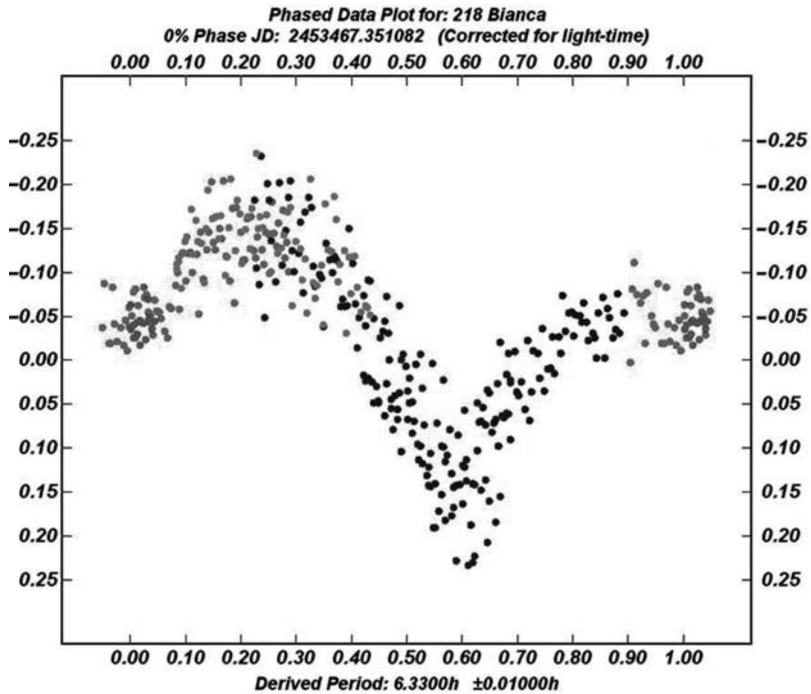
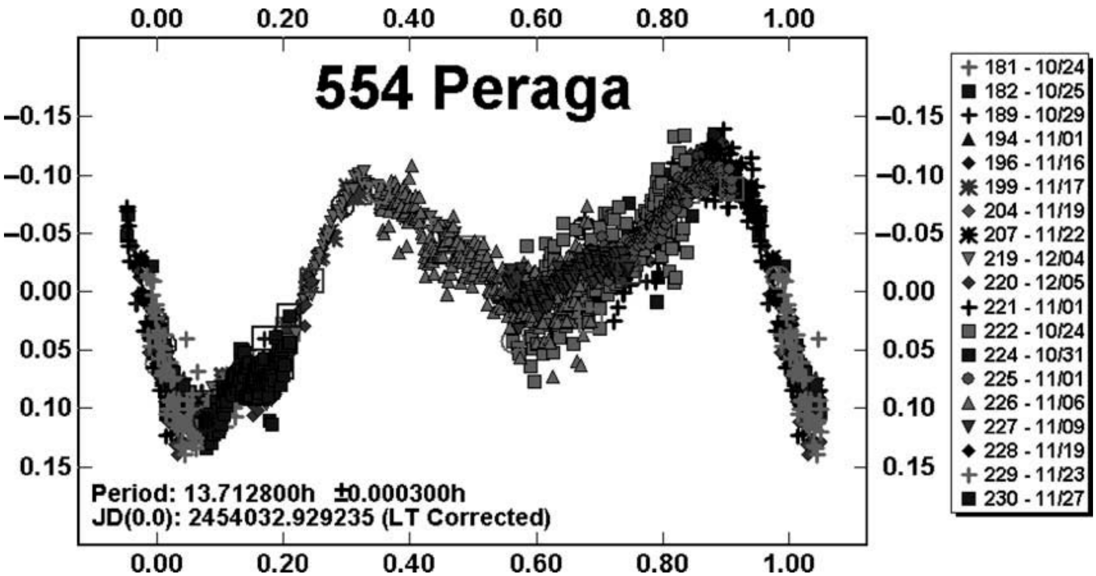


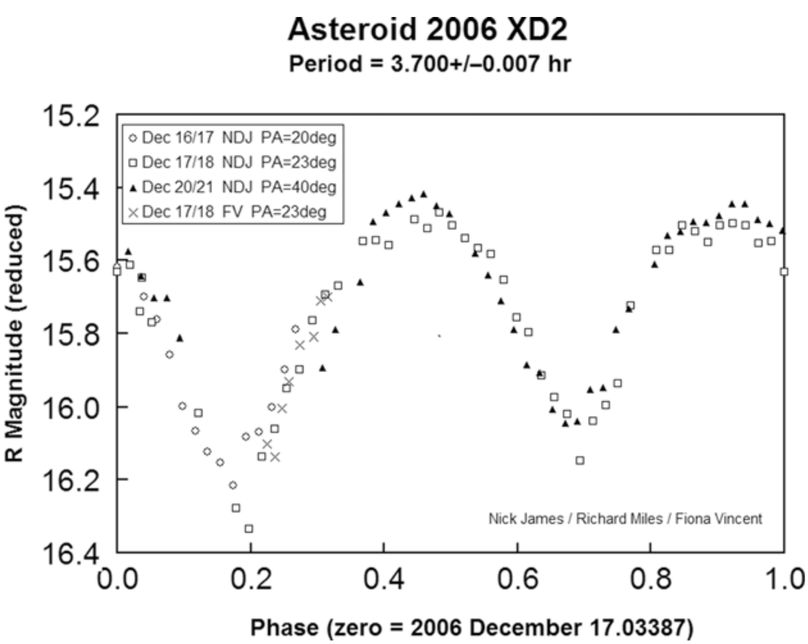
Figure 10.7 Light-curve (brightness versus phase) of asteroid (218) Bianca. See text for details.

Another example of a professional–amateur collaboration concerns the Main Belt asteroid (554)Peraga. In response to a request from Ellen Howell posted on the Minor Planet Mailing List to support her radar observations of this asteroid, several amateur astronomers sent in photometry of it. Figure 10.8 shows the light-curve (again relative brightness versus phase angle) generated by David Higgins from his own data combined with those of Brian Warner, Martin Crow and Roger Dymock. The derived rotation period for this asteroid is 13.7128 hours ± 0.0003 hour.

As a final example Figure 10.9 shows the derived light-curve of the Apollo-type NEA 2006 XD2 (this time the red, R-band, magnitude is plotted against phase-angle). This resulted from a ‘call to arms’ from Dr Richard Miles using photometry produced by himself, Nick James and Fiona Vincent. This little chunk of rock is probably only about 170 km wide and 350 km long and was passing the Earth at a distance of something around 7 million km when these observations secured our knowledge of its 3.700 hours ± 0.007 hour rotation period.

In America, highly dedicated amateur Robert Stephens has won awards for the results he has obtained pursuing asteroids, particularly photometrically. Here I will just point you to his article in the October 2010





issue of *Sky & Telescope* magazine where he describes his work, which includes using his results to model the shapes of asteroids.

Before leaving the subject I should mention that there is a comprehensive book, set at a fairly advanced level, called *Introduction to*

Figure 10.8 Light-curve (brightness versus phase) of asteroid (554) Peraga. See text for details.

Figure 10.9 Light-curve (R-band magnitude versus phase) of asteroid 2006 XD2. See text for details.

Astronomical Photometry. It was authored by Edwin Budding and Osman Demircan and published by Cambridge University Press in 2007.

10.14 ASTROMETRY

The once tricky and very arduous process of *astrometry*, the precise measurement of positions of the celestial bodies, is something that has become very much easier for the amateur to do since the advent of CCD imaging and suitable software. There are pitfalls and those new to the field are faced with having to identify and seek out the appropriate software. Let me first point you in the direction of an excellent paper in the February 2004 issue of the *Journal of the British Astronomical Association* (Vol.114 No.1) titled 'An introduction to Astrometry'. It was written by my friend Nick James. Here I am constrained to give a very short introduction to this field and I will do so by offering some condensed 'do it this way until you know better' advice. I hope that proves acceptable and you will find it sufficient to get you started.

Firstly, the images you use should have been exposed just enough to give a well-defined spot but not so long as to generate a big 'blob'. Ideally, the image scale will be something close to 1 arcsecond per pixel.

Quite a number of image-processing programs have astrometric facilities. One such is *IRIS* mentioned earlier for photometry. One that is particularly easy to use for astrometry is *Astrometrica*. Figure 10.10(a) shows a screenshot of this program in action. In use, you are required to supply the approximate image scale and orientation of the image, as well as the approximate co-ordinates (right ascension and declination) of the centre of the image and it automatically compares the image to a catalogue that you must also have in your computer (more about that in a moment). You can move the cursor (a small box) over the asteroid or other object.

The program busies itself calculating the centroids of all the stars and the object contained in the image. This is done to a potential accuracy of about a tenth of a pixel. The star images are then identified by correlating with the catalogue. Then a complicated set of calculations are performed to work out the true co-ordinates of the centroid of the object you identified in the cursor box (see Figure 10.10(b)). After clicking on the object, though, all **you** have to do is sit back and wait for a short while, maybe just seconds depending on your PC and its set-up – and then read off the desired co-ordinates of your selected object! A good image with an image scale of an arcsecond per pixel will probably result in an accuracy of about ± 0.3 arscecond.

Now to consider the accompanying star catalogue. At the time of writing probably the best for astrometry is the *USNO-A2.0*, which is available via ftp download from ftp.nofs.navy.mil. Beware, though, for it is huge. You will need to burn 11 CDs or 2 DVDs as it contains of the order of 500 million stars, down to the 19th magnitude! Of course, if you have a hard drive on your computer of capacity 100 GB or more then the whole catalogue can be stored in it, without the need for loading CDs or DVDs each time you wish to use it.

An alternative is to have *Astrometrica* and your computer set up to download just the relevant section of the immense *USNO-B1.0* catalogue. This catalogue of billions of stars to magnitude 19 would fill 15 DVDs if you wanted to download it!

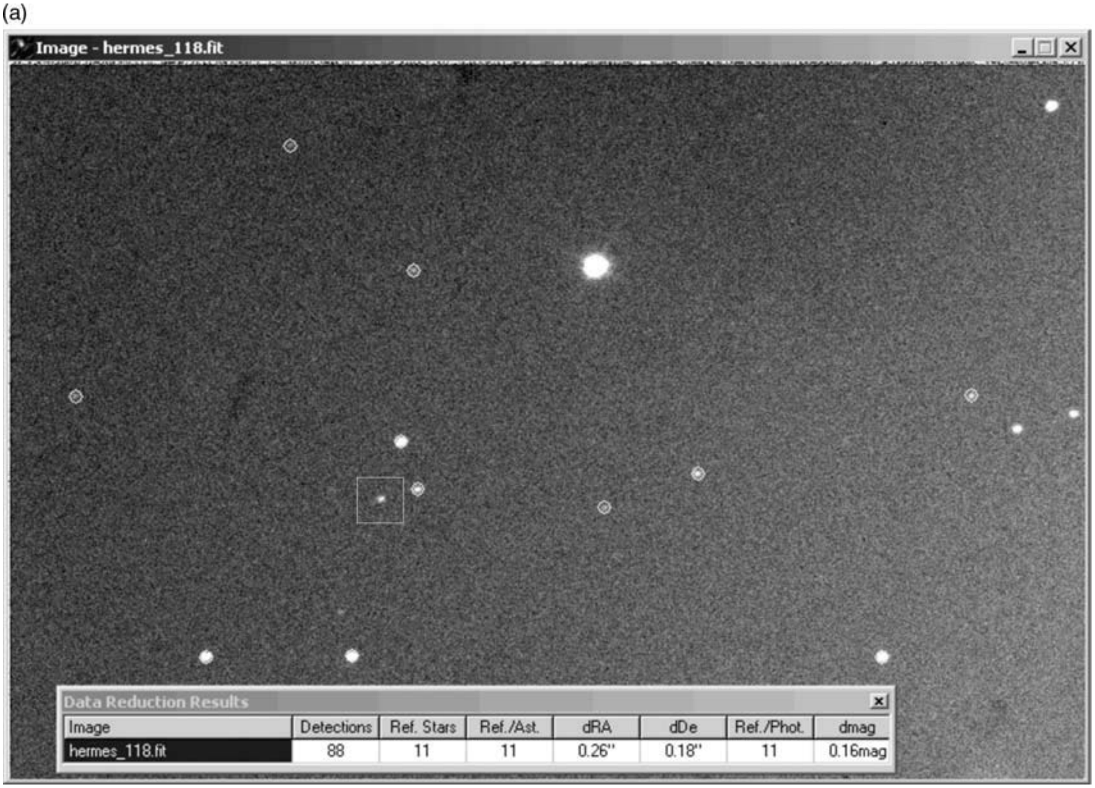
You could report your observations directly to the Minor Planet Centre (MPC). If so you **must** use plain text in their standard format (see: cfa-www.harvard.edu/iau/info/Astrometry.html for instructions). *Astrometrica* can automatically prepare this for you.

10.15 OCCULTATIONS

Asteroids will occasionally pass through your line of sight to a star. These events are extremely rare for any one asteroid but thanks to the huge

Figure 10.10 (a) Screenshot showing an image of asteroid 1937 UB (Hermes) being reduced using Herbert Raab's *Astrometrica* program. The circled stars have been identified and correlated with stars in the USNO-A2.0 catalogue. Hermes is the object in the box. This illustration is courtesy Nick James and Herbert Raab.

(a)



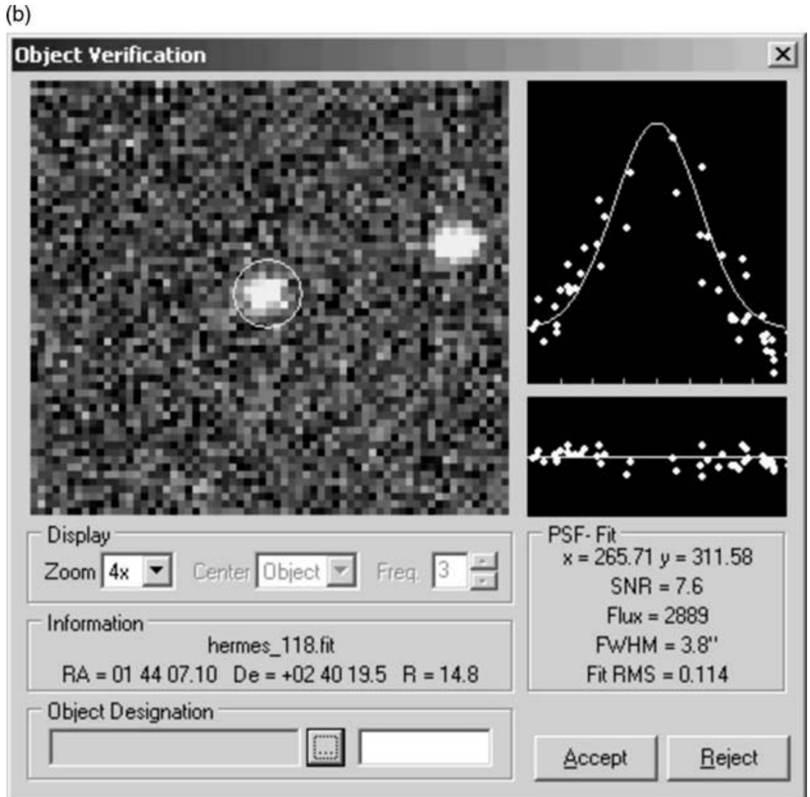


Figure 10.10 (*cont.*)
(b) Screenshot of the panel that appears when the target object is clicked. The program fits the object's luminosity profile to a Gaussian curve, determines its centroid, and then calculates the object's right ascension and declination. This illustration is from a paper in the *JBAA* and is courtesy Nick James, the BAA, and Herbert Raab.

numbers of asteroids you do get the opportunity to observe these stellar occultations from time to time.

Actually, the asteroid casts a shadow in the light from the star which extends into space. This shadow has a profile almost the same size and shape as the asteroid because the star is such an immense distance away. When this shadow falls on the Earth it generates a 'footprint' that will be distorted depending on which part of the curved Earth's surface it falls on at that moment. The footprint will actually sweep a track across part of the Earth. If you happen to be inside that narrow track you will see the star occulted by the asteroid.

You can expect the occultation to last from a few seconds to a minute or two, depending on the size of the asteroid, your position on the Earth, your position inside the track, the size and shape of the asteroid and the relative motion of the Earth and asteroid.

Accurately timing asteroidal occultations is valuable as this generates data that can lead to a determination of the size of the asteroid.

Even better, when a number of observers time the event from differing locations on the Earth the results can enable the shape of the asteroid's profile to be derived. Of course the reduction of these results is far from straightforward and the timings have to be really accurate – but the effort is surely worth it.

One particular organisation that can be taken to be a primary source of information – such as predictions, advice on practical matters, and to whom you could submit observations – is the European Asteroid Occultation Network (EAON) (see: astrosurf.com/eaon).

In essence, all you need is a really accurate clock, preferably radio-synchronised to a standard national timekeeping source, a really good digital stopwatch with a 'lap-time' facility, and a telescope that is capable of seeing the asteroid (or at least the star if this is brighter than the asteroid).

You begin your observing run by making sure that you are set up on the correct star, preferably at least a few minutes before the event. If the asteroid is visible in your telescope then you can watch it approaching the star. You keep watching before the predicted commencement. Beware that the predictions may be a little in error, so the occultation may start early or late.

You are looking for a sudden step-down in the brightness of the merged image of the star and asteroid. Start the stopwatch at the beginning of the event and press 'lap-stop' once at the end of the event. Keep looking for a few minutes to see if there is a second dip in the light. If the asteroid is binary or multiple then you might see more than one brightness-step events. If not, then take the still-running stopwatch to compare with your radio-synchronised clock and stop the stopwatch at a convenient time on the master clock, such as at a whole minute.

The lap-time recorded is the duration of the event and the actual time of commencement of the event can be found by subtracting the elapsed time from the time you first started the stopwatch. Let me give an example:

Stopwatch started at beginning of occultation (Time U = 0.0 seconds).
Lap-timer stopped at end of occultation (Time V = 10.5 seconds).
Stopwatch stopped (Time X reads 1 minute 23.4 seconds) when the master clock reads $21^h\ 33^m\ 00^s.0$ UT (this is Time Z).

From the above, the duration of the occultation (= Time V – Time U) is 10.5 seconds.
The actual time of commencement of the occultation (= Time Z – Time X) is $21^h\ 31^m\ 36^s.6$ UT.
The actual time of end of the occultation is, of course, this last time plus the duration of the event: $21^h\ 31^m\ 47^s.1$ UT.

In submitting your observation there are two more vital pieces of information you will have to supply. One is your exact geographic location – obtainable from a good GPS device or the largest-scale ordinance survey map (which should be available at your local library – or at least obtainable via the inter-library loan service).

The other piece of information is your *personal equation*. This is a measure of the time delay between you seeing the commencement or ending of an occultation and you pressing the button.

You can gauge your own personal equation using your digital stopwatch. Cover up the part of the display that shows the seconds and fractions of a second. Set the stopwatch going. Put it down for a minute or two. Then pick it up (making sure the seconds and fractions indicator is still covered) and stop the watch as sharply as you can after the next whole-minute digit appears. Then uncover the seconds and fractions indicator. Note the extra time indicated. Repeat a large number of times and take the average. This is your personal equation. It will probably be of the order of 0.2 or 0.3 second. Subtract the personal equation from each of the times in your submitted report.

You can observe and time occultations to much greater accuracy using video-based methods. Fast-frame-rate, yet highly sensitive, CCTV security cameras are the ones to choose. It is even possible to use GPS signals to time-stamp the individual video frames and, with the addition of some specialised equipment, achieve timing accuracies of the order of a millisecond. Unfortunately this area is technically complicated with a vast number of cameras, associated hardware, software and freeware in the marketplace and a variety of techniques currently used by advanced practitioners. I do not have the space even to begin to tackle this subject in this book, so if you wish to get involved in this field may I suggest that a best first step would be to log on to the EAON website and take things from there.

Finally, I should warn you that many of the predictions you may act on will fail to produce actual occultations for you to see. This is because of uncertainties in the astrometry of the asteroid and of the star predicted to be occulted. Such negative events are themselves useful and should be submitted as reports, as they help to refine the true astrometry of the objects. Of course negative results owing to bad local weather should not be sent in. Oh yes, you will have plenty of those, too!

10.16 THE *MINOR PLANET OBSERVER* SOFTWARE SUITE

One extremely useful software suite, perhaps especially so for the more advanced practitioner, is *Minor Planet Observer*. This is obtainable from *Bdw Publishing* (www.minorplanetobserver.com). It actually consists of four main programs which can be purchased separately: *MPO Asteroid Viewing Guide* ($25), *MPO Canopus* ($65), *MPO LCInvert* ($150) and *MPO Connections* ($105). Please note that whenever I offer information on prices in this book, these should only ever be taken as rough guides. The chances are that by the time you act on them the prices will have changed – almost always having increased!

Coming back to the *Minor Planet Observer*, this software suite is only available on DVD format. A big plus-point is that it does include the 2007 version of the *MPO Star Catalogue* comprising 110 million stars, packaged with the *USNO CCD Astrographic Catalogue* (*UCAC–2*).

The *MPO Asteroid Viewing Guide* is effectively a piece of planetarium software for asteroids, allowing you to generate ephemerides, finder-charts, predicted occultation (or at least close-approach) positions and more. The *MPO Canopus* is for the reduction and analysis of your observations. You can generate light-curves and determine amplitudes, rotation rates, and more, using *Canopus*. It will even automate much of the process for you. The *MPO Connections* program is for telescope and camera control. If you have the appropriate hardware you can even go as far as to automate the entire observing run! Finally, using *MPO LCInvert* you can computer-generate 3D models of asteroids from their light-curves. The version of the *Minor Planet Observer* suite available at the time of writing is 9.0. For a review of version 6.1 see the October 2001 issue of *Sky & Telescope*.

10.17 FURTHER WORK

There is much more that you can do than I have space to describe in this chapter. For instance, you might like the idea of discovering new asteroids for yourself. Do bear in mind, though, that you will be competing with a number of automated and highly productive professional programmes in addition to some very dedicated amateurs. You might like to observationally confirm other people's discoveries of asteroids. You might like to submit astrometric observations that will help to refine our knowledge of the object's orbit, and so prevent it being lost. In fact, any of the topics I have covered in this chapter can be developed into more specialist studies. You will find plenty of links to relevant institutions such as the MPC, Lowell Observatory, and others, on the webpage of your national astronomical society asteroid observing section. You will also find many via the NASA asteroid links page at echo.jpl.nasa.gov/links.html. Also, software suites, such as that described in the last section, can allow you to perform detailed analysis of your own results.

Finally, I strongly recommend that you become a member of the asteroid observing section of your national astronomical society. You will be exposed to the 'state of play' current at the time and have access to the knowledge and guidance of the director and the other members. It is by becoming a member of a team of observers that you will have the best chance of contributing really useful scientific results.

CHAPTER 11

Comets

Comets come in vastly different sizes, very different brightnesses and, to some extent, different shapes. When we get to see them, most appear as filmy or misty smudges of greyish light against the sky with one end, the *head*, being the brightest and most compact part. The head of the comet is also the site of the comet's *coma*, which appears like a spheroidal ball of mist. Often the coma contains a bright star-like speck of light, the *false nucleus*. A *tail* often fans out from the head, or sometimes extends out as a narrow swath of filmy mist. Not all comets display tails, though.

Long ago, before we understood comets in scientific terms, their appearances generated widespread fear and foreboding. Even today we call their appearances in our skies *apparitions*.

11.1 GHOSTLY VISITORS

The images of comets displayed in this chapter are all very much just 'snapshots' in their lives. A comet's form is not constant but changes and evolves, growing as it moves into our skies. Then it changes further, diminishing as it retreats back into the depths of space. Figure 11.1 shows an idealised diagram of a fully developed comet of larger than average size.

A comet varies its speed as it goes around its orbit, moving very slowly when it is far away from the Sun but then accelerating on the approach to it. This is in accordance with Johannes Kepler's empirically determined laws of planetary motion, later given a mathematical foundation by Isaac Newton. The result is that a comet spends by far the greatest amount of time well away from the Sun and only a very short time close to perihelion.

In the eighteenth century, Edmond Halley discovered that the impressive comets of 1531, 1602 and 1682 travelled along the same path. In fact, he realised that they were one and the same object. This comet moves round the Solar System in an elliptical path, taking 76 years to complete

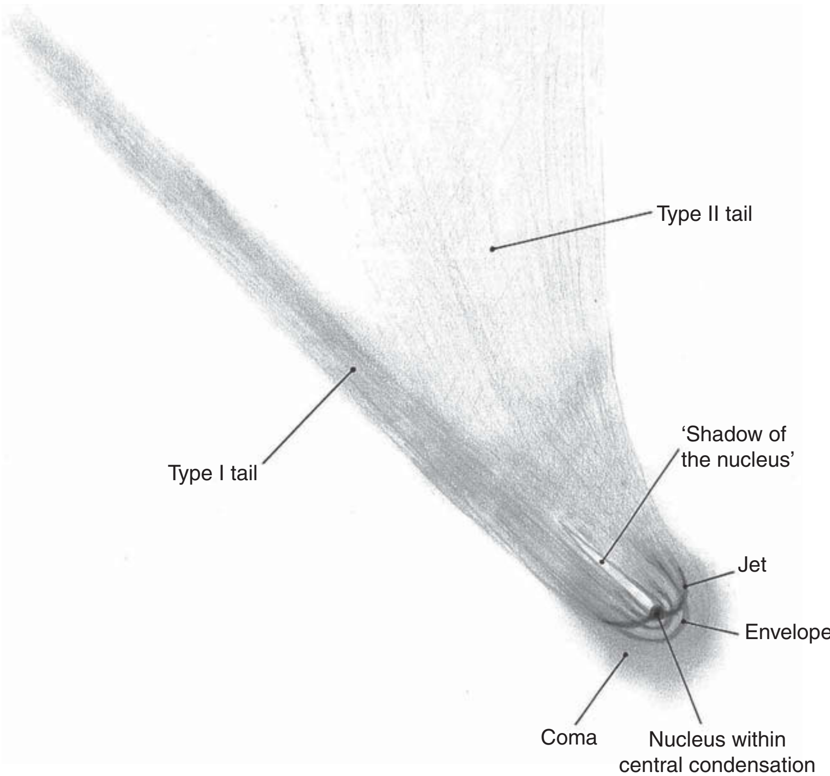
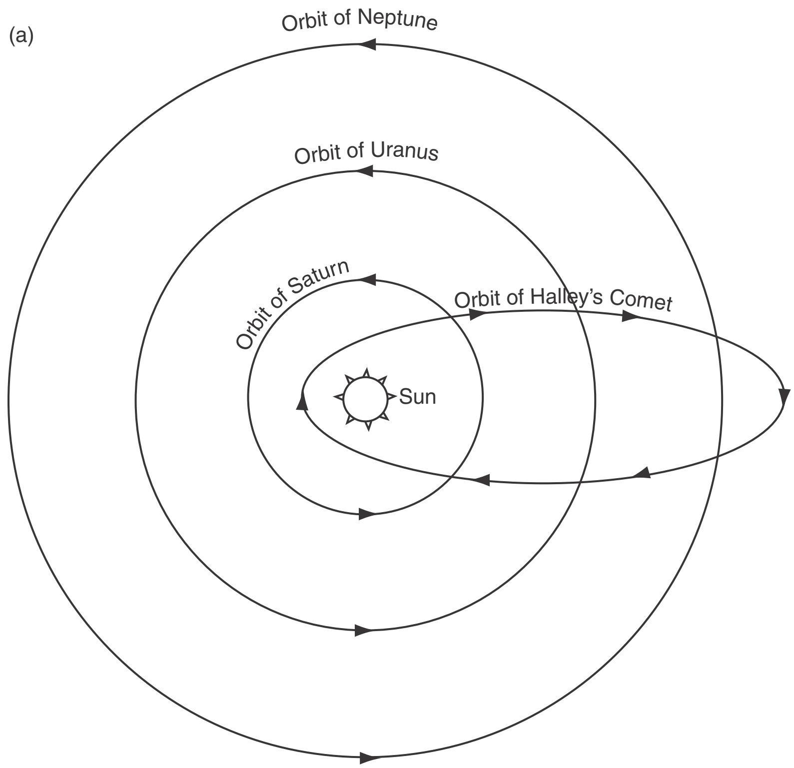


Figure 11.1 The nomenclature used for the visible parts of a comet are indicated here in this idealised diagram. Not all of these features may become visible in any specific comet and at any given time.

one orbit. Halley made the prediction that the comet would return in 1758. It did, being recovered by Johann Palitzsch on Christmas night in that year. Halley had died fourteen years before this vindication but thanks to his discovery this comet became known as 'Halley's Comet'.

Halley's Comet moves in the opposite sense to that of the main planets in the Solar System. We say that it has a *retrograde* orbit (see Figure 11.2(a)). It turns out that about half of all comets orbit the Sun in the 'wrong way' or retrograde sense. The major planets all orbit the Sun in the same direction and in virtually the same plane. However comets have orbits which can be inclined at any angle to the plane of the planetary motions (see Figure 11.2(b)).

Comets seem to be divided into two distinct orbital classes. Some comets frequently return to perihelion every few years or few tens of years. These we call *periodic comets*. Others take many centuries, or thousands of years, and even longer, to return to the inner realms of the Solar System. These are known as *long-period comets*. All the long-period comets have exceedingly eccentric orbits whose aphelia lie at enormous distances from the Sun, often of the order of 50 000 AU. Most of the comets we detect are of the long-period variety.



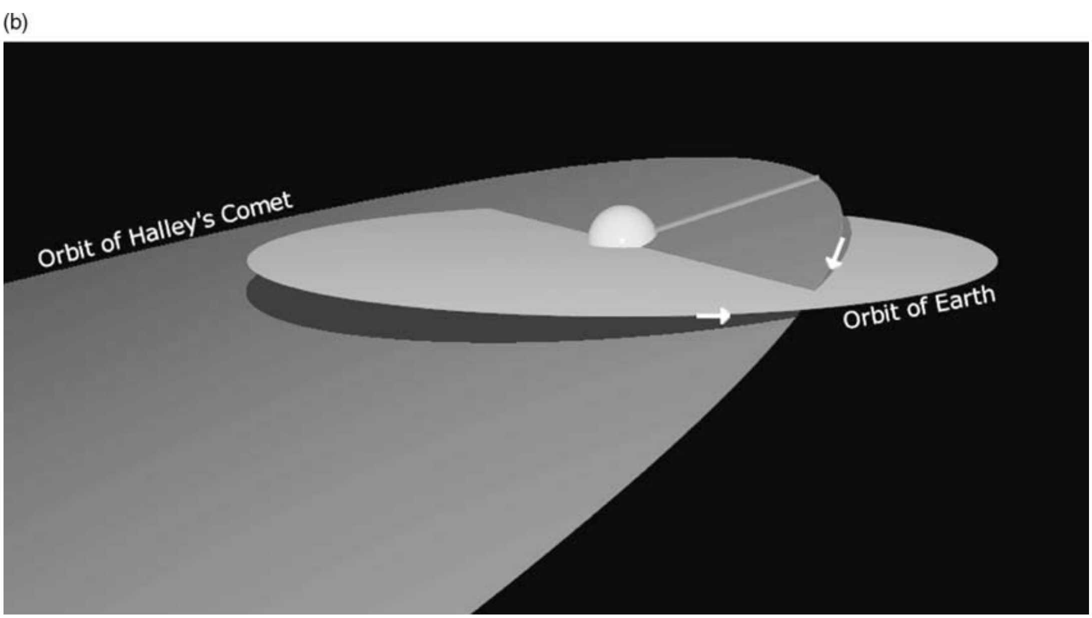


Figure 11.2 The path of Halley's Comet through the Solar System.
(a) A plan view showing its retrograde orbit.
(b) A three-dimensional representation showing the inclination of the comet's orbital plane to the (very nearly) common plane of the orbits of the major planets.

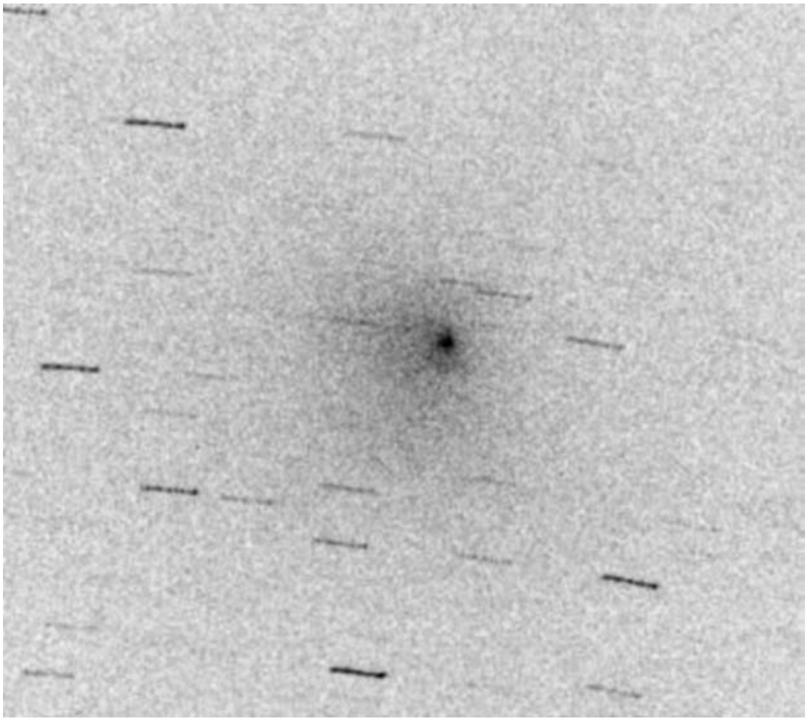


Figure 11.3 Comet C/1983 H1 *IRAS*–Araki–Alcock was not much to look at but this fast-moving celestial visitor came closer to the Earth than any other comet since Lexell's in 1770. Martin Mobberley took this photograph of it on 1983 May 9^{d} 21^{h} 11^{m} UT using a 300 mm telephoto lens on a standard camera loaded with Kodacolour 400 film and mounted piggyback onto a driven telescope. 'Faint fuzzies' are often shown better in negative, as is the case here.

11.2 NAMING COMETS

In most cases a comet is given the name of the first person to see it. This has been the scheme used from the earliest days right to the present time. If more than one person discovers the comet independently (the International Astronomical Union are the arbiters in all cases) then the comet will carry the names of the co-discoverers arranged in their order of discovery. There is one caveat: comets discovered by means of space probes or those by automated search programmes bear the name of the probe or programme, rather than the human being sitting at a console in front of a monitor who made the discovery. Such was the case with Comet *IRAS*–Araki–Alcock, which became notable for its relatively close passage past the Earth in May 1983 (see Figure 11.3). It was first detected in the data downloaded from the *Infrared Astronomical Satellite* (*IRAS*), then by the Japanese astronomer Genichi Araki, and then by the English veteran comet and novae discover George Alcock.

Some comet hunters discover more than one in their lifetimes, so more detail has to be added to the moniker. For instance, Figures 11.4 (a) and (b) show views of the thirteenth comet discovered by William Bradfield. He went on to discover others.

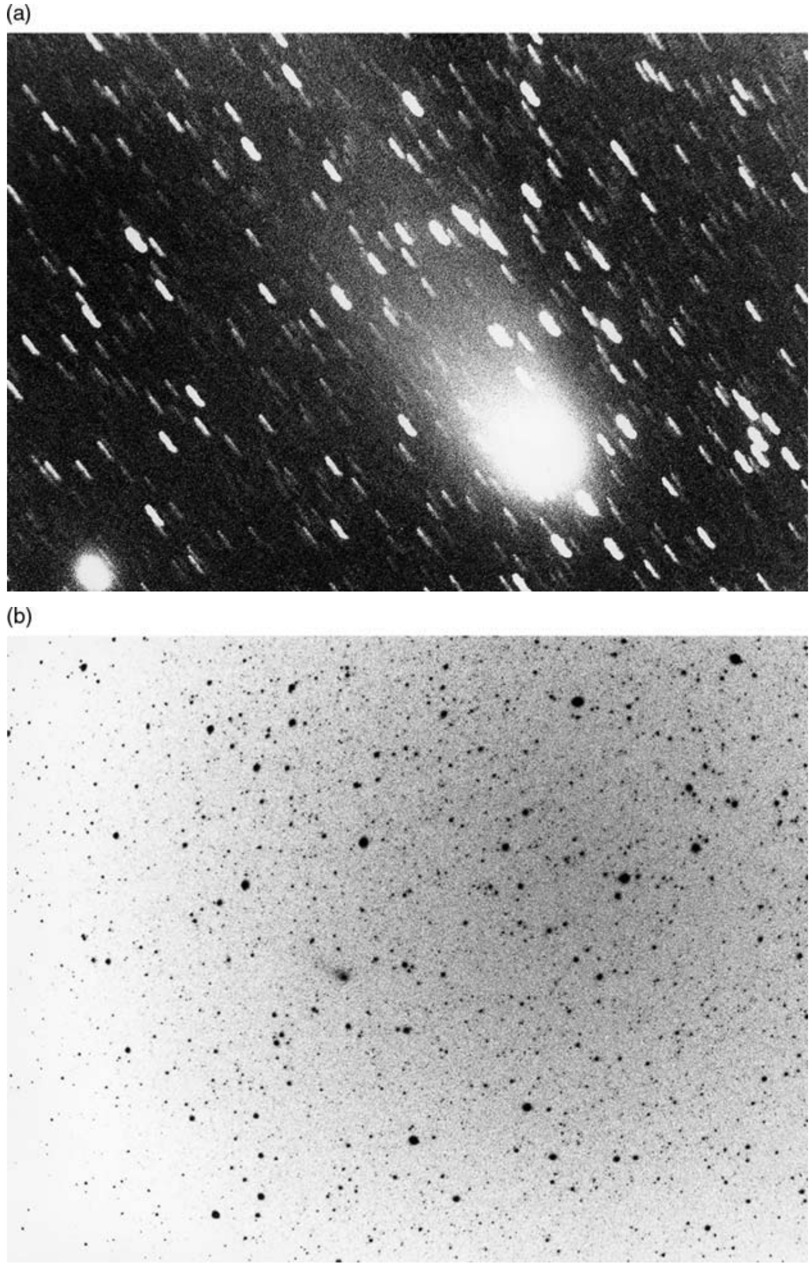


Figure 11.4 (a) Comet C/1987 P1 Bradfield photographed by Martin Mobberley on 1987 November 14^{d} 18^{h} 03^{m} UT. The 17-minute exposure was made on Tri-X film at the f/5 Newtonian focus of his 14-inch (356 mm) reflecting telescope. (b) The comet was well on the wane for this photograph – a 10-minute exposure – taken by the author on 1988 January 14^{h} 18^{m} 45^{m} UT using a standard camera fitted with a 135 mm telephoto lens, loaded with 3M Colourslide 1000 film and mounted piggyback on a driven telescope. The author has printed his original photographic transparency as a negative to show better the faint cometary image.

The IAU introduced a scheme for designating comets in January 1995, which supersedes the older systems in use up to that point. First we have a letter 'C', or a 'P', followed by a forward slash. The letter 'P' is used if the comet is 'periodic', that is, determined to have a period of less than

200 years. 'C' is used for all comets of longer period. There are two other letters that could be used in place of the 'P' or the 'C', though those instances are quite rare. 'D' is used for comets that have disappeared, or no longer exist and 'X' is used for those whose orbits cannot be computed owing to a lack of observations.

The rest of the designation follows exactly the same scheme as used for asteroids (see Section 10.3 in the last chapter): after the C, X or D comes the year of discovery and then a space followed by a letter denoting the half-month of the discovery. Lastly we have the name of the discoverer(s).

Periodic comets do not carry a date of discovery but instead have a prefix number indicating the order of discovery of their periodic status. This starts with Halley's Comet: 1P/Halley. The second periodic comet is Encke's, so this is properly denoted 2P/Encke, and so on.

Let us look at some examples. Do you remember the bright comet that graced our skies in the spring of 1996? (See Figure 11.5(a)–(c).) That one was: C/1996 B2 Hyakutake, meaning that it was the second comet (2) discovered in the second half of January (B) in 1996. The orbit of this comet has a period of more than 200 years (C/) and its discoverer's surname was Hyakutake (the Japanese amateur Yugi Hyakutake). The comet *IRAS*–Araki–Alcock I mentioned earlier is properly denoted as C/1983 H1 *IRAS*–Araki–Alcock and Bradfield's thirteenth comet is properly denoted as C/1987 P1 Bradfield.

11.3 A COMET'S NUCLEUS, JETS AND SHELLS

By the late-nineteenth century long-exposure photography was illuminating our previously dim views of comets, so allowing us to probe much further into their dynamic structures. Also spectroscopy, carried out in wavelengths spanning much of the electromagnetic spectrum, has revealed to us most of what we have learned about the detailed chemical and physical natures of comets. Imaging comets at all wavelengths of the electromagnetic spectrum, in addition to the visual range (sometimes of necessity from above the Earth's atmosphere) has also added much to our knowledge. We have also had a number of flyby missions to comets and learned much from them, too.

Astronomers long ago realised that most of a comet is very insubstantial. Indeed, the greatest volume of what we perceive as a comet we would, in other circumstances, regard as a vacuum. However, there is one part of a comet that, despite being dwarfed in size by the rest of it, is very substantial in nature: the *nucleus*. The vast bulk of all the matter of the comet is concentrated in its nucleus. A large cometary nucleus may have a mass of around several thousand million million kilograms.

The nucleus resides in the head of the comet and it consists of a 'dirty snowball' of silicate rock and ices. It is irregularly shaped and is usually a few kilometres across. It is mostly composed of various ices, with

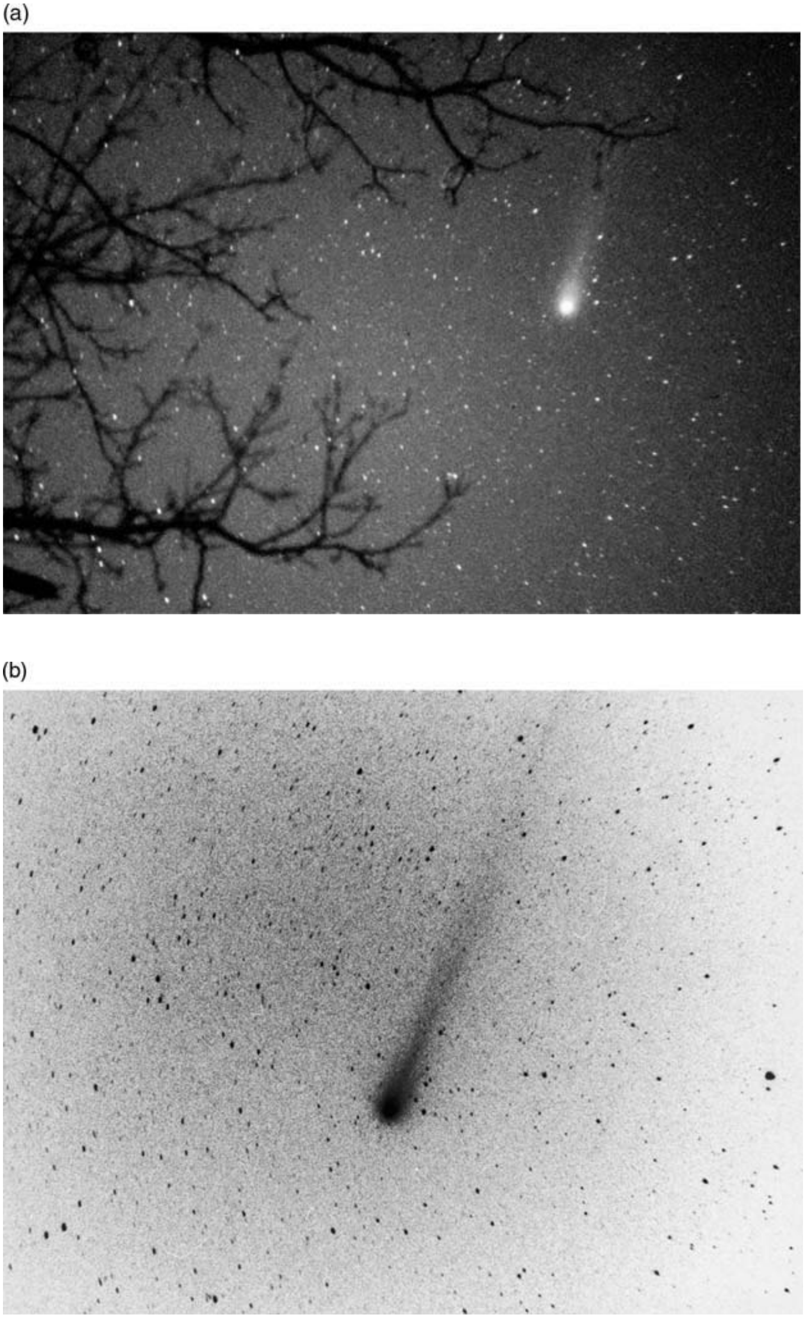


Figure 11.5 Comet C/1996 B2 Hyakutake.
(a) A deliberately framed 'pretty shot' made using an undriven tripod-mounted camera fitted with a standard 58 mm f/2 lens and loaded with 3M Colourslide 1000 film. The comet's proximity to the celestial pole allowed this exposure of 1-minute duration without significant trailing on 1996 March 27^{d} 21^{h} 10^{m} UT.
(b) With the tripod in a different position another 1-minute exposure was made 6 minutes earlier. In this case the author has enlarged and printed the resulting image as a high-contrast negative to show better the extent of the comet's tail.

(c)

Figure 11.5 (*cont.*) (c) This photograph was obtained on 1996 March 24^{d} 01^{h} 12^{m} UT and was made using the same film, camera, lens and exposure as for (a) and (b). However, the comet was then riding high in the sky, well away from the celestial pole, and so the camera was mounted piggyback-fashion onto a driven telescope.
[The image shown in (a) is also reproduced in colour as Plate VI (upper), between pages 304 and 305].

water-ice forming the major constituent. The other ices are mostly frozen organic volatiles.

A typical long-period comet spends most of its time well away from the warmth of the inner Solar System. Way beyond even Neptune. With an ambient temperature of just a few degrees above absolute zero (absolute zero = $-273\,°C$), the comet must then consist of an inert and frozen ball of dirty ice.

It is not until the comet approaches the inner Solar System that the warming rays from the Sun begin to drive the most volatile of the ices to sublime from its surface, so forming the coma and the tails of dust and gases that we actually recognise as a comet. I say 'sublime' because in any environment of extremely low pressure, ices pass straight from their solid phase to their vapour (gaseous) phase, bypassing the liquid phase.

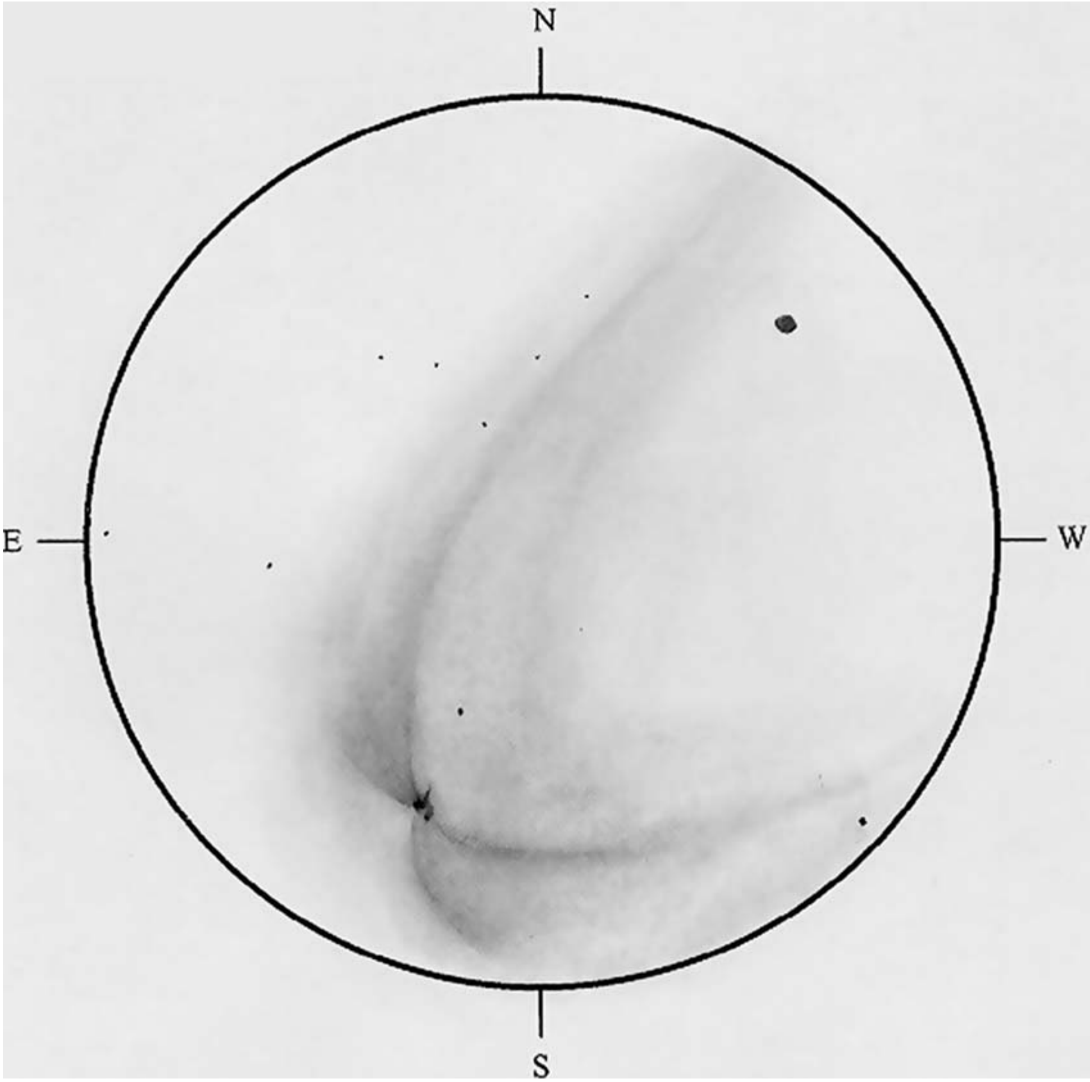


Figure 11.6 Drawing of Comet C/1995 O1 Hale–Bopp on 1997 February 08^{d} 05^{h} 16^{m} UT (mid-time for the drawing) by Robert Bullen, showing prominent jets issuing from the false nucleus. He used a 6¼-inch (158 mm) Newtonian reflector at ×64. The diameter of the field of view is 38 arcminutes.

The gas release tends to be localised, mostly emanating from the surface of the nucleus in sprays of matter that we call *jets*. We know this because many bright comets display jets that can be seen through even minimal optical aid (see Figure 11.6). Thanks to photography, jets can be studied in many more comets so we know that they are a common feature.

Comet nuclei are irregular in shape. They also rotate. Both effects can produce brightness changes in the nucleus, though getting a value of the rotation period from brightness variations is not at all straightforward.

This is especially so because the nucleus is imbedded in the very much brighter false nucleus – and this is dependent on the activity of the comet (which is itself variable). Fortunately, the presence of jets helps us determine the rotation period because they emanate from virtually fixed patches on the surface of the nucleus. Observations indicate that typical comet nuclei have rotation periods in the range of a few hours to a few days.

If one did not suspect that it is the action of the Sun's radiation that drives the jets, then evidence for this is provided by careful study of them as the nucleus rotates. The jets vary their activity, being most vigorous when they are rotated onto the sunward side of the nucleus.

The 'lawn-sprinkler' effect of the jets from a comet's rotating nucleus and the variations in the rate of materials shed into its coma combine with the compressive 'wind-sock' action of the solar wind to produce *shells* within the coma. These are mostly evident on the 'up-wind' side of the coma (see Figure 11.7).

Long ago astronomers, having gone to much trouble to accurately determine cometary orbits, were mystified that comets refused to stick exactly to the paths predicted for them using Newtonian mechanics. We know now that a comet's jets are the main culprit. Acting like rocket engines, jets are often able to nudge a nucleus about by just enough to produce a slight change in a comet's orbit over a period of time.

11.4 A COMET'S FALSE NUCLEUS AND COMA

The coma of a typical comet is a roughly spheroidal volume of gas and dust, extending to perhaps 100 thousand, exceptionally a million, kilometres from the nucleus. It is most tenuous at its outer limits and is most dense near the imbedded nucleus.

In fact, the bright speck that is often seen at the heart of a comet's coma is **not** the nucleus. Instead, we see the greatest concentration of material in the coma. As I mentioned earlier, we call this the false nucleus. The dim true nucleus is buried inside this.

The coma is ephemeral in nature. At distances far from the Sun the nucleus is too cold to generate any coma. As it is warmed on approach towards the Sun the most volatile of the chemical ices sublime first, others adding to the chemical smorgasbord as the surface of the nucleus continues to warm up.

Typically, carbon monoxide and carbon dioxide begin to be released from the nucleus in significant amounts when it approaches to within about 10 astronomical units (AU) from the Sun. Less volatile ices do not sublime to any large extent until the nucleus gets rather closer to the

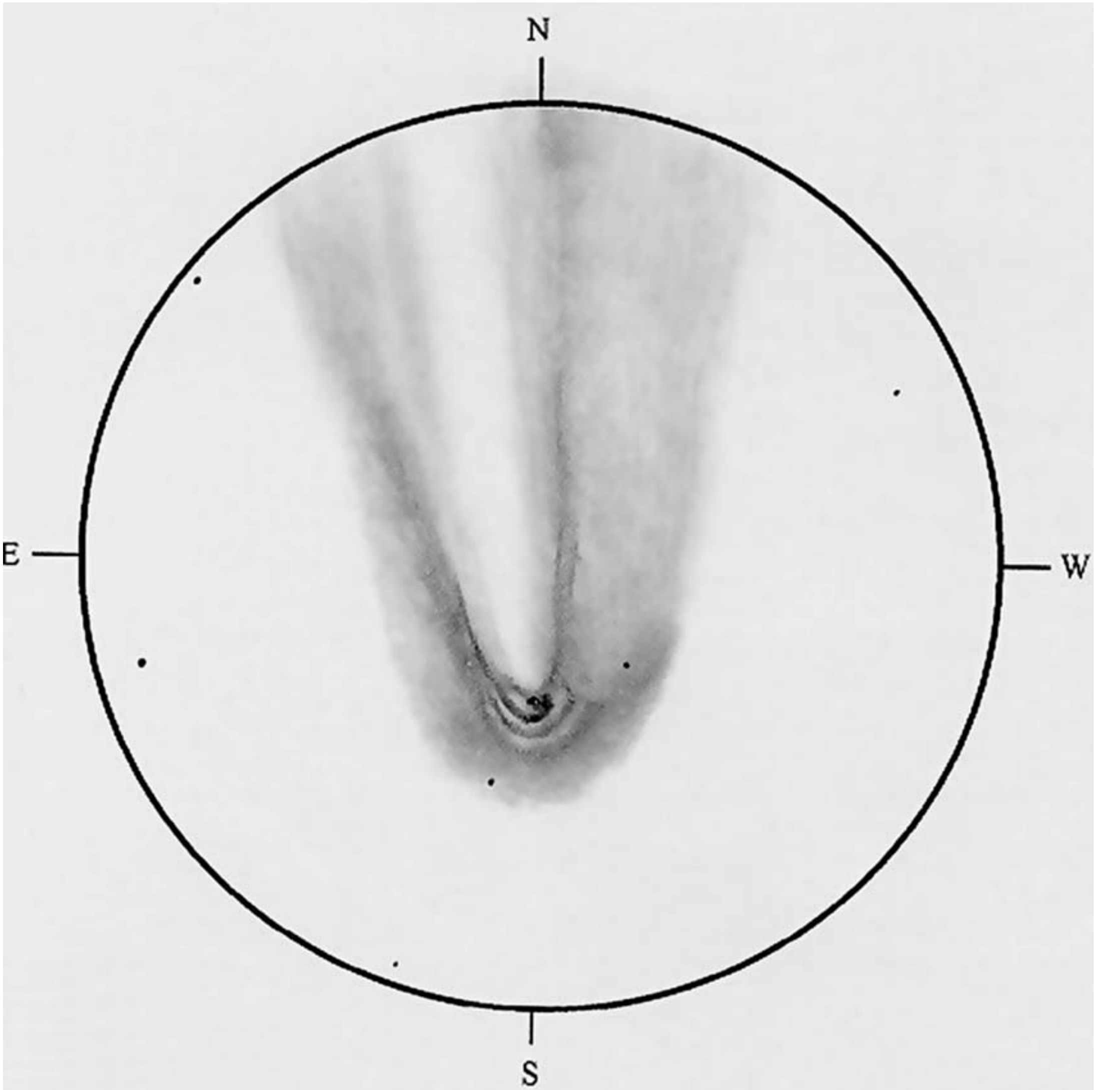


Figure 11.7 Drawing of Comet C/1995 O1 Hale–Bopp on 1997 April 02^{d} 20^{h} 50^{m} UT (mid-time for the drawing) by Robert Bullen, showing prominent shells and hoods around the false nucleus. He used a 6¼-inch (158 mm) Newtonian reflector at ×48. The diameter of the field of view is 50 arcminutes.

Sun. For instance, water-ice only begins to sublime significantly when the nucleus approaches within about 3 AU.

The gas in the coma is warmed as the comet heads towards the Sun and the speeds of the particles composing it increase as a result (this behaviour is part of what is called the *Kinetic Theory of Gases* – a topic that should be covered in any 'school year 12', or sophomore-level undergraduate, general physics or physical chemistry textbook). The particles comprising the vapours that enter the space around a comet's nucleus cannot be contained by the extremely weak gravitational field of it and so they stream off into space. The rate of material loss increases with ambient temperature, and this increases as the comet approaches the Sun.

So, the mass and composition of a comet's coma is not at all constant. The following molecules and radicals are, though, usually to be found in the fully formed comets we observe: water (H_2O), carbon monoxide (CO), carbon dioxide (CO_2), methanal – old name formaldehyde (HCOH), methyl cyanide – also known as ethanenitrile, old name acetonitrile (CH_3CN), methane (CH_4), ammonia (NH_3), hydrogen cyanide (HCN), carbonyl sulphide (OCS); various dihydrides such as CH_2 and NH_2; the hydroxyl radical(OH), and other radicals such as CH and NH. There are many others. Also, there are very small amounts of various elements in atomic form such as hydrogen (H), carbon (C), oxygen (O), nitrogen (N), and sulphur (S).

The list is further extended because the ultraviolet and other short-wave radiations from the Sun cause some *ionisation* of the various chemical species. By this I mean that the energetic solar photons can cause electrons (which are negatively charged particles) to be driven off from some of the previously electrically neutral atoms in certain molecules, leaving them positively charged.

This is not the only mechanism in operation. The solar wind particles colliding with the gases in the coma also cause ionisation. In this way species such as: H_3O^+, H_2O^+, OH^+ – the so-called 'water group', and organics such as: ${CO_2}^+$, CO^+, C^+, CH^+, and many others, including the nitrogen-based so-called 'ammonia group' (NH^+, etc.) ions are created.

The chemistry is still further complicated because the energy imparted to the molecules or radicals in the comet by the solar photons can go beyond causing them to ionise. Sometimes whole molecules (or radicals) can split into sub-species (this process is called *photo-dissociation*) and so new species are born of the destruction of a small number of the molecules of a parent species. In fact, photo-dissociation of some of the hydrogen-bearing species creates a vast cloud of hydrogen gas, tens of millions of kilometres in diameter, which is carried along with the comet.

As well as the gaseous species there are also solid grains of matter. These astronomers refer to as *dust*, though the dust in comets is totally unlike the domestic variety. The dust particles are composed of various silicates, silicon, carbon, magnesium and sodium, together with some more exotic solid species such as CHON (carbon–hydrogen–oxygen–nitrogen), and many others.

The jets of material spraying off the nucleus sweep up solid particles from its dusty surface and carry them into the outwardly expanding envelope of gases that comprises the coma. I am sure that you can see that a comet's coma is actually a dynamic and very complicated system.

A cometary coma is rendered visible to us mainly because of sunlight scattered by molecular fragments such as C_2, C_3, NH_2, H_2O, and CN, as well as by the sunlight reflected and scattered by the solid grains. Hence, the colour of a cometary coma tends often to be predominantly yellowish-brown. However, a mixture of gas and dust, as well as certain fluorescing gases such as carbon, can blend to produce a very strong green colour in some comets.

As stated earlier, the materials comprising the coma are ephemeral. Originating from the nucleus as the comet comes out of its 'deep freeze', some of the materials expand radially away, while others are channelled into the tail, or tails.

11.5 A COMET'S TAILS

Not all comets sport well-formed tails. Of those that do most have not one but two tails, each with a different composition. Sometimes they are blended together. In other comets they are well separated and distinct.

Type I tails are composed of ionised gases, while *type II* tails are made of the dust mentioned previously. Physicists often refer to a gas which is composed of ionised particles as a *plasma*. So type I comet tails are also known as *plasma tails* while type II tails are often called *dust tails*.

Spectroscopy reveals that type I tails contain ionised molecules and radicals such as: CO^+, ${CO_2}^+$, OH^+, CH^+, CN^+, as well as very many others. It is the cold and near-vacuum environment of a comet's tail that allows these highly reactive species to remain distinct. Under Earthly conditions they would aggressively combine with other ions, striving to form neutral molecules.

The ionised gases of the type I tails can absorb short-wave radiations from the Sun. They then re-radiate the energy at longer wavelengths. This *fluorescence* causes their type I tails to glow with a bluish colour.

Type I tails always point away from the Sun, deviating no more than a few degrees from the anti-solar direction. The consequence of this is that the tail follows the comet when approaching perihelion – but the comet actually moves tail-first after perihelion!

Type I tails are usually rather straight. However, they are far from being formless. Waves, like the ripples one sees in a flag in the breeze, often form in them. So do bright knot-like concentrations. These features are sometimes seen to work their way slowly along, or through, the tail. In fact, the analogy with the ripples of a flag in the breeze belies the clue to what causes these features, as well as explaining why the tail always points away from the Sun (see Figure 11.8). The cause lies with the Sun, itself.

The Sun sends out electrified particles streaming radially into space. This is the solar wind referred to earlier. These particles carry intricately confused

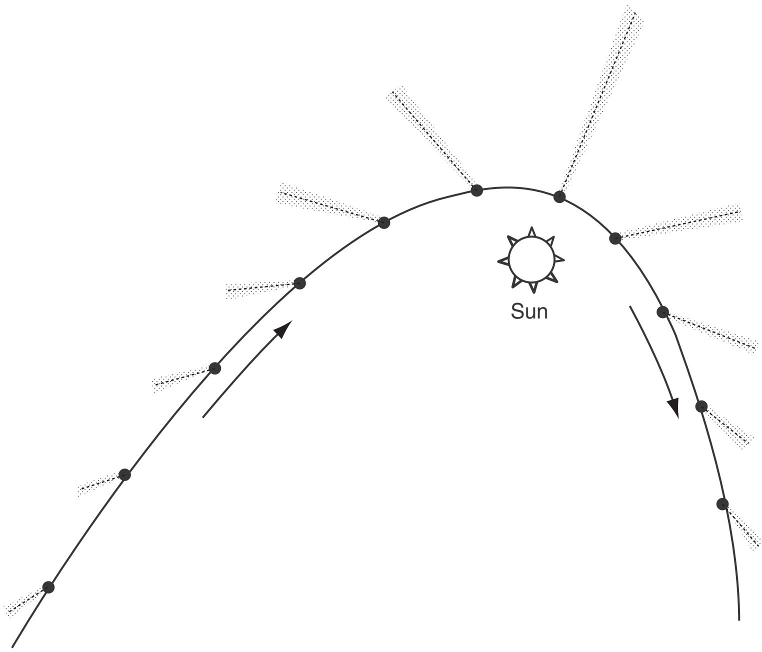


Figure 11.8 Figurative illustration of how a comet's tail always points away from the Sun. The length, shape and prominence of the tail also varies according to the comet–Sun distance, though usually in a more complex way than represented here!

magnetic fields locked in with them. The ions in a comet, themselves being electrified particles, react to their relative motions with the magnetic fields in such a way as to try to reduce that relative motion. Hence the cometary ions are also forced in a direction radially away from the Sun.

By studying photographs of comets in order to calculate the accelerations of transient features, astronomers have deduced that the forces acting on the ions in a comet due to the solar wind are of the order of a hundred times greater than the size of the Sun's gravitational force acting at the distance of the comet. Once the ions are created in the coma, this *magnetic-coupling* mechanism is responsible for selectively carrying them away into the comet's type I tail.

When a comet is far away from the Sun it is moving in a direction which is approximately radial to the direction of the Sun. As it passes perihelion, though, the comet has a significant transverse motion through the solar wind. This can cause a type I tail to develop a slight curvature. However, type II tails are usually very much more curved, and especially so when the comet is passing through perihelion.

Type II tails are different in other ways. As well as being generally more curved, they are often much broader. While the type I tails appear bluish in colour, type II tails are noticeably yellowish, or even brownish-orange. I should say here that these colours are only obvious to the naked eye in the very brightest comets. The comets C/1995 O1 Hale–Bopp

Figure 11.9 Comet C/1995 O1 Hale–Bopp photographed by Martin Mobberley on 1997 March $13^{d}\ 03^{h}\ 54^{m}$ UT onto Fuji Super G 800 film, using his Takahashi E-160 hyperbolic astrograph (160 mm aperture, 530 mm focal length). This instrument was piggybacked onto a driven telescope, itself guided on the false nucleus of the comet by means of a 4.7-inch (120 mm) refractor at ×120 for the duration of the 12-minute exposure. The width of the photograph spans roughly 3° of sky. [This image is also reproduced in colour as Plate VI (lower) between pages 304 and 305].

(see Figure 11.9) and C/1996 B2 Hyakutake (see again Figure 11.5(a)–(c)) showed the colours well. Binoculars or a telescope help still further and photography can reveal the colours in even faint comets. Comet C/2004 Q2 Machholz (see Figure 11.10) was notable for its very vivid shade of green. I well remember the head of C/1987 P1 Bradfield looking decidedly reddish-brown through my 18¼-inch (0.46 m) reflector. The head of the brilliant Hale–Bopp looked strongly brownish-yellow. Even the head of the almost dustless Hyakutake appeared a greenish shade of blue. Where the blue type I and yellowish-brown type II tails are blended together there can also be an apparent greenish hue produced.

Type II tails show spectra very similar to that of the Sun. In fact, they shine by reflected sunlight. Hence, we know that type II comet tails are composed of colloidal sized (a thousandth of a millimetre, or so, in diameter) dust particles. Of course, this dust originates from the nucleus, via the coma.

The large curvature of type II tails indicates that the forces repulsing the dust grains from the coma are only just a little larger than the attractive gravitational forces. The main source of this is *radiation pressure*. The pressure exerted by sunlight drives the particles in a direction outward from the Sun.

Comet tails usually extend to lengths of millions of kilometres. Some 'gassy' comets develop extensive type I tails but only weak type II tails. In other 'dusty' comets the reverse is true. Some comets have only faint tails, of either type, and some comets develop practically no tails at all. At the other extreme, rare comets have tails longer than 1 AU!

Figure 11.10 This portrait of comet C/2004 Q2 Machholz passing near the Pleiades star cluster on 2005 January 8^{d} was made by Bob Samuel using his Canon EOS–300D camera set to ISO 1600. The camera was fitted with a zoom lens set to 300 mm f/5.6. The camera was tracked on a driven telescope mount for the duration of the seventeen separate 2-minute exposures. These images were subsequently combined in *RegiStax 3*, with some further processing carried out in *Adobe PhotoShop Elements 3*.

The author subsequently performed some further processing in *Adobe PhotoShop* version 7.0 to enhance the visibility of the extremely faint plasma tail of this comet.

You might just be able to make out the faint image of the plasma tail extending horizontally to the left from the head of the comet. The unusually broad dust tail is most obvious where it extends vertically downwards from the coma, giving the appearance that the coma has a distorted shape. The reflection nebulosity surrounding the Pleiades (visible at the lower left) is also well revealed in this portrait.

[This image is also reproduced in colour as Plate VII (upper), between pages 304 and 305].

11.6 COMETARY DEBRIS

A comet can survive many passages through perihelion. Thirty apparitions of Halley's Comet have been observed in recorded history, for instance. One of the main reasons for a comet's longevity is the fact that a very large amount of heat energy – known as the latent heat of vaporisation – is needed to turn the chemical ices on the surface of a comet's nucleus into vapour. Some of this energy is robbed from the rest of the nucleus, so tending to refrigerate it. You might have experienced a similar 'refrigeration' effect yourself on emerging from the sea after a swim, even if you are standing in warm sunshine and there is little breeze.

Despite the refrigeration effect, the appearance of a comet's coma and tail indicate that it **is** losing some of its storehouse of matter to the interplanetary medium. The comet will be gradually whittled away with every perihelion passage.

In Chapter 1 I related how the observed splitting-up and disappearance of Biela's Comet (properly 3P/Biela) and the birth of an associated annual meteor shower first pointed to a link between cometary fragments and annual meteor showers. This link is now well established. Some comets do not survive the roasting they get as they pass through perihelion. Others do not survive the gravitational tidal forces acting during any close passages by one of the more massive planets, particularly Jupiter . . .

In the 1990s, Eugene and Caroline Shoemaker, together with David Levy, were undertaking a systematic search for comets by taking photographs with the 18-inch (0.46 m) Schmidt camera at Mount Palomar.

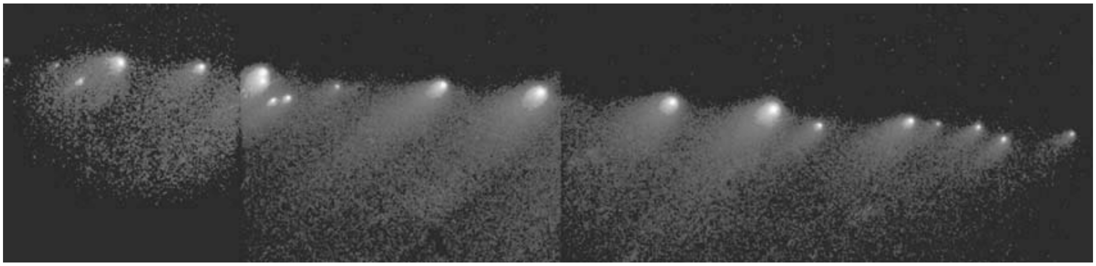


Figure 11.11 Hubble Space Telescope image of the pieces of the disintegrated nucleus of Comet D/1993 F2 Shoemaker–Levy 9 in January 1994, on their way to impact with the planet Jupiter 7 months later. [Courtesy NASA and STScI]

Their ninth jointly discovered comet was particularly intriguing. They were sure that it was a comet but their discovery image showed its brightest part to be strangely elongated, rather than point-like. Other telescopes were turned towards the object. It was revealed to be a comet with a nucleus which was fragmented into a number of pieces (see Figure 11.11). When its orbit was determined accurately enough, astrometrists could back-track their calculations to investigate the comet's past history. This showed that the comet had made a very close flyby of the planet Jupiter in July 1992.

The comet was disrupted by the gravitational forces imposed on it as it flew past the massive planet. When astrometrists forward-tracked their calculations they received a big shock: next time around the comet would not merely fly past Jupiter – it was going to collide with the planet!

Professional and amateur astronomers watched with growing excitement as the separate nuclei of comet Shoemaker–Levy 9 (properly D/1993 F2 Shoemaker–Levy 9, it being their ninth jointly discovered comet) evolved and inexorably moved towards the great planet Jupiter. Some of the fragments were very small. Some even vanished altogether, showing that they must have been very insubstantial in nature. Some further subdivided. Altogether there were about 21 members, the number varying from time to time as they headed towards their fateful encounter.

We witnessed the first of the fragments slam into the great planet at 60 km/s on 16 July 1994. The carpet-bombing continued for the next 6 days and produced remarkable temporary scars in the Jovian atmosphere, as I described in Chapter 8 (Section 8.10).

11.7 COMETARY CLOSE ENCOUNTERS

Thanks to the Earth being poorly positioned for the 1986 return of Halley's Comet, this apparition was a rather disappointing one from the point of view of Earth-based observers. However, it did mark the first really close-range examination of any comet by a passing space probe. Actually, a fleet of six space probes were launched to meet our famous visitor.

We learnt much from all six probes but one of them, *Giotto*, took the prize for producing the most spectacular results. It passed through the inner coma of Halley's Comet and took many colour pictures while it was also busy taking many physical measurements of its environment. Some spectacular pictures of the nucleus were obtained showing the jets of gas and dust in action erupting from the nucleus. The images also showed the nucleus of Halley's Comet to be an extremely dark, potato-shaped, body spanning about 8.2 km×8.4 km×16 km. This dark covering was unexpected and a definitive explanation for it still has to be found.

Gravimetric measurements indicated that the average density of Halley's nucleus ranges about 500 kg/m^3. This is about half the density of normal ice and was a surprise at the time. This indicates that the nucleus is a very loose agglomeration of ice crystals. Astronomers have since realised that many other cometary nuclei must have even smaller densities because many have been seen to easily fragment since that first famous case of 3P/Biela.

Since 1986 there have been several more close encounters with other comets. One mission, *Stardust*, achieved the capture of a tiny quantity of comet dust in a material called aerogel and brought it back to Earth for study. Another mission, *Deep Impact*, fired a projectile into a cometary nucleus and remotely observed the resulting eruption of material. Still more close encounters are in the pipeline at the time I write these words. Despite the space probes there is still plenty we Earth-based astronomers can do to advance our studies of these celestial phantoms.

11.8 TELESCOPES AND BINOCULARS FOR OBSERVING COMETS

There is no one ideal telescope you could choose for observing comets. A comet that appears as an excessively faint misty patch spanning a mere few arcminutes – and most of them appear like this – would be best appreciated with a fairly large magnification applied to a large-aperture telescope. Perhaps ×200 to ×300 on a 20-inch (0.5 m) (or even larger) reflector would be a good choice, if you can afford a telescope that big.

A similar magnification and large size of telescope might be best for observing certain details, such as jets and hoods, in the coma of even the really large naked-eye comets that come along every decade or so. Yet, to frame that same comet complete with much of its tail would need a field of view of many degrees wide, which is a challenge even for powerful binoculars.

I recommend adopting a positive attitude of mind and press whatever equipment you have into service. Having said that, if you are purchasing a telescope primarily for observing comets, then I would always advise choosing one with the potential to deliver a wide field of view. This is not just to frame the largest comets when these rarities come along. Locating objects is also very much easier when the telescope's field of view is large. The widest fields of view come from binoculars and from *rich-field telescopes*, which are telescopes of moderate aperture and low focal ratio.

A typical rich-field telescope will have an aperture in the range of 100 mm–200 mm and a focal ratio in the range of f/4 – f/6. That is a fairly good compromise between aperture and field of view (both of which should be as large as possible, though making one big inevitably makes the other small). Many manufacturers market telescopes that come into the rich-field category.

The reason for using an instrument of low focal ratio (and hence low focal length for a given aperture) is that it has the potential to provide a much larger apparent field of view. The image scale, expressed in arcseconds per millimetre, at the principal focus (using no additional optics) of a telescope is given by:

$$\text{image scale} = 206265/f,$$

where f is the focal length of the telescope, in millimetres. As an example, a 150 mm f/4 telescope has a focal length of 600 mm and an image scale of 344 arcseconds per millimetre. A 150 mm f/8 telescope has twice the focal length and an image scale of 172 arcseconds per millimetre.

How much of this image is presented to the eye of the observer depends on the size of the field-stop aperture in the eyepiece. Let us say that we are using one of the standard 1¼-inch (31.7 mm) barrel-diameter eyepieces. Further suppose that it has a field-stop aperture of 28 mm (it obviously has to be at least a little less than the diameter of the barrel). What field of view will we see when we look through it? Plugged into the 150 mm f/4 telescope we will see a field of view amounting to 28×344 arcseconds, or 9632 arcseconds. This is a field of view of $2^\circ.68$, or about 5 times the diameter of the full Moon.

With the same eyepiece used on the 150 mm f/8 telescope the diameter of the field of view we can see is halved (though, of course, the image we see will be magnified twice as much). Our field of view now only amounts to about 2½ times the diameter of the full Moon. That is one quarter of the area it was previously. A field-stop aperture of 28 mm is just about as large as we can get in any eyepiece assembly that has to fit into a standard 1¼-inch barrel; so you see the advantage of using the telescope of low focal ratio when we wish to image large fields of view.

What design makes for a good rich-field telescope? In years past, short-focus refractors were traditionally chosen, though aperture for aperture they were, and still are, expensive. One can have a reflecting telescope of the same aperture and the same (or maybe even smaller) focal ratio as the refractor but for a **very** much smaller outlay. Another advantage of reflecting optics is that they do not produce any chromatic aberration. The eyepiece, which of course uses lenses, will only give significant trouble in this respect if the inappropriate eyepiece design is chosen. I discuss telescope eyepieces in Chapter 2 (Sections 2.5 and 2.6).

The simplest, cheapest, and overall the most efficient design you could choose to use as a rich-field telescope is the Newtonian reflector. As ever, an aperture of 100 mm–200 mm and a focal ratio of *circa* f/5 is most appropriate. They do, though, have a couple of flaws not possessed by the rich-field refractor.

One problem arises from the on-axis obstruction in the light path due to the diagonal mirror. Take a careful look at the image of the exit pupil shown in Figure 10.2 in the last chapter. The exit pupil has silhouetted within it the obstruction due to the secondary mirror of the telescope (in this case a 18¼-inch (0.46 m) Newtonian reflector, with a secondary obstruction spanning a quarter of the diameter of the primary mirror). Normally, the observer is not aware of the secondary's silhouette but when the exit pupil is large enough, the silhouette can then be a substantial portion of the size of the observer's eye pupil. Then it does make itself felt.

Of course, using a magnification low enough to produce an over-large exit pupil is always wasteful but one can still do so with the unobstructed refractor without incurring any extra penalties. To do so with the reflector is yet more wasteful of the light with only an annulus of the celestial light passing into the observer's eye. The secondary's silhouette can even produce an unpleasant shadowing effect if it is big enough. So, if you use a Newtonian reflector you really are limited to magnifications not much lower than the aperture of the telescope in millimetres divided by 5.

The other problem with the Newtonian reflector is that the usual paraboloidal primary mirror is afflicted with a particular optical aberration called *coma*. If the mirror is a good one it will produce good images close to the centre of the field of view. Stars, for example, will look as they should do – intense points of light – near the centre of the field of view. Stars away from the centre will be stretched out into small comet-like shapes (with the tails fanning outwards), the aberration increasing with distance from the centre of the field of view. This aberration gets very, very, much worse with decreasing focal ratios.

Fortunately, the limited coma-free fields of Newtonian reflectors can be expanded by means of correcting lenses plugged in just before the eyepiece (in the same manner a Barlow lens is normally used). An example is Tele Vue's 'Paracorr' lens, though this unit does produce a 1.15× increase in the magnification, and so reduces the field of view an eyepiece gives to 0.87× the value without the corrector. That may still be preferable when the stars are sharp right to the edge of the field, rather than cometic.

The Meade line of Schmidt–Newtonian telescopes are worthy of consideration for low-power wide-field visual observing and imaging. Currently you have a choice of a 152 mm f/5; a 203 mm f/4; and a 254 mm f/4. The adverts state that the coma afflicting them is half the extent of the equivalent Newtonians. As such they should make excellent rich-field telescopes but do bear in mind that their low focal ratios demand expensive eyepieces if they are to provide quality imaging. When it comes to the mechanics of mounting the telescope, a simple altazimuth mounting, such as a Dobsonian, will suffice for any telescope to be used solely for low-power visual observing. Smooth motions and a vibration-free mount are the primary concerns.

The advice I offer in Section 10.6 in the last chapter about choosing binoculars to observe asteroids also applies to choosing them for observing comets. Image-stabilised binoculars are excellent but expensive. Mounted binoculars will also allow steady views. Avoid hand-held binoculars with magnifications in excess of ×10. In particular, avoid heavy hand-held binoculars.

11.9 WIDE-FIELD EYEPIECES

Any low-focal-ratio telescope will deliver its widest possible field of view only when you use it with an eyepiece of large apparent field. Apparent fields of view of more than 55° come from complex designs of five to eight element eyepieces – such as the Tele Vue company's 'Radian' (60°), 'Panoptic' (68°), 'Nagler' (82°) and Ethos (100°), and Meade's 'Super Wide Angle' (67°), and 'Ultra Wide Angle' (84°). These cost hundreds of dollars each, so you may well have to set your sights lower.

One thing I should warn you about is that with many eyepieces you get a slightly smaller real field in practice than you might expect using the equation

$$\text{real field} = \text{apparent field}/\text{magnification},$$

with the manufacturer's stated value of apparent field for the eyepiece. Almost all eyepieces suffer to a small degree from pincushion distortion. That is, the magnification of the image increases a little away from the centre of the field of view. This aberration is usually worst in eyepieces of large apparent field. For instance, a Nagler eyepiece, with its stated '82°' apparent field, will behave like an eyepiece with an apparent field closer to 78°, as far as the equation predicting the real field is concerned. The outstandingly good Ethos eyepieces are a notable exception. They really do deliver apparent fields very close to their advertised value of 100°.

When you go shopping for equipment, I recommend that you consider the eyepieces in combination with the telescope, rather than treating them as an afterthought. In particular, consider the cost of the eyepieces you will need when selecting the focal ratio of the telescope. You will be able to achieve the biggest field of view at the smallest cost if you balance the focal ratio against the eyepiece type needed.

11.10 IMAGE CHARACTERISTICS

As I discussed in Section 10.5 in the last chapter, stars and star-like objects appear brighter in larger-aperture telescopes. Higher magnifications can further assist their visibility by apparently darkening the sky background.

Since a comet forms a diffuse extended image, you might think that the lowest-possible magnification will be best in order for the light from the comet to be most concentrated. Actually things are somewhat complicated when it comes to imaging diffuse extended objects.

To start with, as the magnification is reduced, so the diameter of the exit pupil increases. Once it becomes bigger than the diameter of our eye pupil some of the light gathered by the telescope is being wasted. The image on the retina of our eye will certainly be further compressed at still lower magnifications but it will also be formed from less light. Despite appearing smaller, the comet actually appears no brighter than with the magnification that produces an exit pupil the same size as our eye pupil. This magnification is numerically equal to the aperture of the telescope divided by the pupil diameter of your eye. The maximum eye-pupil diameter will be about 7 mm for a twenty-year-old but gets smaller at the rate of about 0.5 mm per decade thereafter.

Physiology also has an important bearing. First, the size of an image is relevant to how we perceive it. A large dim object is usually easier to see than a very small dim object. Secondly, and maybe surprisingly, the darkening of the sky background that comes from increasing magnification does help with the visibility of even ‘faint fuzzies’. Go too far with the magnification, though, and the image then becomes too diluted and dim.

Given a reasonably dark sky, your best view of the comet may well be at a magnification that produces an exit-pupil diameter of somewhere around 3 mm, ‘best’ being defined as seeing any filamentary detail there might be with the greatest ease. This is a magnification equal to about $\times 0.32$ of the telescope aperture in millimetres (about $\times 8$ per inch). If your sky is not so dark then an even higher magnification may prove beneficial to ‘separate’ the comet from the background glow. Much, though, does depend on the comet. The most diffuse comets will always look at their best with a lower power.

The advice usually peddled concerning observing diffuse objects through telescopes is always to use the lowest-possible magnification. Many authorities like to talk of ‘equalisation magnification’, or ‘visual equalisation’, or some other similar phrase which means using a power as low as possible and having the exit pupil the same size as your eye pupil. This advice is most definitely wrong. **Limit yourself to such a low magnification and you will be throwing away much of the potential performance of your telescope** – but don't just take my word for it; try this out for yourself.

11.11 USEFUL WEBSITES

The British Astronomical Association and the Society for Popular Astronomy have a joint comet website at www.ast.cam.ac.uk/~jds/. In it you will find the latest news, current comet magnitudes, ephemerides, links galore – including to the important publication *International Comets Quarterly*, finder-charts, orbits, details of upcoming comets and invites to submit observations, plus links to format templates and lots more besides. The equivalent ALPO site can be accessed via their homepage (www.lpl.arizona/alpo).

You will find extensive comet ephemerides and orbital elements at www.minorplanetcenter.net/iau/Ephemerides/Comets/index.html. The head of the first page also has a set of links to the latest Minor Planet Electronic Circulars (MPEC) list of observable comets, a list of the comets discovered in the last year, an interactive conversion between old-style and new-style comet designations, orbital elements in a form suitable for download into popular planetarium software and links to recent comet magnitude estimates and the *International Comet Quarterly*.

Space is pressing so I will briefly mention the Minor Planet and Comet Ephemeris Service at: cfa-www.harvard.edu/iau/MPEph/MPEph.html; and Visual Comets of the Future at: www.aerith.net/comet/future-n.html. There are other websites, including some Yahoo groups you can join, but I will leave you to search out these for yourself if you so desire. The examples I cite here should be enough to serve your needs.

11.12 LOCATING COMETS

Where reasonably bright comets (needing no more than binoculars to see them) are concerned, the various glossy magazines are useful in that they often give partial sky maps on which the comet is plotted for specific dates. If you know the sky at least reasonably well that should be enough for you to find the comet.

Your telescope might have good setting circles or a GOTO mount that works well enough to point at a target to an accuracy of a degree or so. That could be sufficient if you have the figures from a published ephemeris which you can use. Even then, you might still have to 'stir the telescope about a bit' in order to find the comet if the field of view of the eyepiece is not very wide. Faint comets demand a more precise GOTO or the use of finder-charts, or star-hopping. You should then follow one of the procedures I outlined in Section 10.7 of the last chapter for setting a telescope onto a chosen asteroid.

11.13 OBSERVING AND DRAWING COMETS

Once your eyes are dark-adapted and you have your telescope set on the comet, the first thing you should do is to try the effect of a wide range of magnifications on its image. In the following notes I will consider the comet in two parts: first the details visible close to the false nucleus and then the comet as a whole . . .

The immediate surrounds of the false nucleus

This brightest region of the comet is especially interesting. Within it lurk details very often lost to 'white-out' in photographs which are exposed to render the fainter parts of the comet. Yet here dramatic physical processes occur that define the comet's very heart and soul.

Look carefully at the false nucleus. How bright is it? Try the full range of magnifications you have at your disposal. You will often find that this part of the comet can stand very high magnifications – and you might then see details revealed that would remain indistinguishable at lower powers. The false nucleus is usually very small, almost star-like. However, in very active comets it can expand in size to several arcseconds across. What is its shape? Is it spherical, or elongated, or even irregular? A high magnification is a must, here.

Are there any jets visible issuing from the false nucleus? They usually emerge pointing in a sunward direction for a few arcseconds, or maybe arcminutes, and then curve round to trail off in the direction of the comet's tail. What about hoods, shells, jets and rays?

Provided they are carefully executed, drawings based on what you see through the eyepiece still have real scientific value. This is especially the case for drawings of these innermost parts of the comet. For instance you, or the co-ordinator to whom you send your observations, may have a chance to determine the rotation period of the nucleus from a sequence of your (or yours and other people's) drawings. This way of determining the rotation period can give more definite results than by photometric (brightness) measurements.

One spin-off (no pun intended) is the possibility of determining the inclination of the rotation axis of the comet. This demands that the orientation of your drawing is carefully determined and marked. Also, the regions of particular activity (the roots of the jets) on the nucleus may be mapped. What is possible depends, though, on the details visible (which you cannot control beyond using the best-possible technique) and the quality of your recording/drawing (which is your responsibility).

Building up sequences in the course of a night, and from night to night, is particularly instructive. Look at the drawings of C/1995 O1 Hale–Bopp by Robert Bullen displayed in Figure 11.12(a)–(d) and you will see how much detail can be recorded by means of eye and pencil. These drawings show how the comet changed and developed. You will also

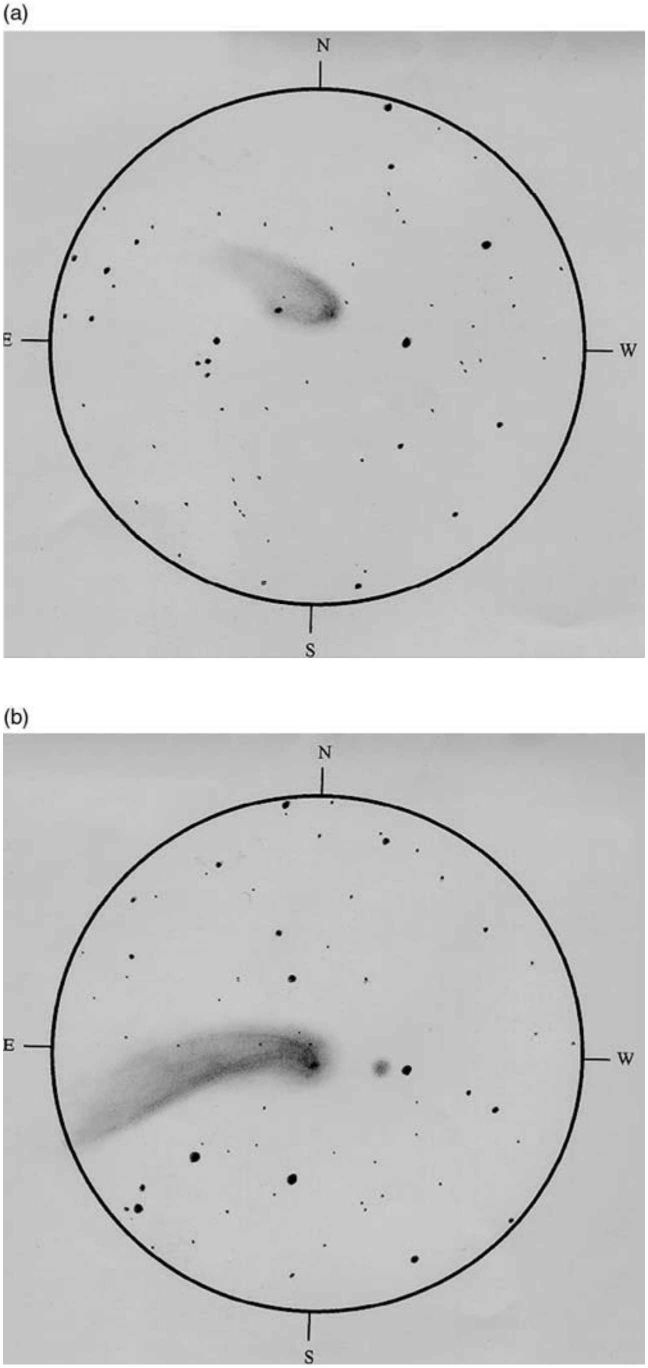
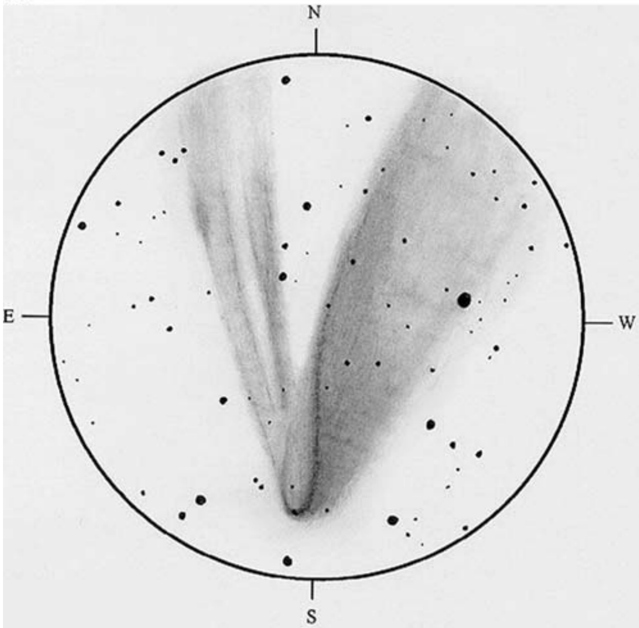


Figure 11.12 These drawings by Robert Bullen show the development of the spectacular comet C/1995 O1 Hale–Bopp. They were all made using 11 × 80 binoculars and the field of view represented has a diameter of about 4°.5 in each case.
(a) 1996 September 15^{d} 21^{h} 10^{m} UT.
(b) 1996 October 01^{d} 19^{h} 30^{m} UT.

(c)



(d)

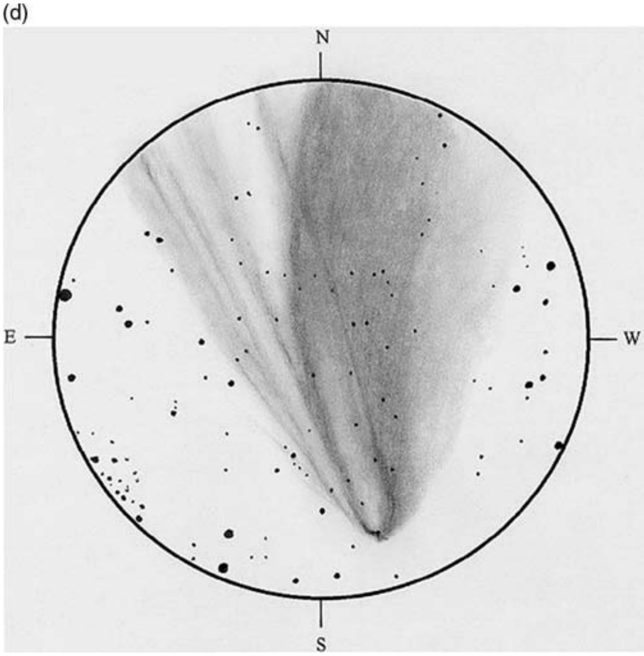


Figure 11.12 (*cont.*)
(c) 1997 March 28^{d} 20^{h} 30^{m} UT.
(d) 1997 April 05^{d} 20^{h} 20^{m} UT.

notice that Robert used binoculars to observe and record this unusually spectacular comet. He also made drawings using his 6¼-inch (158 mm) reflector (see again Figures 11.6 and 11.7).

The full set of Robert Bullen's superb drawings that he made during the apparition of this great comet can be found on the CD–ROM that is packaged with the book *Observing Comets*. This book was written by Nick James and myself and was published by Springer-Verlag in 2003. The accompanying CD–ROM also contains large galleries of images and drawings of C/1995 O1 Hale–Bopp, C/1996 B2 Hyakutake, and a number of other comets. As an aside, it also contains various resources including an ephemeris generator and some image-processing software.

Given the faint and nebulous nature of most comets, a red filter and shielding from the direct view of the bulb is necessary on your illuminated drawing board (as described in Chapter 1, Section 1.4). Pencil and paper, or any other combination of artistic media, can be used to make the drawings. Black on a white background is fine, though you might prefer white on black. Everyone will have their own preferences; all that really matters is that the drawing is as accurate in its proportions and in its represented intensities as you can possibly make it.

You might care to brush up your observing and drawing techniques on suitable deep-sky objects, while you are waiting for the next comet to appear. You will find that considerable practice is necessary before you will be happy with your results but the end product will be worth it.

Take special care with all the proportions and sizes. Try to accurately record the positions of the field stars, as well as the comet – in fact I recommend doing this as your first main task. The stars, once placed, will help you achieve positional accuracy in the rest of your drawing. If you find that sketching a faint grid of lines on the drawing paper helps you, then do it. You will have your own way of working but, I say again, the most important aspect of your final drawing has to be its accuracy.

The overall appearance of the comet

A comet's coma rarely appears perfectly circular. Its shape and size, its brightness, and the distribution of brightness within it reflect the vigour and type of activity of the nucleus, as well as the character and extent of its interaction with the solar wind. This is even more true when one considers the comet's tail or tails.

Some comets can display significant brightness and structural changes over a period of less than an hour. All comets show considerable changes over much longer periods (hours, days or weeks). How does one make sense of all this? The answer is to break down the various aspects or features of the comet and separately try to quantify them. To begin with, here are a few pieces of data you should attempt to determine whenever you visually observe a comet:

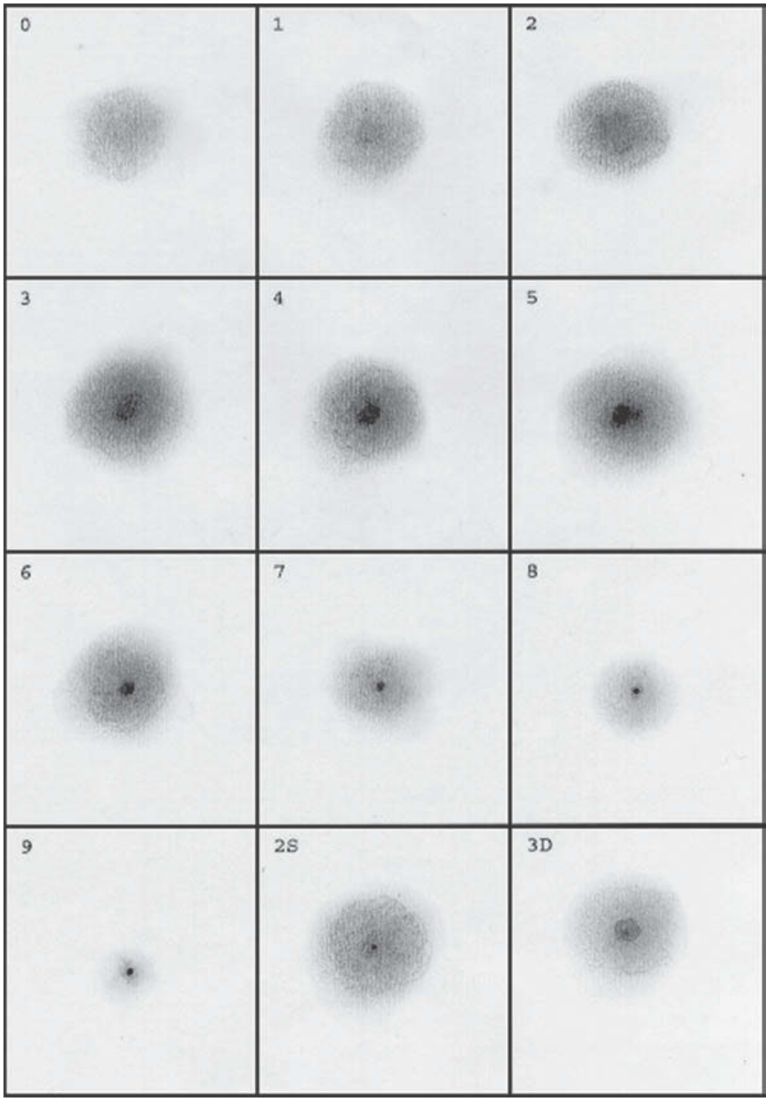
- How condensed is the false nucleus and coma? There is a scale for this. This is called the *degree of condensation* (*DC*). The scale runs from 0 to 9. A comet with a DC of 0 appears totally diffuse while one with a DC of 9 appears star-like. You should use the 'key' of comet appearances and associated DC numbers presented in Figure 11.13 as an aid to making your determinations.

  If there is an additional feature visible in the coma, then add 'D' after the DC value if this feature is disk-like and makes a significant contribution to the total brightness of the coma, changing the DC value by more than 2. If the disk-like condensation makes a less significant contribution to the overall brightness then register its presence by adding a 'd' after the DC number. If the condensation is star-like then add an 'S' or an 's', depending on whether it changes the overall DC number by more or less than 2, respectively. If any condensation is intermediate between being disk-like or star-like then add an 'N' or an 'n' if it is bright or faint, as for the other added letters. You will find a couple of representations of a cometary coma with condensations in the lower-right two cells of Figure 11.13. In these hypothetical cases the CD numbers assigned to them would be 2S and 3D.

  The best you can do is to make an estimate and accept that it is bound to be imprecise. Further, the value of DC you determine will often differ when you view the comet through different equipment! Nonetheless, the DC value is still much used in comet studies.
- What shape is the coma? Is it circular, or some other symmetrical shape, or does it tend to appear fan-shaped or parabolic, or is it irregular in outline? Linked to the foregoing, how diffuse does it appear and what structure is visible within it? How is the brightness distributed? For instance, is the coma diffuse all round, or does it have a sharper edge along one side?
- How long is the tail (or tails)? What is (are) the shape of the tail(s) – fan-shaped, narrow, curved or straight. Type I tail? Type II tail? How bright? How is the brightness distributed throughout the tail(s)?
- What features, such as knots, waves, disconnections (parts of the tail apparently broken away from the main body) are visible in the tail?
- Are there colours anywhere in the comet? Normally any colours are pastel shades if they are visible at all. Most comets appear a nebulous grey to the eye, even when seen through a telescope.

In addition to your drawings and simple notes there are some other measurements and other determinations you can make. These are briefly discussed in the following sections.

Figure 11.13 Degree of condensation (DC). Note that the contrast of the images are here exaggerated for the sake of clarity. To assist in estimating a DC number, here follows a descriptive Key: (Diagram and key courtesy Jonathan Shanklin and the BAA).



KEY:
0. Diffuse coma of uniform brightness
1. Diffuse coma with slight brightening towards centre
2. Diffuse coma with definite brightening towards centre
3. Centre of coma much brighter than edges, through still diffuse
4. Diffuse condensation at centre of coma
5. Condensation appears as a diffuse spot at centre of coma - described as moderately condensed
6. Condensation appears as a bright diffuse spot at centre of coma
7. Condensation appears like a star that cannot be focused - described as strongly condensed
8. Coma virtually invisible
9. Stellar or disc-like in appearance

Measuring sizes and position angles

The most accurate visual method to find sizes for any object within the field of view is to use an eyepiece micrometer. However, very few amateurs have these instruments nowadays and since space here is limited I will refer you to Chapter 14 of my book *Advanced Amateur Astronomy* for more about these devices and how to use them, should you be interested.

If you know the size of the field of view of your eyepiece you can always make estimates of the extent of any object within that field of view. You should always compare the size of an object with the size of the field of view when you draw it, anyway (at least, that is the case when you draw the complete field of view within a representative large circle on your drawing paper).

The foregoing estimate can be made more accurate if you can more precisely determine the east–west span of any particular feature (the coma of a comet, just to take one example). You can do that by switching off the motor drive and letting the feature drift out of the field of view. You time from the moment the leading edge reaches the western edge of the field of view until the moment its following edge just disappears. The time taken for egress is t and this value is used in $D = 15t \cos \delta$, the same equation used to determine eyepiece fields of view. In this case D is the east–west span of the feature you are wishing to measure.

What do you do if you want to measure the span of a particular feature in the north–south direction, or at some angle to the north–south or east–west directions? Here we are dealing with *position angles*. As shown in Figure 11.14, position angles are measured as a compass direction radially away from a reference point. The position angle (PA) is defined to be 0° in a direction due north, increasing through 90° due east, further increasing through 180° due south, through 270° due west and finally to 0° (equivalent to 360°) once again.

The length of a feature, such as a comet's tail, is then equal to its east–west span multiplied by the sine of the PA. Ignore the negative sign that PAs greater than 180° will generate in the answer.

How does one go about measuring position angles? You may be able to get an estimate accurate to within a few degrees from your drawing if you have the east–west or the north–south line accurately recorded on it. Letting a star track across the centre of the field of view and recording its entrance and exit points on your drawing will define the east–west line if you have an altazimuthly mounted telescope. If your telescope is mounted equatorially, and provided the polar axis is within a degree of its proper alignment, then clamping one axis and slewing through the other will do the same job. For instance, a star's apparent motion in right ascension, with the declination axis clamped, will adequately define the east–west line.

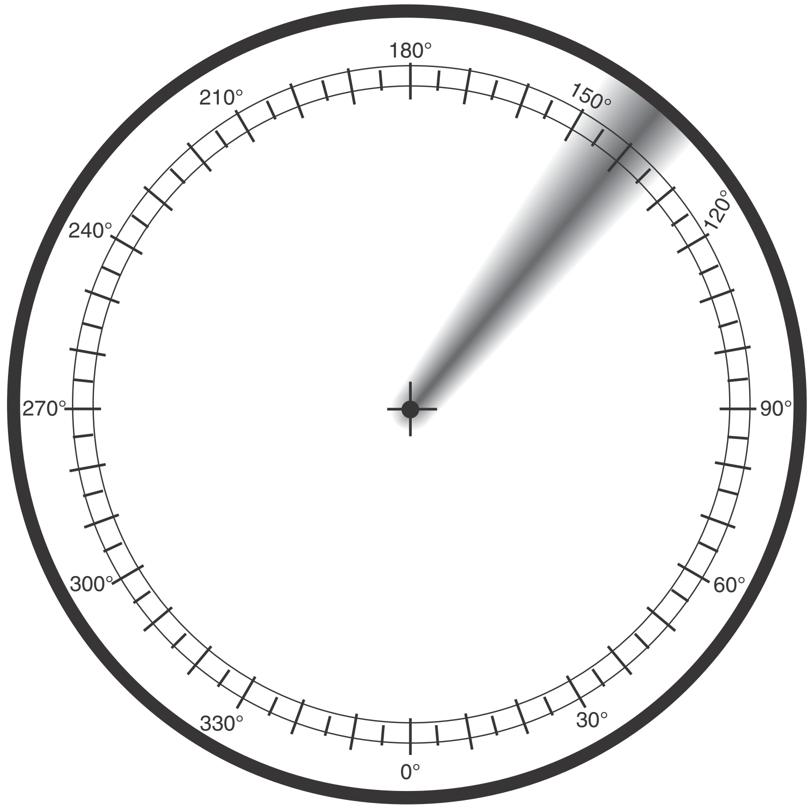


Figure 11.14 Measuring position angles (PAs) using a simple reticle eyepiece. In this example the PA of the mid-line of the comet's tail is 140°.

Another method that some people recommend is to carefully plot the star positions on your drawing and then use an atlas to identify the same stars, finally measuring the PA of the line between selected stars on the atlas. The line between the corresponding stars on your drawing will have the same PA and this can be used as a basis to measure other PAs on your drawing. In my view this method is clumsy and involves so many steps, with the potential for inaccuracy in each one of them, that the accuracy of the end result must surely suffer.

Perhaps a more satisfactory procedure is to measure PAs directly on the field of view you see through the eyepiece (again, see Figure 11.14). Once again, the expensive, and nowadays rarely used, eyepiece micrometer is the best tool for this job. However, a number of manufacturers do produce eyepieces with a *reticle*, consisting of one or more engraved scales simultaneously in focus with the field of view of the telescope, which do allow measurements to be made.

Even a simple crosswire eyepiece will be of some aid, though the accuracy of your determined PA values will obviously not be as good. One

Table 11.1 *Photographic field sizes and recommended maximum lengths of exposure for an untracked camera with lenses of specific 35 mm-format-equivalent focal lengths*

Focal length (equivalent mm)	Approximate field size (degrees)	Recommended maximum exposure length (seconds)
50	27.5 × 41.3	10
135	10.2 × 15.3	3.6
200	6.9 × 10.3	2.5
300	4.6 × 6.9	1.6
500	2.8 × 4.1	1.0

thing that is mandatory for even the simplest reticle or crosswire eyepiece is some form of illumination. Otherwise you will not be able to see the scale, or crosswires, against the nearly black field of view. Mind you, it is also true that the faintest comets will be extinguished from your gaze when you switch the illumination on! You will just have to do the best you can.

For measuring the PAs and lengths of features that are larger than the field of view of the telescope eyepiece, you could plot the two points – one at each end of the feature – on a star chart and then make your measurements on that. If the comet's tail is significantly curved then you should determine and record PA values at the head of the comet and at the end of its tail.

There are other methods you could use. For instance, if your telescope has particularly accurate setting circles then these can be pressed into service, setting the telescope on each point and noting the readings. Choose whatever method will work for the equipment at your disposal and the particular comet at hand. Of course, the features in a comet can also be measured directly from photographs ...

11.14 PHOTOGRAPHING COMETS I – FIXED CAMERAS

Occasionally a comet comes along which is large and bright enough to be visible to the unaided eye. For those rare comets an exposure of a few seconds made using a fixed tripod-mounted camera may be enough to capture the scene. Figures 11.5(a) shows a view of the great comet C/1996 B2 Hyakutake I took just that way. With a standard lens ('35 mm-format-equivalent' focal length of 50 mm) on a modern DSLR one should limit the exposure to about 10 seconds, except when the camera is pointed near to the celestial pole as was the case for the photograph in Figure 11.5(a). Longer exposures will produce star trails (as well as smudging the image of the comet).

Camera lenses of longer focal lengths demand proportionately shorter maximum exposures. Of course, they also give larger and more detailed views of any comet. However, you can synthesise a longer exposure by aligning and stacking a series of short exposures, using methods such as those I describe in the last chapter (Section 10.8).

If you have a proper astrocamera – one such as the models marketed by SBIG, Apogee or Starlight Xpress – you can use it with surplus camera lenses as I have already described in Chapter 3, Sections 3.2 and 3.3. I also describe there how you can work out the field of view knowing the size of the imaging area of the CCD and the focal length of the lens.

The 35 mm-format-equivalent focal length lenses on a DSLR will give fields of view as shown in Table 11.1. In this table I also include the recommended maximum exposures in each case to avoid noticeable trailing.

11.15 PHOTOGRAPHING COMETS II – CAMERAS ON DRIVEN PLATFORMS

If you mount your digital camera, or your astrocamera fitted with a camera lens, 'piggyback' on a telescope with a driven equatorial mounting you will be able to give individual exposures up to the thermal-noise limit of the camera without any trailing problems. This is particularly useful when using long focus lenses, which are much more sensitive to tracking errors. The comet photograph shown in Figure 11.5(c) was made using a camera mounted piggyback-fashion on a driven telescope.

You may even achieve success with an undriven equatorial telescope, as I did in my teenage years. I mounted a standard small ball-and-socket camera mount onto the middle of the top side of a flat piece of wood about 12 mm thick, 100 mm across, and about 200 mm long. I attached a small cork at each corner on the underside (to act as feet). I also attached two hooks on each of the 12 mm$\times$200 mm sides, one near each end. Two elastic straps with hook ends then were all that was needed, attached to the plank's hook and wrapped twice around the solid tube of my 6¼-inch (158 mm) reflector, thus 'clamping' the plank to the tube. The cork feet gripped the telescope tube with sufficient friction not to slip. Crude and simple it certainly was but it carried the camera firmly enough.

That particular telescope had no motor drive, nor even slow-motions. I simply selected a star for guiding and kept that star's image (as seen through the telescope) just on the edge of the field of view while operating the camera's cable-release. Exposures of several minutes showed no significant image-trailing. However, the camera lens focal length was only 50 mm and so an error equivalent to several seconds of diurnal motion would have been tolerable before star images showed noticeable elongation.

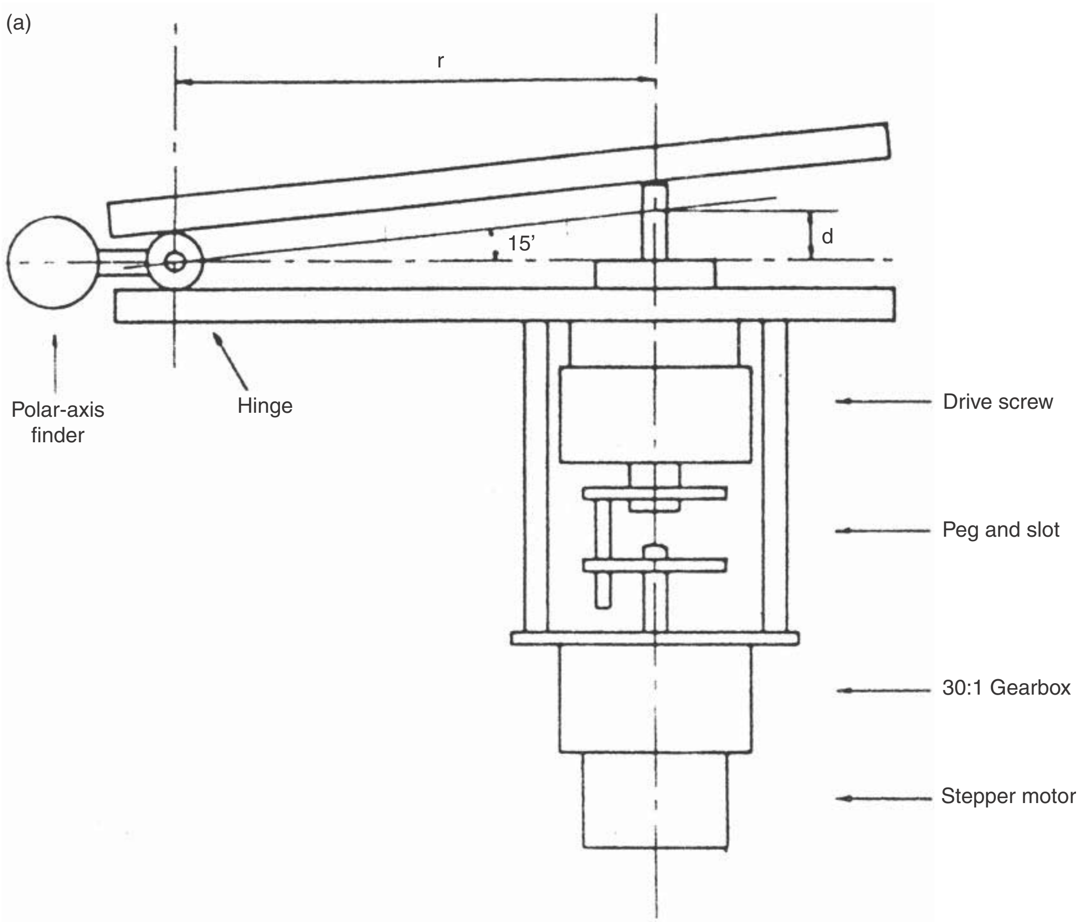


Figure 11.15 (a) The mechanical layout for Nick James's barn-door camera mount. See text for details.

Of course, you can also mount the camera directly on a driven equatorial mount without the need for the optical parts of a telescope, provided you have the mounting set up correctly beforehand. The comet photographs shown in Figures 11.4(b), 11.5(c) and 11.10 were made that way. In the absence of a telescope, or even a driven telescope mount, you can resort to using a homemade mount of the 'barn-door' design.

The 'barn-door' camera platform

This consists of two small planks of wood, or some other material, joined along one edge by a hinge. One plank is held fixed to a tripod or other support and is orientated so that the hinge is aligned to the celestial pole. The camera is attached, via a ball-and-socket camera mount, to the moveable plank. A conventional threaded bolt (a 'screwbolt') passes through the fixed plank at the opposite end to the hinge. This screwbolt

(b)

Figure 11.15 (*cont.*) (b) Nick James's barn-door camera mount in operation. The fixed platform is attached to the top of the tripod. The camera is mounted on the moveable platform.

can be turned by hand, or it can be driven via a motor and gearbox (see Figure 11.15(a)).

In use the screw is slowly turned and this increases the separation of the planks at the end opposite the hinge. Thus, the angle the moveable plank makes with the fixed plank slowly changes. In fact, if the rate of rotation of the screwbolt is just right then the camera will follow the diurnal motion of the stars.

Figures 11.15(a) and (b) show one variant built by Nick James. He used it to good effect many years ago before he acquired a large equatorially mounted telescope. In Nick's version, the screwbolt was driven by a stepper motor through a gearbox. With reference to Figure 11.15(a) the required linear drive rate, D, expressed in millimetres per minute is given by:

$$D = r\tan(0^\circ.25),$$

where r is measured in millimetres.

Of course, the drive rate can only be strictly accurate at one angle, since the drive screwbolt is linear and its point of contact does not follow an arc centred on the hinge. Fortunately, this error is negligible in practice. The required rotation rate, R, of the screwbolt is simply the required linear drive rate divided by the pitch of the screw's thread, P, measured in millimetres:

$$R = D/P$$

where R is measured in turns per minute.

If you decide to construct a barn-door guiding platform for yourself, do ensure that the hinge you select is sturdy and has little side-play. Nick's version incorporated a small polar-axis sighting telescope made from a discarded telescope finder-scope, which he set parallel to the hinge.

Since Polaris resides nearly a degree from the true celestial pole he made use of a home-constructed star chart showing the field around the celestial pole. You could print one off from a planetarium software such as *Starry Night Pro*. Nick then orientated his chart according the position of Ursa Major in the sky at the time. Sighting through the finder-scope then allowed him to align it, and so the hinge, to within a fraction of a degree of the true celestial pole. Another feature of this unit was a camera lens heater made by sewing 1.8 metres of 20 Ω/m resistance wire into a Velcro strip. The strip was wrapped around the top of the lens. Supplying it with 12 V caused 4 W of heat to be dissipated, enough to keep the lens dry even on very dewy nights.

If you are inclined towards practical electronics you could build your own oscillator to drive a stepper motor as Nick did. A lower-tech version might utilise a synchronous motor and gearbox, so dispensing with the oscillator circuit. For instance, if the final drive can be arranged to rotate at 1 rpm this would drive a barn-door unit at the correct rate if the distance between the contact point of the screwbolt and the hinge (the distance shown as r on Figure 11.15(a)) is 200 times the pitch of the thread on the screwbolt.

However you drive the screwbolt, you must include provision for rewinding it at the end of several-minutes-worth of driving. I suggest simply uncoupling it and rewinding by hand. For the unit shown in the diagram unscrewing the peg would allow the screwbolt to be turned independently of the motor and gearbox, though Nick actually arranged a switchable fast rewind as part of his self-designed and self-built oscillator circuit.

An even lower-tech version might dispense with the electric motor and gearbox altogether. Turning the head of the screwbolt by hand (maybe via an affixed handle) to the sounds of a slow-ticking clock or other audible device that can act like a metronome would do. A screwbolt with 0.5 mm pitch would need to be turned at one complete rotation every 30 seconds if the contact point-to-hinge distance is 200 mm, for instance. Even so, manually driven tracking will only be accurate enough for driving a camera with a lens of not much more than 50 mm focal length. The motorised versions described previously could be good enough to produced well-tracked images made from exposures of several minutes even when using telephoto lenses.

11.16 PHOTOGRAPHING COMETS III – AT A TELESCOPE'S PRINCIPAL FOCUS

A DSLR or a proper astrocamera can be arranged to image at the principal focus of a telescope as previously described in Chapter 3, Section 3.4.

The choice of procedures for making exposures longer than a few seconds are the same as those I describe for imaging asteroids (see Section 10.8 in the last chapter).

A comet's apparent motion against the background stars can be rapid. In fact, so much so that an exposure of just a few minutes can produce considerable image smear in some cases if the telescope tracks accurately on the stars. In the days of film-based photography the most usual remedy was to have a second telescope – a *guide-scope* – mounted on the one used to take the photographs. The guide-scope was provided with a crosswire eyepiece. The crosswires were set on the false nucleus of the comet and fine adjustments were made to the photographing telescope's declination and right ascension in order to keep the comets image stationary on the film. Obviously the background star images then appeared as trails. This is how the film-based photographs shown in Figures 11.3, 11.4(a) and 11.9 were obtained.

You can use the same technique if you really want to but in these days of CCD imaging and computer software you can achieve excellent results with much greater ease using 'track-and-accumulate' mode. Also, there is then no need for a guide-scope. If the false nucleus is sufficiently prominent for the track-and-accumulate function in the astrocamera software to work then this will be the easiest solution.

Otherwise you could use software such as *Astrometrica*'s track-and-stack function in the same way as described for imaging faint, fast-moving asteroids (see Section 10.8 in the last chapter). You will have to input the comet's direction and rate of motion. This is usually given in the comet's ephemeris. If not then you can calculate this for yourself using two ephemeris positions of the comet. To get the most accurate figure for the comet's motion you should use positions just before and just after the date of your photography.

An alternative procedure is to take a series of snapshot exposures of the comet (maybe just 15 seconds each) and combine them afterwards into one image using image-processing software such as *Adobe Photoshop*. I describe how you might go about this in Chapter 4, Section 4.3. If you are using a DSLR camera for your astrophotography then you will be limited to taking a series of relatively short exposures, anyway.

11.17 PHOTOGRAPHING COMETS IV – IMAGE PROCESSING

The post-production processing that is necessary, or even desirable, depends on what camera was used to take the image. The onboard electronics of a DSLR camera will produce an image that is already cosmetically pleasing. Even so, some processing will allow the enhancement of the magnitude limit and of whatever details may lurk hidden within the comet's fuzzy image.

The output of a CCD astrocamera will be much more rough and will definitely need some further work on it if the best possible final portrait is to be obtained. A first step is the application of flat-field and dark-frame calibration images to the raw image, as described in the last chapter (Section 10.9). After that you could either stay in the astrocamera manufacturer's operating software package to utilise its image-processing facilities, or you could import the image (usually as a bitmap, a TIFF or a FITS file) to your own preferred software suite.

Never convert the file to a JPG and then try to do further processing on it. Files in this 'lossy' format will not stand much processing unless they are at least hundreds of kilobytes big. You will be able to use the processing tools much more aggressively if you work with the image in another file format.

There are plenty of processing software packages you can use. One of the *Adobe Photoshop* versions will serve you very well, as will simpler programs such as *Image Editor*. DSLR users will find *Images Plus* particularly useful. As an example of simple image processing in action can I refer you to Figure 11.16(a)–(d), which shows stages in the processing of a cometary image. The comet in question is C/2001 Q4 NEAT. Ian Bennett and I used an SBIG STV camera on the Breckland Astronomical Society's 0.5 m (19½-inch) reflector to obtain the image. At the time the comet appeared fairly low in a sky of rather poor transparency. Visually through the telescope the coma appeared as a faint fuzzball against a light sky background and no tail could be seen but we persevered and decided to attempt photography of this comet anyway.

The image was composed of a set of thirteen 5-second exposures made in track-and-accumulate mode. The telescope is an amateur-built computer-controlled Dobsonian of decidedly rough-and-ready tracking characteristics and the best method with this telescope was to take a series of short exposures and combine them to avoid trailing due to tracking problems. The STV camera has a very small CCD chip and it was used binned 3×3 so that the effective pixel size was 22.2 μm and the image was composed of 164×216 'effective pixels'. The camera was plugged into the Newtonian focus of the telescope together with a fitted telecompressor lens, so producing an effective focal ratio of f/2.9. Each effective pixel then spanned 3.2 arcseconds and the image as a whole spanned 8.6 arcminutes × 11.4 arcminutes. Calibration frames were applied at the time of the observing run.

The accumulated image from the telescope was captured in the camera's SBIG software as a proprietary STV format file. After the observing run I opened this file in SBIG's *CCDOPPS5*. My first job was to select

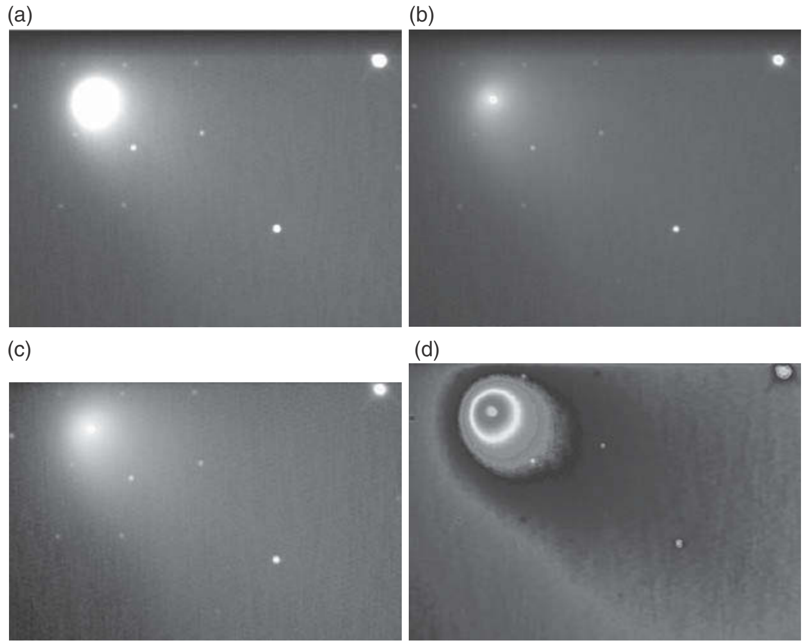


Figure 11.16 Comet C/2001 Q4 NEAT photographed by Ian Bennett and the author on 2004 May 27^{d} 22^{h} 21^{m} UT, using the 19½-inch (0.5 m) reflector of the Breckland Astronomical Observatory). (a) The image captured from the camera resized but otherwise unprocessed. (b) The image after the application of a DDP filter. (c) The image after slight trimming and manipulation in *Adobe Photoshop* using 'Curves'. (d) After the application of a colour palette to reveal isophotals. [The image (d) is also reproduced in colour as Plate VII (lower), between pages 304 and 305].

and click on the 'Resize Utilities' function that appears on clicking the 'Utility' tab. I selected 'enlarge $\times 2$' from the drop-down menu. This synthetically quadrupled the amount of pixels comprising the image.

Resizing the image has the benefit of reducing the blocky nature of the pixelation, and so produces a smoother finished effect. If a sharpening tool was to be used (it wasn't on this occasion) then resizing becomes even more important. Figure 11.16(a) shows the image at this stage of the proceedings.

Given that the head of the comet appeared rather burned out I decided to select 'DDP' under 'Filters'. This function causes slightly differing brightnesses at the 'bright end' of the range to be stretched out, though at the expense of compressing the brightnesses at the 'dimmer end' of the range. Figure 11.16(b) shows the result. The site of the false nucleus is now revealed.

At this point I saved the image as a TIFF file and moved it out of *CCDOPPS5* and into *Adobe Photoshop* in order to make use of the very flexible 'Curves' function in this program. With the image opened in *Photoshop*, I clicked on 'Images' and then selected 'Adjustments' from the drop-down menu. A second drop-down menu appeared from which I selected 'Curves'.

On clicking on 'Curves', a small window appears showing a graph with the graph line being straight and running from the lower-left to the upper-right. Moving the cursor onto this line and holding the mouse button down allows any point on it to be dragged about, so making the graph line as a whole bend about as if it was made of rubber. At the same time one can watch the image changing in response.

A good first step when processing an image of anything nebulous is to explore the effects of moving the anchor points of the graph line, one at a time, from the corners. You might try moving each anchor point both vertically, and then again horizontally, along the graph's axes. The changes you will see in the image allow you to explore if there are any extra details hidden at either the top end or the bottom end of the brightness range. In the case in question there were no extra details revealed and leaving the anchor points in the corners proved to be the best starting point for further manipulation.

This comet was rather bland in its coma and tail and I just wanted to tweak the image a bit to brighten the extensive, dimmer, parts of the comet's image without once again burning out a large area around the false nucleus. To do this I latched onto the graph line about a third of the way down it and dragged it downwards just a little. That made the line become concave and the image responded in the way that I wanted it to, as shown in Figure 11.16(c).

As my last job I trimmed the image slightly, removing areas that were not built up from the full image because of the telescope's tracking errors whilst the series of exposures were being made.

The resulting image of C/2001 Q4 NEAT is hardly spectacular but a bland monochrome image can always be 'jazzed-up' by the application of a colour palette as shown in Figure 11.16(d). The boundaries between colours are actually *isophotals*, meaning lines of equal brightness. As such they do reveal some scientific information about the structure within the comet, as well as producing a striking visual effect. The real science, though, comes from the rigorous analysis of a properly prepared image. One such analytical technique is photometry and this is detailed in the next section. Meanwhile, let me give some very brief details of what I got up to with the images of a rather unusual comet in late 2007 . . .

Comet 17P/Holmes is normally a rather faint object, reaching about 14th or 15th magnitude when close to perihelion every 6.9 years. However, it was rather brighter than this when discovered by Edwin Holmes in November 1892 because it was at that time undergoing an immense surge in brightness, known as a *superoutburst*.

Having caught the nineteenth-century astronomical community's attention, the comet's coma proceeded to expand and fade until a sudden second superoutburst in January 1893. Again, the same subsequent expansion of coma and fading were seen. The comet displayed interesting and unusual structure within its coma at these times of superoutburst. The comet has been observed at most perihelic passages ever since but never repeated its odd behaviour – until October 2007, that is.

The comet was its usual self when recovered on 13 May 2007, nine days after perihelion at a distance of 2.05 AU from the Sun. It was then roughly 15th magnitude and astronomers watched as it steadily faded to 16th magnitude by mid October, just as expected.

On the early hours of October 24, though, the comet's brightness was seen to have jumped to eighth magnitude. Hour on hour it continued to brighten. In less than a day the comet had reached magnitude $2^{m}.4$. In roughly 20 hours the comet had somehow multiplied its apparent brightness by about a third of a million times!

The comet quickly became hot news and I was determined to get some images of it using the BAS 0.5 m telescope and STV camera. While most of the UK had excellent weather, that over Norfolk was obstinately bad and I had to be content with a few brief visual observations made from my back garden until 30 October. Even on that night the transparency was rather poor but such an unusual object demanded that I set out on the three-quarter hour drive to the BAS observatory.

The basic set-up and settings used were identical to those used for imaging C/2001 Q4 NEAT, the only differences being the lengths of exposures and variations in the subsequent processing. Figure 11.17(a) shows the result of a 2-second exposure, subsequently opened in *CCDOPPS5*, resized $\times 2$, and saved as a TIFF. Then I opened it in Adobe Photoshop version 7.0, and sharpened it using a standard sharpening filter. Next, I used curves to adjust the image to better show the fainter parts of the comet against the sky background. I finished by applying an unsharp mask (setting: amount = 50%, radius = 2 pixels, threshold = 0). The resulting image is similar to that seen through the telescope at the same time, just a little enhanced.

Figure 11.17(b) shows a 1-second exposure subsequently processed using the same basic steps as for Figure 11.17(a) though with a differently set 'curve' and different settings for the applied unsharp mask (amount = 457%, radius = 15 pixels, threshold = 0). I intended to show the inner structure of the comet's coma a little more clearly and simply experimented until I got the result I wanted.

Again I used an empirical approach to obtain Figure 11.17(c), which reveals coarser brightness variations in the coma. This 3-second exposure was treated using the same steps, though of course with a different 'curve' setting and different unsharp mask settings (amount = 500% (full), radius = 22 pixels, threshold = 0).

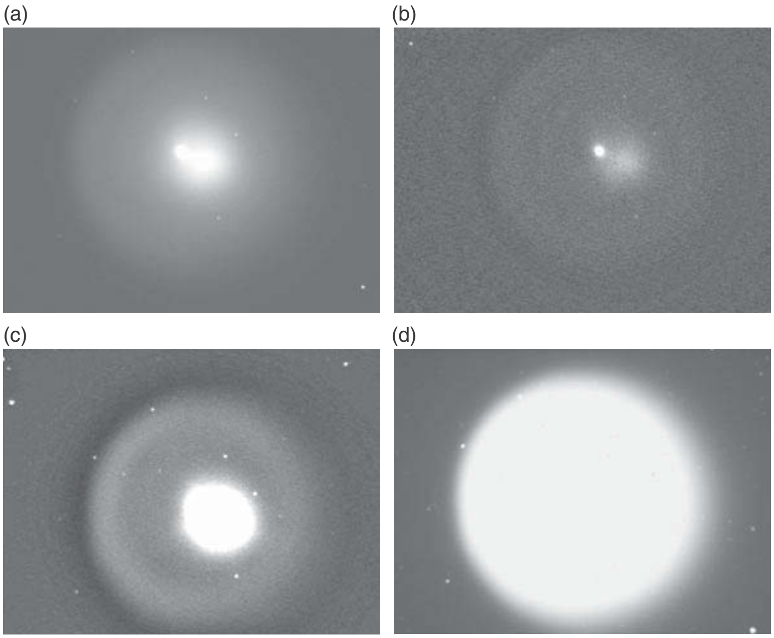


Figure 11.17 Comet 17P/Holmes imaged by the author using the 19½-inch (0.5 m) reflector and STV camera of the Breckland Astronomical Society (see text for details).
(a) 2007 October 30^{d} 18^{h} 10^{m} UT. A 2-second exposure processed to give a picture similar to that seen visually through the telescope at that time.
(b) 2007 October 30^{d} 18^{h} 06^{m} UT. A 1-second exposure processed to reveal details in the innermost coma.
(c) 2007 October 30^{d} 18^{h} 04^{m} UT. A 3-second exposure processed to show the brightness structure in the wider coma.
(d) 2007 October 30^{d} 18^{h} 15^{m} UT. A 15-second exposure processed to show the full extent of the comet against the sky background.
Each frame covers 11.5 arcminutes × 8.7 arcminutes.

Finally, I wanted to reveal the full extent of the comet image so a 15-second exposure was treated the same way as before but this time without the application of an unsharp mask and the result is shown in Figure 11.17(d). Some other details are given in the caption accompanying Figure 11.17(a)–(d).

Much stronger image-processing software can be used on better-quality images to spectacular effect. As an example of this see Figure 11.18 for a montage of alternative results of the processing of an image taken by Martin Mobberley using high-quality equipment.

11.18 PHOTOMETRY OF COMETS

Until recently, I would have included instructions for making visual estimates of a comet's brightness in this chapter. The visual methods – various techniques based on comparing out-of-focus star images with a comet's image – are only ever capable of low accuracy. Even the most experienced practitioners produced magnitude determinations that varied depending on the size of telescope used. Also, different observers would produce very different magnitude estimates of the same comet viewed at the same time, even when using similar equipment!

Nonetheless, in the absence of anything better, making visual estimates of a comet's brightness was worthwhile. Now, though, the capability of CCD-based photometry is becoming widespread among amateur

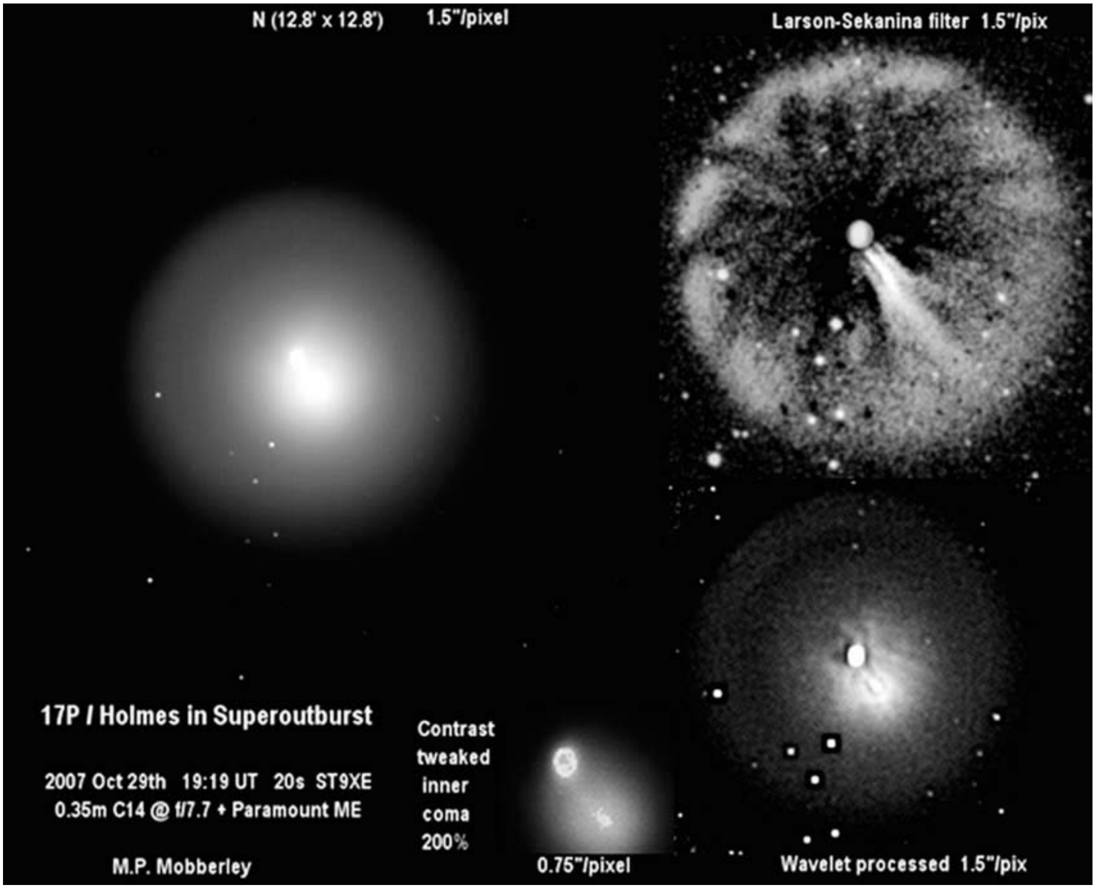


Figure 11.18 A montage of processed images of comet 17P/Holmes produced by Martin Mobberley – each based on a single image taken on the date and time shown, with the equipment indicated – showing the effects of various image-processing techniques applied to the captured image.

astronomers. Consequently, I think it is time to phase out the making of visual brightness estimates. Visual brightness estimates of stars and anything star-like are still useful because the results can be relied upon to be accurate to better than $\pm 0^{m}.3$ and are often as good as $\pm 0^{m}.1$. Those already using visual methods of cometary brightness determination may wish to continue but I would no longer encourage new observers to take up this practice. Nowadays, CCD photometry is the way to get worthwhile cometary brightness measures.

As to the methods of CCD photometry, these are basically as I describe in Chapter 10, Sections 10.10–10.14, for the photometry of asteroids. One thing worth repeating here is that if you intend using a DSLR camera for photometry then you must work with the images in the camera's RAW format to avoid the cosmetic manipulations imposed on images outputed in other formats.

There is one important difference between the photometry of asteroids and comets that has to be taken account of, though. An asteroid's image is star-like while most comets are rather diffuse. This creates a problem when deciding what photometric aperture to use when sampling the image (see Chapter 10, Section 10.11 for more about this). The remedy is to take readings using known-sized photometric apertures and to report their sizes along with the magnitude determinations. In each case, using a median function is highly desirable as larger sampling apertures will encompass more sky background and so more background stars.

First, set the minimum size of aperture to that required to fully encompass the false nucleus, though with as little of the surrounding coma as possible, and use that for a magnitude determination. For another reading you might set the photometric aperture at just big enough to fully enclose the coma. In each case you could work out the true diameter of the photometric sampling apertures from the known field size of the image. Remember the sky background and comparison-star samples have to be made using the same size of photometric aperture as used for the comet reading in each case.

It is an advantage if the image scale is such that the comet's coma occupies only a small portion of the image. For large comets it may well be best to use photographic lenses rather than a telescope for photometry. If the comet's image is small enough – and remember most comets appear as small faint balls of fuzz – then the aperture can be set to encompass the whole of the comet. A set of readings made this way would be very valuable.

In order to perform photometry you must have properly prepared the image by applying calibration frames as I described in Chapter 10, Section 10.9. Many image-processing and image-analysis software suites will allow you to plot the intensity of the image along a defined row of pixels through it. Provided you use the properly calibrated image (with no further cosmetic manipulations applied) then intensity plots made through particular slices of the image – for instance through the centre of the coma, and the false nucleus; then another through the coma and false nucleus but this time at right angles to the first plot – would be valuable especially when combined with your photometric measures.

11.19 ASTROMETRY OF COMETS

We can only see a comet when it approaches the inner realms of the Solar System. Nonetheless, comets can be tracked and their orbits calculated to include the part – actually the major part – that we cannot see. It is in this way that we know that the majority of comets come from well beyond the outermost known planets of our Solar System.

By the middle years of the twentieth century it was realised that the lifetimes of the observed comets were very short compared to the lifetime of the Solar System, and yet there seem to be a fairly steady supply of pristine comets arriving for their first perihelic passage each year. Clearly there has to be some vast reservoir of comets.

We now think that comets reside in a huge spherical, shell-like, cloud now known as the *Oort Cloud*, after Jan Oort who originated the idea. The Oort Cloud definitely extends over 50 000 AU from the centre of our Solar System. Indeed, the outermost reaches of the Oort Cloud are thought to reach out to something like 100 000 AU from the Sun. This is roughly 1½ light years. The Oort Cloud is estimated to contain something like 200 thousand million comets in deep freeze. Their total mass comprises roughly 6×10^{23} kg, or about one tenth the mass of the Earth.

Out there, these frozen ice-balls experience tidal forces caused by the motions of the other nearby stars in our Galaxy (in our region of the galactic disk the stars have average separations of about 4 light years). These forces are a significant fraction of the gravitational pull that keeps the ice-balls gravitationally bound to the Sun and so have a marked perturbing effect on them. Some even topple from their precarious orbits and plunge in towards the Sun. In fact, the continuing process produces a 'rain' of comets to shower the inner Solar System.

I mentioned in the last chapter that the demarcations between rocky asteroids, icy asteroids and the nuclei of comets is far from clear cut. They all seem to have a range of sizes and compositions. The Centaur asteroids are a case in point. (2060) Chiron, the first Centaur to be discovered, was found to be icy and even sported a weak comet-type coma. It has now even been numbered as a comet (95P/Chiron). Centaur asteroids have highly chaotic orbits that cannot survive beyond a few tens of millions of years, often less than that. The speculation is that Centaurs may be objects derived from the Kuiper Belt (which extends outwards to about 200 AU from the Sun) and are in a transitional state to becoming short-period comets in the inner Solar System.

Some asteroids have been discovered whose compositions suggest that they are really extinct comets. Also, it has long been known that many meteor showers are linked to known short-period comets. Recent results, particularly from the *Deep Impact* and *Stardust* probes I mentioned earlier, indicate that cometary nuclei contain a surprising amount of materials that formed in a high-temperature environment. Undoubtedly the dynamic and evolutionary relationships between the inner Solar System small bodies, the Kuiper Belt and the Oort Cloud – along with the formation and evolution of the Solar System itself – is highly complicated.

Where does all this get us? To be honest, cutting-edge theoretical studies of the dynamics and evolution of the Solar System as a whole are completely beyond amateur resources. However, the amateur can do useful work by undertaking comet astrometry. The method is exactly the same as I detailed for asteroid astrometry in Chapter 10, Section 10.14. One crucial factor, though, is to ensure that the images you measure have been made with the minimum exposure possible. You want only a distinct image of the false nucleus. The astrometric program you use, for example the excellent *Astrometrica*, will derive positions from the centroids of the star and object images. The 'blob' formed when a comet is given a longer exposure will not be spherically symmetrical. This can mislead the software, producing an error in the determined position of the nucleus of the comet.

11.20 FURTHER WORK

Earlier I mentioned the book *Observing Comets*. In it Nick James and I detail much more than I have room to cover in this single chapter. Even so, one topic that is only touched on in *Observing Comets* is spectroscopy. Currently, very few amateur astronomers even entertain thoughts of exploring this field, despite it being a mainstay of professional astronomy. For a practical introduction to this field, with some basic theory, can I point you to Chapter 15 in the Second Edition of my book *Advanced Amateur Astronomy* (Cambridge University Press, 1997). Also there are a couple of books that may prove useful to you. One is *Practical Amateur Spectroscopy*. This was edited by Stephen F. Tonkin and published by Springer-Verlag in 2002. The other is *Astronomical Spectroscopy for Amateurs*. This was written by Ken M. Harrison and published by Springer-Verlag in 2011. The brighter comets are ripe targets for amateur spectroscopy using quite simple techniques and inexpensive equipment.

I should also mention that since the publication of *Observing Comets* there have been a couple of other books on this subject that you may well find useful: *Hunting and Imaging Comets*, by Martin Mobberley, and *Comets and How to Observe Them*, by Richard Schmude. Both books were published in 2010 by Springer-Verlag.

As ever, my strongest recommendation is to join an astronomical society with a strong observing section in your field of interest and get to know what others are doing and what are the current hot topics. I especially recommend the comet observing sections of ALPO and the BAA.

CHAPTER 12

Our daytime star

A stellar astrophysicist might consider our Sun to be just another star, maybe even rather a humdrum example amongst the couple of hundred thousand million stars that populate our Galaxy. However, to us Solar System observers it is something special. As compared to all the other Solar System bodies, the Sun's characteristics are extreme. Of course the light and heat energy we receive from the Sun are vital to humankind's very existence but those same properties pose real dangers for those of us who choose to study it.

You need to know what you are doing. Get it wrong and you could give yourself a lifetime of impaired sight or even total blindness in at least one eye. Even if you are very experienced and normally work safely, the briefest moment of carelessness is enough to result in irreparable eye damage. You could also ruin some of your expensive equipment. There is also the possibility of burning yourself or starting a fire. You need to proceed with the utmost care, continuously putting safety first. The Sun is truly the monarch of the Solar System and it will severely punish its subjects for even the most fleeting lapses of respect.

12.1 HOT STUFF

In general, especially when dealing with chemical elements rather than chemical compounds, if you heat a solid it will melt to a liquid. Heat a liquid and it will turn into a gas. Admittedly the situation can be complicated by the instances in which chemical changes or reactions also take place – burning for instance – but I am sure that you get the general principle of what happens in the instances where chemical elements are heated in a suitably unreactive environment.

Continue heating a gas to a high enough temperature and the very atoms that compose it themselves start to fragment. With increasing temperature first one, then some more, and finally all of the negatively charged electrons are shaken or knocked free of the positively charged atomic nuclei they normally 'orbit'. To be more accurate I should really replace 'orbit' with 'surround in a standing wave pattern'. The gas has become *ionised*. It now consists of two co-existing components: a gas of atomic nuclei – maybe with a fewer number of electrons still attached, maybe with all of them removed – and an interspersed gas of electrons. We generally refer to a gas in this ionised state as a *plasma*. Even the coolest regions of the Sun and most other stars have temperatures of thousands of degrees. So, the matter composing them is almost entirely made up of plasma.

A note about temperatures in science. If you read widely about the Sun and other stars you will often encounter temperatures in the literature expressed in a unit that may be unfamiliar to you. The very common Fahrenheit and Centigrade (properly Celsius) scales of temperature are fine for everyday use but they have rather arbitrary foundations. The Fahrenheit scale has 180 divisions, or degrees, separating the temperatures of boiling and freezing water under normal atmospheric pressure, with the freezing point being fixed at 32°F. In the Celsius scale 100 degrees separate the boiling and freezing points of water, with the freezing point being fixed at 0°C.

Astrophysicists prefer to use a scale that has a more fundamental foundation in thermodynamic theory. This is the *absolute*, or *Kelvin*, scale of temperature. The zero point of this scale, known as *absolute zero*, is set at the temperature at which all particulate motions cease. These particles include atoms and molecules. At any higher temperature the atoms/molecules in a gas possess kinetic energy and so are in constant random motion. This gives rise to gas pressure because of the momentum the particles possess as they strike the walls of the containing vessel. A temperature of absolute zero corresponds to zero kinetic energy – and zero kinetic energy means the particles are stationary.

Zero on the absolute scale happens to be equal to −273°C on the Celsius scale. For convenience, scientists have set the divisions of the absolute temperature scale equal in size to the divisions (degrees) of the Celsius scale. This allows for easy conversion. To convert temperatures from the Celsius scale to the absolute scale all one has to do is add 273. A temperature on the absolute scale is expressed in kelvins (K), **not** degrees kelvin as you will often see incorrectly written in popular literature.

While I have used the everyday Celsius scale for expressing planetary temperatures earlier in this book, we really ought to be using the absolute scale in the arena of astrophysics. So, temperatures in this chapter will be expressed in kelvins (K). Of course the higher the temperature the smaller is the percentage difference in the figures on the two scales, anyway – and in the Sun we are dealing with very high temperatures indeed!

12.2 THE SOLAR ORB

If you were to look at the Sun through a thick mist – in general, though, you should **never** look directly at the Sun – it would appear as a luminous disk that subtends an apparent angular diameter of slightly over half a degree. Astronomical observations inform us that our Earth orbits the Sun at a mean distance of 150 million km and so it is a simple matter to work out the Sun's diameter and volume. It is a vast globe, 1.4 million km in diameter. This about 109 times the diameter of our Earth, so it has a volume equivalent to 1.3 million Earths.

Knowing the values of the Earth's orbital distance and period, we can use Newton's law of gravitation to calculate the mass of the Sun. It turns out to have the incredible value of 2 million million million million million kg (more conveniently written as 2×10^{30} kg). This is 330 000 times the mass of the Earth. Even if the masses of all the planets, satellites and other bodies of the Solar System could somehow be brought together, they would form a body only about a thousandth of the mass of the Sun.

Knowing its mass and its volume, the mean density of the Sun works out to be 1410 kg/m^3; about 1.4 times as dense as water. However, theoretical models indicate that the globe of the Sun is not of uniform density throughout but is very rarefied at its outer edge and very dense towards its centre. These values of density range from 1×10^{-6} kg/m^3 (one-millionth of a kilogram per cubic metre) to about 1.5×10^5 kg/m^3 (150 000 kilograms per cubic metre). By comparison, the density of our atmosphere close to the Earth's surface is 1 kg/m^3, so you can see that the visible 'surface' of the Sun is really very rarefied.

The light from the Sun can be analysed by passing its light through a spectroscope to find out what its light-emitting surface is made of. Our theoretical modelling leads us to believe that the Sun has a fairly uniform chemical composition throughout most of its globe. So we are reasonably sure that the Sun is largely composed of hydrogen (about 73 per cent by mass), with helium as the next major constituent (25 per cent by mass), followed by trace amounts of many other chemical elements.

The temperature of the Sun's visible surface, properly called its *photosphere*, averages 5800 K. The temperature increases rapidly with depth to reach an estimated 15.6 million K at the Sun's centre. The pressure at the centre of the Sun is calculated to be a colossal 250 thousand million Earth atmospheres. It is thanks to the extreme conditions in the cores of stars like the Sun that they shine. We are the grateful recipients of the light and heat our nearest star sends us.

The value of the energy per second (= power) intercepted per square metre by the Earth just above its atmosphere (this is always the value quoted to avoid having to allow for atmospheric absorption factors) is termed the *solar constant*. Its value is 1.368 kW/m^2. Knowing the radius of the Earth's orbit and the radius of the Sun, we can use the solar constant to calculate the power emitted from every square metre of the Sun's visible surface. This turns out to be 6.3×10^2 kW (630 thousand watts). Total that up for the whole of the Sun's surface and it comes to 3.86×10^{20} MW. Simply put, the Sun is pouring out energy into the Solar System at the rate of nearly four hundred million million million million watts! We think that the Sun's output has not been entirely constant over its lifetime. However, it has certainly been producing somewhere near this power output without a break for 4.6 billion years.

Until well into the twentieth century we simply did not know how the Sun managed to produce so much energy over such a long period of time. We now understand that nuclear fusion is responsible. The extreme conditions of temperature and pressure in the core of the Sun cause hydrogen nuclei to combine together to form helium nuclei. A hydrogen nucleus is just a single proton, but a helium nucleus is made up of two protons and two neutrons (for the common 'type' – more correctly *isotope* – of helium known as helium-4). By a somewhat complicated route (see Table 12.1), four hydrogen nuclei are combined to form one nucleus of helium.

Now, the mass of one helium nucleus happens to be slightly less than four times the mass of a hydrogen nucleus. So, some of the mass disappears as a result of the fusion process. What happens to this missing mass? The answer is that it is converted into energy. Einstein theoretically demonstrated that under the right conditions mass and energy are convertible, the equation relating them being the famous $E = mc^2$. In this equation E is the amount of energy, in joules, liberated by the annihilation of m kilograms of matter. The speed of light, c, is 3×10^8 m/s (3 hundred million metres per second) so the energy–mass exchange rate is quite generous. For every kilogram of mass converted, 9×10^{16} joules of energy are released (that is 90 thousand million million joules).

Referring to Table 12.1, the conditions at the centre of the Sun are right for the *proton–proton cycle* to be the main source of energy generation. As you can see from the table this cycle is actually made up of three separate chains of reactions. The PPI, PPII and PPIII chains each

Table 12.1 The energy-producing reactions in the Sun

Proton–proton cycle (PPI)
$H + H \rightarrow D + e^{+} + \nu$
$D + H \rightarrow {}^{3}He + \gamma$
${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2H + \gamma$
Secondary proton–proton cycle (PPII)
${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$
${}^{7}Li + H \rightarrow {}^{8}Be \rightarrow 2{}^{4}He$
Tertiary proton–proton cycle (PPIII)
${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
${}^{7}Be + H \rightarrow {}^{8}B + \gamma$
${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu \rightarrow 2{}^{4}He$
CNO cycle
${}^{12}C + H \rightarrow {}^{13}N + \gamma$
${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu$
${}^{13}C + H \rightarrow {}^{14}N + \gamma$
${}^{14}N + H \rightarrow {}^{15}O + \gamma$
${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu$
${}^{15}N + H \rightarrow {}^{12}C + {}^{4}He$

Key:
H hydrogen nucleus
D deuterium (heavy hydrogen) nucleus
Li lithium nucleus
He helium nucleus
Be beryllium nucleus
B boron nucleus
C carbon nucleus
N nitrogen nucleus
O oxygen nucleus
e^{-} electron
e^{+} positron
ν neutrino
γ gamma-ray photon
Differing isotopes are indicated by the raised numbers in front of the species (e.g. ${}^{4}He$ is the isotope of helium which has an atomic mass number of 4).

produce 70 per cent, 29 per cent and 0.1 per cent of the Sun's power, respectively. The CNO cycle, often known as the *carbon cycle*, produces less than 0.1 per cent of the Sun's power. Owing to the processes of fusion going on in its interior, the Sun is losing mass at the rate of 4.3 million tonnes every second to produce its energy output. However, there is plenty left and we are sure that the Sun will continue to shine for several thousand million years to come.

In other stars, the differing central conditions cause a marked redistribution of the power-generation figures among the reaction processes. For instance, in the case of massive stars it is the CNO cycle which is the dominant energy-producing reaction. The total power output of a massive star is disproportionately very much higher than a less massive one. This shortens their lives, even though their greater masses mean they start out with more nuclear fuel. Also, many stars suffer marked variations in brightness, photospheric temperature and total power output. Our continued existence is thanks to the relatively placid star of just the right characteristics at the centre of our planetary system.

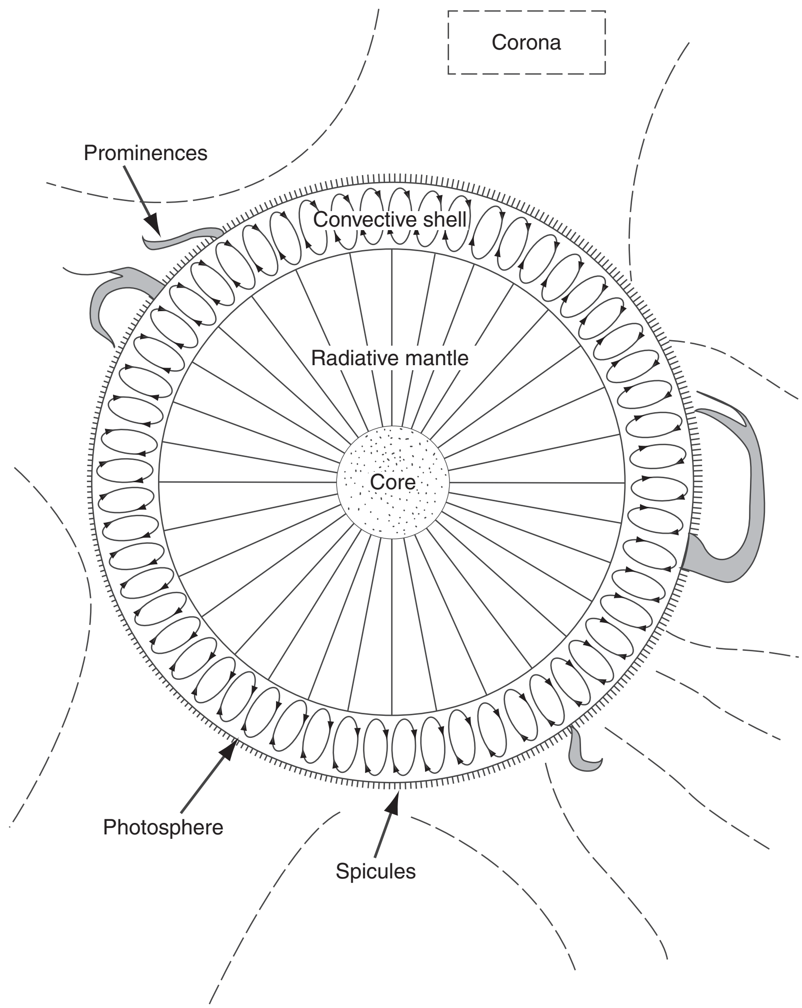
Nobody has actually seen inside the Sun but we can deduce a lot about its interior structure. Astrophysicists can extrapolate the information astronomers get from studying its surface. They can also use the fundamental laws of physics and apply our understanding of the behaviour of matter to deduce the nature and conditions within the solar globe.

Recently, this has been added to by the study of *helioseismology*. Seismologists have built up a picture of the Earth's interior by studying the vibrations generated by earthquakes. The Sun also vibrates very slightly in a number of different ways and with a range of frequencies. These can be analysed by studying the slight shifts in the frequency of the Sun's light that the vibrations produce in patches on its surface (an application of the Doppler effect). Helioseismologists make use of these data to infer the structure of the Sun's interior regions. The Global Oscillation Network Group (GONG) came into operation in 1996 to intensively study the Sun by means of observing its oscillations.

Also, a dedicated spacecraft, *SOHO*, the letters standing for *Solar and Heliospheric Observatory*, was launched by the European Space Agency (ESA) at the end of 1995. It was parked in a position of neutral gravity (a *Lagrangian point*) about a hundredth of the way along a line from the Earth to the Sun. From that vantage point it can continually monitor the Sun and the solar wind from outside the Earth's magnetosphere. As well as observing the Sun in a variety of different wavebands, it is also equipped to do helioseismology. The *SOHO* spacecraft is still making and transmitting observations.

Helioseismologists have shown that the motions of material on the surface of the Sun, and extending deep into its exterior, are much more complex than had been expected. The more we learn, the more we realise that we have even more still to learn! Having said that, a picture of the Sun's interior is emerging which is unlikely to be very wrong in its

Figure 12.1 The structure of the Sun. The author has greatly exaggerated the height of the spicules for the sake of clarity. Similarly, the chromosphere (not labelled here), actually the root of the spicules, is a thin layer that would be indistinguishable from the photosphere (which is labelled) at this scale. The prominences are also somewhat exaggerated in size.



coarsest details. Figure 12.1 represents pictorially the structure of the Sun as we understand it at present.

Most of the Sun's supply of energy is created in its central core. The core emits most of this energy in the form of short-wave electromagnetic radiations, mainly γ-ray photons. Each photon has a large amount of energy and this corresponds to a short wavelength (and it is these short wavelengths that define them as γ-rays). These photons travel only about a centimetre before being absorbed by the surrounding matter. However, this matter quickly re-emits the radiation as yet more photons.

This process continues. So, the radiation gradually works its way to the surface is what is termed a 'random walk'. In the process, the radiation gradually loses energy (actually there are more photons produced but they each have a lower value of energy). Lower-energy photons correspond to longer wavelengths of electromagnetic radiation. Believe it or not, it takes a time span ranging from about a hundred thousand years to over a million years for the radiation to get from the Sun's core to the photosphere! By the time it does so, most of the photons emerging from the photosphere each have an amount of energy (and therefore wavelength) that corresponds to visible light. There is actually a spread of the energies of the emitted photons. The remainder have either higher or lower energies, corresponding either to ultraviolet radiation and X-rays or to infrared radiation, microwaves and radio waves, respectively.

The energy-producing core of the Sun extends from the centre out to a quarter of its total radius. The process of absorption and re-emission is the dominant mode of energy transport out to 71% of the Sun's radius. The region between the core and this radius is consequently known as the *radiative zone*.

Outwards beyond the radiative zone the temperature is low enough to allow electrons to be captured by nuclei to form partially ionised atoms. Below this level the gas is totally ionised. The partially ionised atoms absorb photons very much more readily than the material of the radiative zone. As a result, a steep temperature gradient develops within the gas and this causes convection. Thus between the radiative zone and the photosphere we have the *convective zone*, where convection is the major process of energy transport.

The top of the photosphere marks the edge of the main body of the Sun, though layers of very low density gas extend above that. In fact, rarified solar gas extends even further out through the Solar System to eventually merge into interstellar space. The photosphere is the site of many of the interesting phenomena, including the sunspots we can observe if we use the right equipment and techniques.

A layer of gas, called the *chromosphere*, lies above the photosphere. The features known as *spicules* and *prominences* extend from the chromosphere. Nowadays, even amateur astronomers can acquire the specialist equipment needed to study the chromosphere.

Moving still further out we have the *corona*, which is effectively the Sun's atmosphere. Each of these features are discussed more fully in the following pages. First, though, it is time we considered how we might go about safely observing the intensely brilliant photosphere of our daytime star.

12.3 INTEGRATED (WHITE)-LIGHT SOLAR VIEWING

Sorry, I just have to say it: **On no account look at the Sun through any ordinary telescope, binoculars, camera viewfinder or any other optical device not specifically designed for safe solar observing.**

In addition, if you come across any telescope that is supplied with a small 'Sun Filter' that screws into the eyepiece barrel (with no additional special solar filter to go over the sky end of the telescope) DO NOT USE IT.

I mean you no disrespect by putting this elementary warning in this book, when I am sure that your knowledge and common sense will suffice. However, I feel sure that you will agree with me that if this warning saves just one person from even contemplating taking a chance and having a quick peek at the Sun though inappropriate equipment then it is very worthwhile including.

Also, you might think that I am being alarmist when I even warn against using one of the so-called Sun Filters that are intended to screw into an eyepiece barrel. Surely they must be completely safe if they are issued by the telescope manufacturer? I am afraid they are not safe. They can crack or even splinter under the concentrated heat. A tiny fraction-of-a-second exposure to concentrated solar radiation through a telescope eyepiece is certain to cause permanent eye damage and very likely permanent blindness.

I have heard anecdotally that some people have indeed been blinded when these old-style Sun Filters have failed. As far as I know today's telescope suppliers have completely ceased issuing them. I certainly hope so but you might come across one if you buy second-hand equipment. If you value your eyesight please never be tempted to use it.

Projecting the Sun's image onto a screen

The classic safe method of observing the surface of the Sun (for the observer at least, if not always for the instrument!) is by projecting its image onto a white screen. A shade will keep the direct sunlight off the screen, as illustrated in Figure 12.2(a). Better still, the screen can be enclosed in a box which has a large section cut away in its side to allow the observer an unobstructed view of the screen, like that shown in Figure 12.2(b). Apart from the screen itself, all the inside surfaces of the box should be painted mat-black (or lined with mat-black material) to help darken the interior as much as possible and reduce the nuisance of light from internal reflections falling across the screen.

If your telescope has a large aperture I recommend that you stop it down to 6 inches (152 mm) or less so that it gathers less heat radiation, to reduce the danger of its optics or its tube and fittings being damaged. The average seeing conditions in the daytime are often far worse than at night, thanks to the ground heating up and causing turbulence in the air above it, so most often large apertures will not resolve details any finer than what can be seen by eye through a telescope of around 3 inches

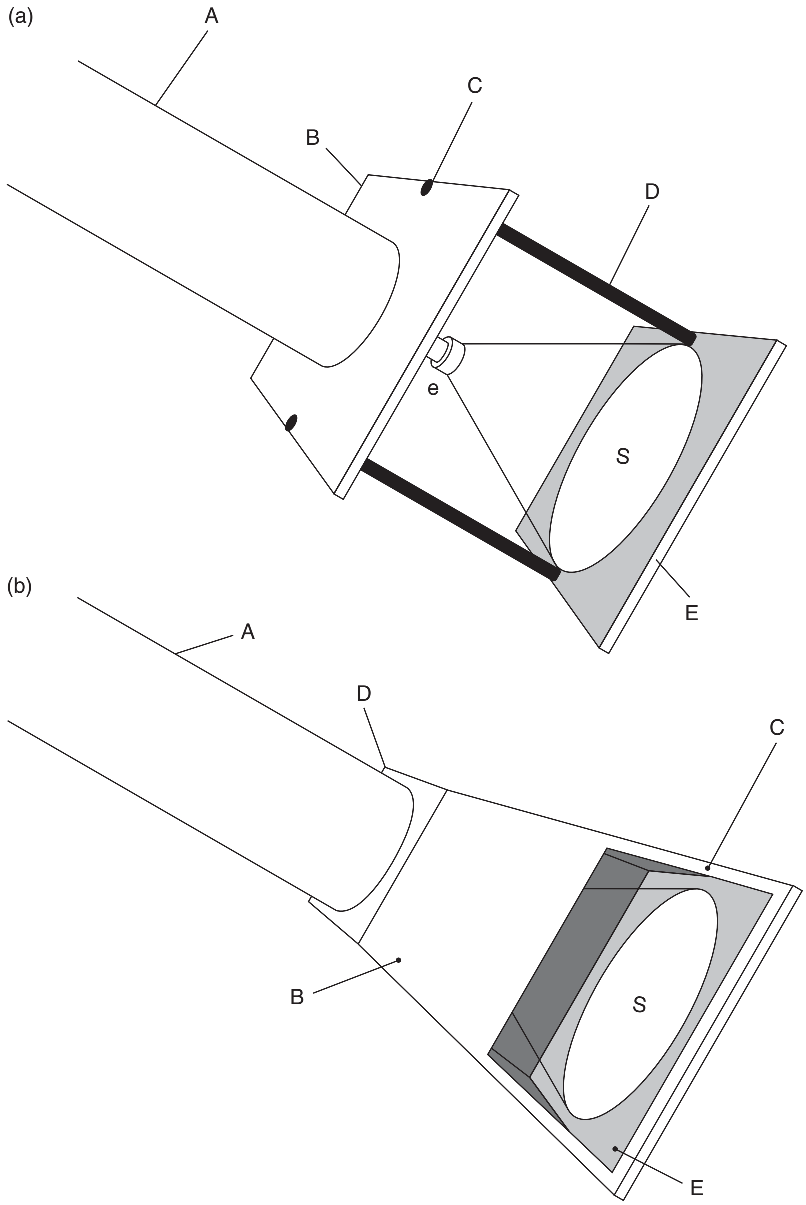


Figure 12.2 (a) Projecting the Sun with a refracting telescope by means of a shaded screen. On the diagram A represents the eyepiece end of the telescope tube. B is a thin but stout board which is clamped (clamp not seen in this view) to the eyepiece focuser and e is the eyepiece. The rods D (two shown here) connect the screen E to the board, C representing the fixing bolts, while S represents the image of the Sun that may be observed using this arrangement;
(b) A slightly more refined arrangement is a projection box. Here, A, E and S represent the same as before, C is the frame of the box and B and D represent light-weight cladding. The cladding B on the facing side B extends only part way from the eyepiece (hidden in this view) to the projection screen to allow the image of the Sun to be viewed. A lip added to the screen-end of section B (not shown here) would improve the shading of direct sunlight from the screen.

(76 mm) aperture anyway. As an aside, it is true that certain techniques used in imaging can benefit from the use of larger apertures but here I am discussing only visual observations.

I must warn you that the projection method is not suitable for all types of telescope. The much preferred instrument to use for solar projection has always been the refracting telescope. I have used a refractor this way at times in the past and can certainly highly recommend it for this method of observing.

However, I have never owned a sizeable refracting telescope of my own. For many years I conducted solar observing by projecting the image using my 6¼-inch (158 mm) f/7.7 Newtonian reflector (see Figure 12.3(a) and (b)). **I did so in the full knowledge that I was running a risk of damaging it**. The Sun's image and heat energy are most concentrated at the focal plane. However, the heat is also fairly concentrated at the secondary mirror of any compound telescope. It is possible this mirror could be fractured if it gets too hot. If the reflective coating on the mirror is good the glass will probably not heat up very much. A tarnished or dirty mirror will most definitely get very hot as it will be absorbing, instead of reflecting, a significant portion of the solar radiation.

In the case of my old Newtonian reflector the reflective coating on the secondary mirror was always in good order. Also, the glass the mirror was constructed from was Duran 50, a good low-expansion material less liable to crack with heating than many other types of glass. A Pyrex, Monax, or other borosilicate glass secondary mirror would do almost as well in this respect as Duran 50. I should also add that in my telescope the secondary mirror was held in an old-style metal holder, or 'cell'. The mirror and its cell could expand independently (the metal expanding away from the glass) without causing the glass to be stressed. While the refracting telescope was always considered to be best for projecting the Sun's image, I was certainly not alone amongst amateur astronomers in using a Newtonian reflector.

Currently manufactured Newtonian reflecting telescopes often have the secondary mirror glued to a small metal or plastic backing plate, rather than being contained within a proper cell. So, although I have displayed photographs of my own reflecting telescope – which I can assure you I used for solar projection successfully and without damage for many years – I must caution that a modern Newtonian reflector may very well be unsuitable for projecting the Sun. You could risk breaking the secondary mirror or detaching the secondary mirror from its glued mount – and then burning or melting the glue and mounting plate.

Consider these risks before proceeding. If you go ahead and use a Newtonian reflector for projecting the Sun's image, then be prepared for the possibility of it getting damaged. **I have warned you of the danger – if you choose to proceed and damage your telescope then the responsibility for this has to be yours and yours alone**. At least a replacement secondary mirror ought not to be too expensive – as long as that is all that has been damaged.

So, refractors are best for projecting the Sun's image as they have no secondary mirror. Newtonian reflectors can be used effectively though

(a)

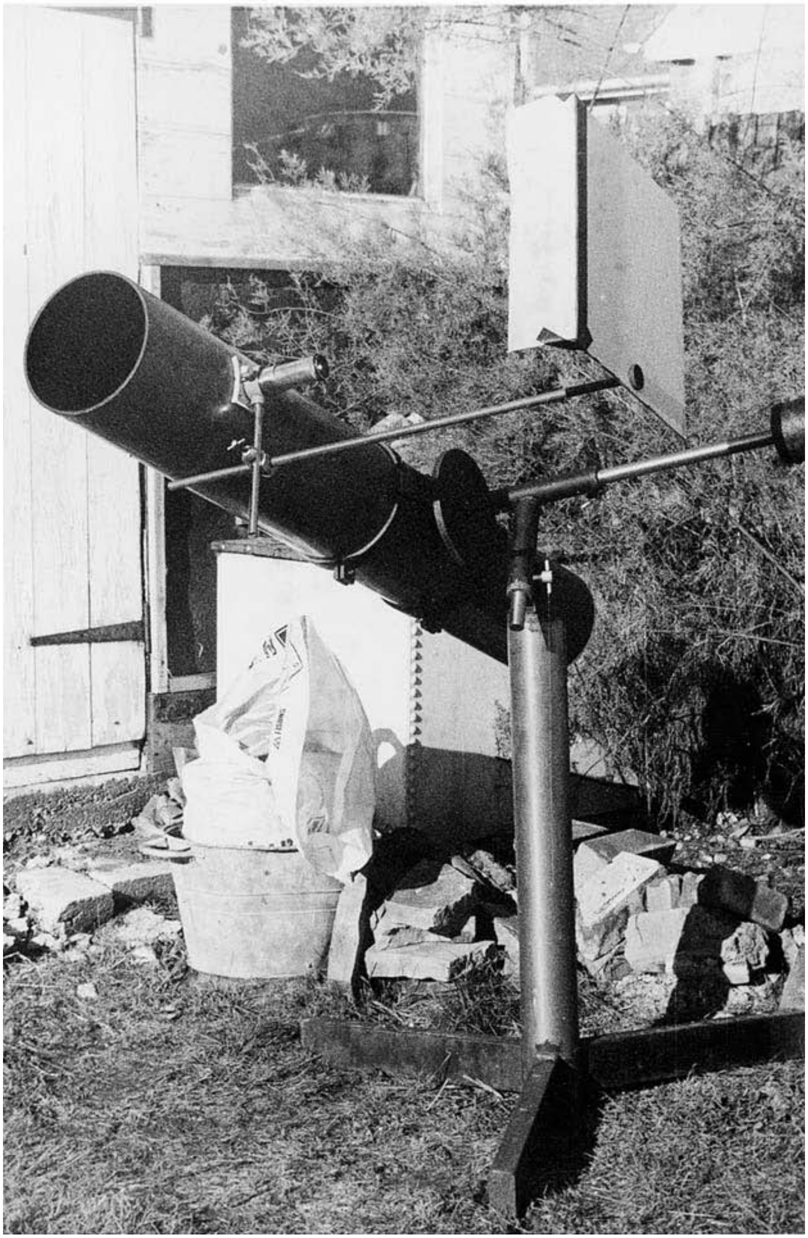


Figure 12.3 (a) In the past the author used his 6¼-inch (158 mm) Newtonian reflector to project the solar image onto a screen. Note the shade on the edge of the board.

there is some risk of damage to the instrument. I took a chance and got away with it but you might not be so lucky.

I most strongly urge a total ban on using any other type of telescope for solar projection. For instance, anyone that pointed their expensive

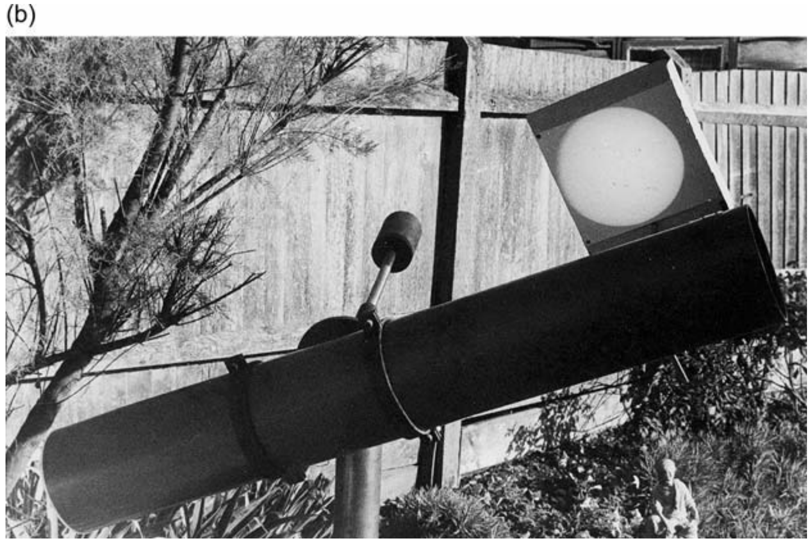


Figure 12.3 (*cont.*) (b) This projected image is approximately 11 inches (280 mm) across, yet it is still bright enough for effective observation thanks to the presence of the shade. As explained in the text, there is risk of damage to the telescope when used this way, especially so for a modern Newtonian reflector with its secondary mirror glued in position.

Schmidt–Cassegrain telescope at the Sun, even if stopped off-axis to a few inches clear aperture, would be just asking for trouble. These telescopes have internal parts of plastic, metal, glass and glue, which would very likely be variously scorched, melted, detached and/or cracked. To add to the woes, fumes or smoke from charred paint, plastic or glue would stain everything inside the telescope, including the optical surfaces. The repairs would be very costly.

Eyepieces used to project the Sun's image are also vulnerable to damage because of the concentrated heat radiation passing through them. In particular, the optical cement used to join glass lens elements together can become discoloured and the glass elements themselves can be cracked, particularly by differential expansion. I recommend that the eyepiece you choose should have the longest possible focal length. This is in order to have the maximum separation between the lens elements and the plane within which the Sun's heat is most concentrated. If the eyepiece has a rubber eyeguard fitted then remove it lest it melts or burns if the eyepiece body gets hot.

I am pleased to report that I have never had the slightest damage to any eyepiece I used. Even so, I recommend that you use only your simplest and cheapest eyepieces for projecting the Sun. Never gamble with anything you cannot afford to lose. If you use a star diagonal in order to project the light sideways at right angles to its original direction then, of course, there is always the chance this could be heat-damaged, too. To sum up, please always bear in mind that anything placed near where the Sun's heat radiation is most concentrated could potentially suffer damage.

Also beware that anything at the same place may get hot enough to burn you. In particular, tentatively touch the eyepiece to test that it is not too hot to hold before removal at the end of the observing session. **If you choose to use this method of observation proceed with caution. I repeat, you have to accept full responsibility for the risks to yourself and to your equipment**.

Here is a formula which will predict the approximate diameter, D, of the Sun's image on your projection screen:

$$D = \frac{F}{107}\left(\frac{d}{f_e} - 1\right)$$

where F is the principal focal length of the telescope, f_e is the focal length of the eyepiece and d is the distance between the eyepiece and the projection screen. All these quantities need to be in the same units; for instance all in millimetres. The formula is approximate, partly because the apparent diameter of the Sun varies a little during the course of a year, partly because the actual focal length of the telescope – and especially the eyepiece – is likely to be a little different from the manufacturer's stated value, and partly because the eyepiece–screen distance should really be measured from a specific optically defined position (called a nodal plane) rather than just from the front of the eyepiece. It is accurate enough to be useful as a predictive formula, though.

Perhaps an even more useful form of the equation is the following, which will allow you to choose an eyepiece–projection-screen distance, d, having decided on which telescope and eyepiece you are going to use and what diameter you want the projected image of the Sun to be:

$$d = f_e\left(\frac{107\,D}{F} + 1\right)$$

To give an example, if I wanted to project the Sun's image with my 1220 mm focal length telescope using my 30 mm focal length eyepiece and desired the Sun's image on the projection screen to be exactly 152 mm in diameter, then I would initially set the eyepiece–screen distance to 430 mm. If you put the figures into the foregoing equation you will see this is the necessary value of d it predicts. After initially focusing the image and checking its size, I would make any necessary tweak of the eyepiece–screen distance so that I could produce a focused solar image of exactly 152 mm diameter. Clearly you will need to build in a provision for adjusting the eyepiece–screen distance to follow the Sun throughout the year if you are always to project it to a precise diameter for the purpose of recording details on it (more about that later).

Just how big you can enlarge the image and still see solar details depends on the ambient lighting around you. If you observe outside with only a simple shade casting a shadow over the projection screen, such as that illustrated in Figure 12.2(a) then you will probably be limited to an image around one and a half times the clear aperture of the telescope before the image becomes too washed-out. A projection box like that illustrated in Figure 12.2(b) will allow the image to be enlarged much further. If the seeing conditions are adequate and the optical quality of the telescope and eyepiece are good then the image could potentially be enlarged to the point that the full diameter of the Sun is several times that of the telescope's clear aperture and still the image will be reasonably sharp.

Using 'over-the-aperture' Sun filters

A specially made filter that fixes to the sky end of your telescope can allow you to use it to observe the Sun in the normal way you would for viewing astronomical objects. It can also allow you to use any of the many types of telescope without fear of damage because the Sun's fierce heat is blocked from entering the optical tube assembly.

However, it has to be a genuine solar filter. If you come across a sheet of some material that you can put up to your eye, peer through it at the Sun and see its disk, don't even think of mounting this on your telescope. Even if that material cut down the visible light sufficiently and it gave you a sharp image, the chances are that the amounts of near-infrared and near-ultraviolet radiations streaming through it and concentrated by your telescope would seriously damage your eye. Please bear in mind that the retina you have in each eye has no pain sensors to give you any warning of ongoing damage. The damage will only become apparent after the event – when it is too late. Further, even if all seems well after a moment and you think you have got away with it, latent eye damage can sometimes take time to become apparent.

Don't be a cheapskate when it comes to safeguarding your eyesight. Invest in a proper solar filter. If you are really sure that you are up to the job, then you can make your own mount for the solar filter. You **must**, though, be sure that it is 100 per cent reliable and secure. Crucially, you also **must** ensure that you have obtained the filter material from a trustworthy and reliable source.

My heart always sinks when I see a sheet of solar-filter material held onto the sky end of a telescope with bits of cardboard and parcel tape. Even in the absence of a breeze all it needs is the tape to peel or loosen a bit while the observer is absorbed in the view through the telescope to potentially result in a lifetime of eye injury and regret.

First, the filter material. What you need is 12 μm thick polyester, which has been metallised with aluminium on both sides. This is generally known as *Mylar*. Something almost the same is *Baader solar film*. It can be obtained with various values of optical transmission (in other words what fraction of the light passes through) and the material you need should transmit only one hundred thousandth of the light. Any filter with that level of attenuation is given a rating of 'ND5'. The ND stands for neutral density (meaning all visual wavelengths are attenuated equally) and the 5 stands for the logarithm to base 10 of the attenuation value.

Your next task is to make a mount to securely hold the filter to the solid tube of your telescope. The telescope tube has to be enclosed, or 'solid', to avoid you being troubled with bright reflections from the shiny underside of the Mylar/Baader filter, so I am afraid this device is unsuitable for a skeleton-tubed telescope. In the following I shall refer to the solar-filter film as 'Mylar', even if you have obtained the very similar Baader film.

First, cut two rings or squares of flat cardboard and cut a central hole in each to form the aperture through which the filtered sunlight is to pass into the telescope. Coat one side of one of these with adhesive.

Cut a square or a disk of Mylar just a little bigger than the cardboard and lay this flat on a clean surface. Gently lay the cardboard adhesive side down onto the Mylar. Cover with a clean piece of paper and use a small book or other flat object as a light weight to gently press the Mylar and cardboard together. Leave the adhesive to set. When it has set remove the book and turn over the cardboard so that the Mylar is now uppermost.

Coat one side of the other piece of cardboard with adhesive and gently lower it onto the top of the Mylar. Position it so that the central holes and the edges of both cardboard parts all line up. You now have a 'sandwich' with the cardboard representing the 'bread' and the Mylar representing the 'filling' (admittedly each piece of 'bread' has a large circular whole central within it!). Replace the paper sheet and small book, or other gentle weight, and again allow plenty of time for the adhesive to set.

Before proceeding to the next stage carefully check that the cardboard pieces are firmly stuck and that the Mylar appears unblemished and with no pinholes or tears. Don't worry if the Mylar is wavy and looking as if it is a little slack. Despite what you might think it will not degrade the image in this state. In fact, this is much better than having the Mylar stretched tight. Trim any overhanging Mylar back to the edges of the cardboard using a very sharp pair of scissors.

The next job is to construct a robust cap or lid for your telescope's tube. The design of this I must leave to you but make sure it is sturdy and that it will properly attach to your telescope without the slightest danger of it falling off. Figure 12.4(a) and (b) shows the one I made for my square-tubed 8½-inch (216 mm) Newtonian reflector back in the summer of 1995.

When you have made the sturdy cap for your telescope, cut a circular hole in it to match the big hole in each of the cardboard pieces of your filter sandwich. Next, fashion a ring or square of stout wood or metal that has the same size and shape as each of the cardboard pieces of your filter, including the big central hole. Then offer it up to the cap, with the big holes both lining up. Drill four clearance holes through both to take the fixing nuts and bolts that will eventually hold them together.

Take the solid piece you have just made and the cardboard–Mylar sandwich and line all their edges up. Put them down, solid piece uppermost, onto a clean surface such as a sheet of paper on a piece of wood or other flat surface of no importance (since it will become marked with holes spiked into it). Next, use a thin sharp spike – the needle of a drawing compass will do very well – offered through the drilled holes in the solid piece to pierce right through the sandwich.

After cleaning and painting the cap and the solid piece you made – mat-black for the interior surfaces – assemble the filter sandwich between the cap and the solid piece, lining up the pierced holes in the cardboard with both sets of drilled holes. You should now be able to push small bolts through the entire assembly and secure it with washers and nuts.

So, a new sandwich has been formed. This time the 'filling' is the Mylar–cardboard assembly. One piece of the 'bread' is the sturdy telescope tube cap and the other is the wood or metal piece you made to the same shape as the cardboard pieces. The whole of this arrangement is now securely clamped together by the small bolts, with washers and nuts, that pass through all the components. Figure 12.4(a) and (b) should make all this clear.

Re-check the Mylar, inspecting it with a magnifying glass and holding it up to the light to ensure that it is still in good order. The process of forcing a spike through to create holes for the bolts to pass through might have disturbed the Mylar, maybe even stretched or torn it. If the adhesive you used has done its job properly, though, the Mylar should still be OK.

When you are ready to try out your new filter on the telescope proceed with caution. Having aimed the telescope at the Sun, put the palm of your hand up close to the eyepiece and check that no bright light is streaming through before you put your eye up to it. Check also that there is absolutely no sensation of radiant heat coming through the eyepiece. I recommend then screwing in your darkest filter into the eyepiece and very cautiously putting your eye up to the eyepiece. Then you can try a lighter filter.

Referring again to the arrangement I made shown in Figure 12.4(a) and (b), the clear aperture of the filter assembly is 62 mm in diameter. As you can see, I set the aperture off-axis so that the incoming sunlight would miss the telescope's central secondary mirror and the secondary support vanes. To finish the job I constructed a carry case to store the filter-cap assembly whenever it was not on the telescope. This also serves to keep the filter clean and protected from damage.

(a)

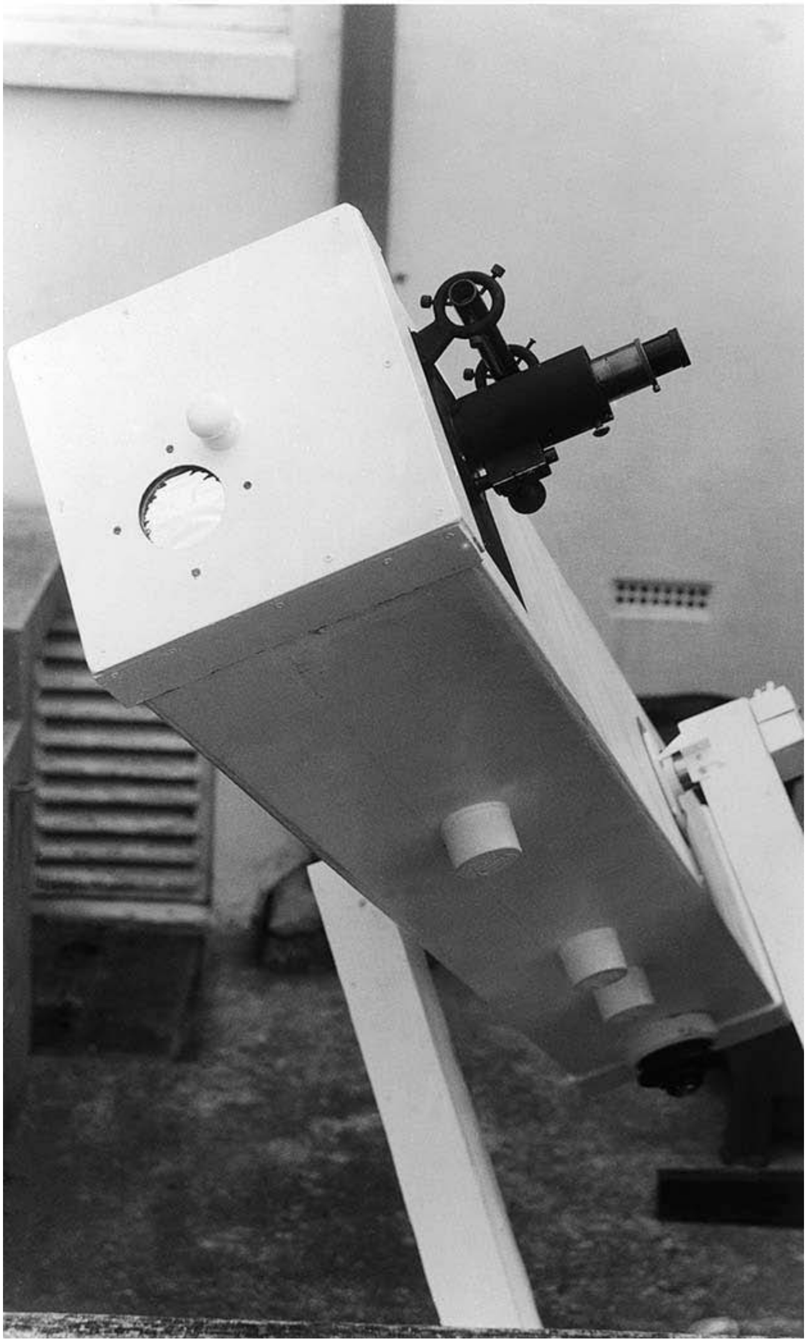


Figure 12.4 A Mylar filter is mounted in the lid that closes the tube of the author's 8½-inch (216 mm) Newtonian reflector for solar observation. A 62 mm off-axis aperture was considered adequate for visual solar observing, given the daytime seeing conditions usually experienced but a larger aperture is recommended if one is to take high resolution AVIs for stacking and subsequent processing;

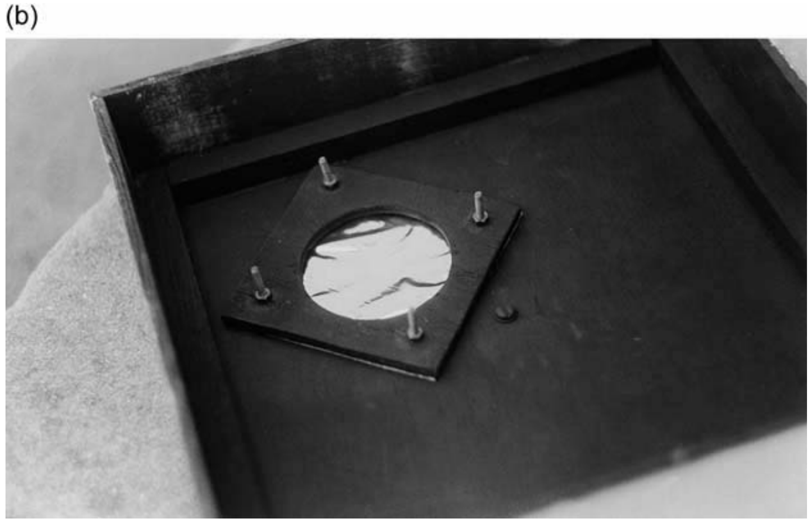


Figure 12.4 (*cont.*) (b) shows how the filter is securely mounted in the lid (the construction method is detailed in the main text).

My solar filter has been a joy to use. In all the years since 1995, I have never desired its aperture to be any bigger as the daytime seeing has proven to be the limiting factor for discerning fine details. My favourite accessories for observing the Sun with this solar filter and telescope is a glass green 'Moon Filter' filter screwed in to an 18 mm Orthoscopic eyepiece. This gives a magnification of ×93 with my 1670 mm focal length telescope. The image is just the right brightness and I find that I can comfortably see all the details visible even in conditions of better than average seeing. Yet in poor seeing conditions the image is not badly over-magnified.

Mylar transmits more light at the blue end of the spectrum than the red end (it is only approximately 'ND'), so the solar image looks a light shade of blue when seen through a Mylar filter. If this is considered undesirable then a pale yellow filter can be added at the eyepiece to give a more natural effect. Actually, an additional filter screwed into the eyepiece may be found helpful to further attenuate the light when low magnifications are used. The effect of sky haze is also reduced and the image contrast consequently improved. An orange filter will eliminate more sky haze than a yellow filter, and a red filter will do better still.

The reason I prefer the addition of a green eyepiece filter, rather than a yellow, orange or red one, is that while the image is still better contrasted than with no additional filter, some specific solar surface details (known as plage and faculae – more about them later) show up just a little better in green than through those other coloured filters.

As well as buying solar-filter material for you to fit into your homemade filter-cap, you can buy ready-made over-the-aperture solar filters designed to fit a wide range of off-the-peg commercial telescopes. The least expensive of them use Mylar or Baader film as the filter material. Others you can buy are made from a thin sheet of optical-quality flat glass with the required reflective coating vacuum-deposited on it. This type is often known as an *Inconel filter*. In terms of quality of image, the glass-type filters do not produce the advantage you might think, given their cost. What you can say about them is that they are less easily damaged than Mylar or Baader film. Baader film produces a whiter image than conventional Mylar and most Inconel filters produce an orange-yellow solar image.

The following is a list of the websites of current suppliers of ready-made solar filters, some of them also supplying filter material:

Baader Planetarium:	www.baader-planetarium.com
Celestron International:	www.celestron.com
Kendrick:	www.kendrick-ai.com
Orion Telescopes & Binoculars:	www.telescope.com
Roger W. Tuthill:	www.tuthillscopes.com
Thousand Oaks:	www.thousandoaksoptical.com

Provided it is securely held onto the telescope and the filter material is genuinely solar-safe, an over-the-aperture solar filter offers a good way of observing the Sun. You will be able to see the most delicate and lowest contrasted details much easier than by using the projection method.

Locating the Sun through your telescope

When it comes to aiming your telescope at the Sun, you certainly can't look through either the telescope or its finder unless a specially made solar filter has been fitted to the sky end of them. Neither is it a good idea to squint along the telescope tube. A much better procedure is to move the telescope tube while watching the shadow it casts onto the ground or onto a wall behind it. If you do your best to minimise the size and shape of this shadow you will then achieve pointing the telescope to within a degree or two of the Sun. Admittedly, any shade, screen or projection box fitted to the telescope can make this more difficult.

A card momentarily held 10 or 20 cm behind the finder will then show where the Sun is in relation to the finder's field of view (the finder projecting the solar image). If no solar image is visible straight away, simply minimise the shadow the finder assembly casts onto the card. Then the projected solar image will appear and you can centre it. This will allow you quickly and easily to refine the pointing of the main telescope until the Sun enters the field of view of the eyepiece that is plugged into it.

If you have arranged a projection screen fixed to the main telescope then at least part of the solar disk should be visible on it at this stage. If you are observing using a proper solar filter fitted to the sky end of your telescope, cap the finder-scope before looking through the main instrument – **after first double-checking that the solar filter is in place**. I must admit that on one occasion I almost put my eye to the eyepiece when a brilliant glint of light from the eyelens alerted me just in time that I had forgotten to put the filter on!

Assuming the filter is in place, the Sun should at least be partly within the field of view of a wide-field eyepiece. A final tweak to the telescope's pointing, maybe changing its eyepiece and focusing, and you are ready to begin your observation.

Image orientations

If you are sending in your observations to the director of the solar observing section of your national astronomical society then you should submit those observations in the format the director requires. This will usually include a stipulation as to the preferred orientation of the image. For instance, the director of the solar observing section of the British Astronomical Association requires that wherever possible all images are sent in with the same orientation as the naked-eye view in the Earth's northern hemisphere – in other words with north uppermost and with east to the right.

However, what you get using your telescope depends partly on the telescope (in particular, does it have an even number or an odd number of reflections in the light path) and partly on which arrangement you use to view the image. Figure 12.5(a)–(e) covers the most common situations. In each case the image will be as seen or projected through a standard refracting telescope, or through a conventional two-mirror Newtonian reflector, or a Schmidt–Cassegrain or Maksutov–Cassegrain telescope.

Whatever the arrangement you use, you can check the orientation by letting the image drift with no telescope drive running. The image will move to the **west**. Then nudge the sky end of the telescope just a little in a direction towards the north celestial pole. The direction the image moves towards in response defines **south**.

12.4 THE SOLAR PHOTOSPHERE AND MAGNETOSPHERE

If you use a telescope to project the Sun's image, one thing that will become apparent straight away is that the Sun's photosphere darkens noticeably towards its edge. This effect is called *limb darkening*. It occurs because the photosphere is actually a layer of plasma a few hundred kilometres deep, rather than being a solid shell or surface.

As well as emitting light because of its high temperature, the material of the photosphere also absorbs light. The temperature, density, and thus the brightness, of the photosphere increases with depth. At the top of the photosphere the temperature is about 4400 K. The light produced

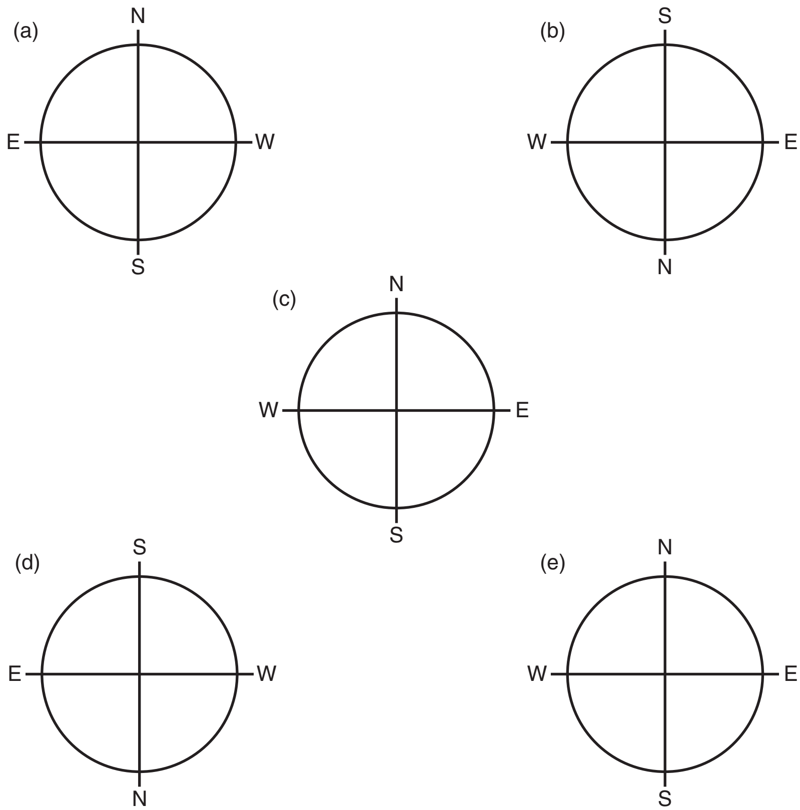


Figure 12.5 The orientation of the image for five situations in using a normal astronomical telescope, compared to (a) which shows the normal naked-eye view. (b) Direct view using a normal eyepiece through a normal astronomical telescope. (c) Image projected onto a reflective screen. (d) View through an eyepiece using a star diagonal and viewed from the side. (e) View through an eyepiece using a star diagonal and viewed from the top.

there is both redder and less bright than it is deeper down. When we look at the centre of the solar disk we can see down to a depth of a few hundred kilometres before the photospheric material becomes totally opaque. The temperature there is about 6400 K. The majority of the light we receive comes from an intermediate region within the photosphere where the temperature is about 5800 K. The light produced there has the 'creamy-white' colour we are so familiar with.

When we look near the limb we are effectively looking along a greater path-length of solar material and so cannot see to as great a depth below the top of the photosphere before the radiation is totally absorbed. Figure 12.6(a) shows the principle. Since the higher layers in the photosphere are not as hot as the lower layers they are also not as bright. Hence the darkening we see towards the limb. For the same reason the colour of the Sun's photosphere takes on a distinctive flesh-brown tint close to the limb. This is very noticeable when projecting the Sun's image onto a screen and can sometimes show up well on whole-disk photography (see Figure 12.6(b)).

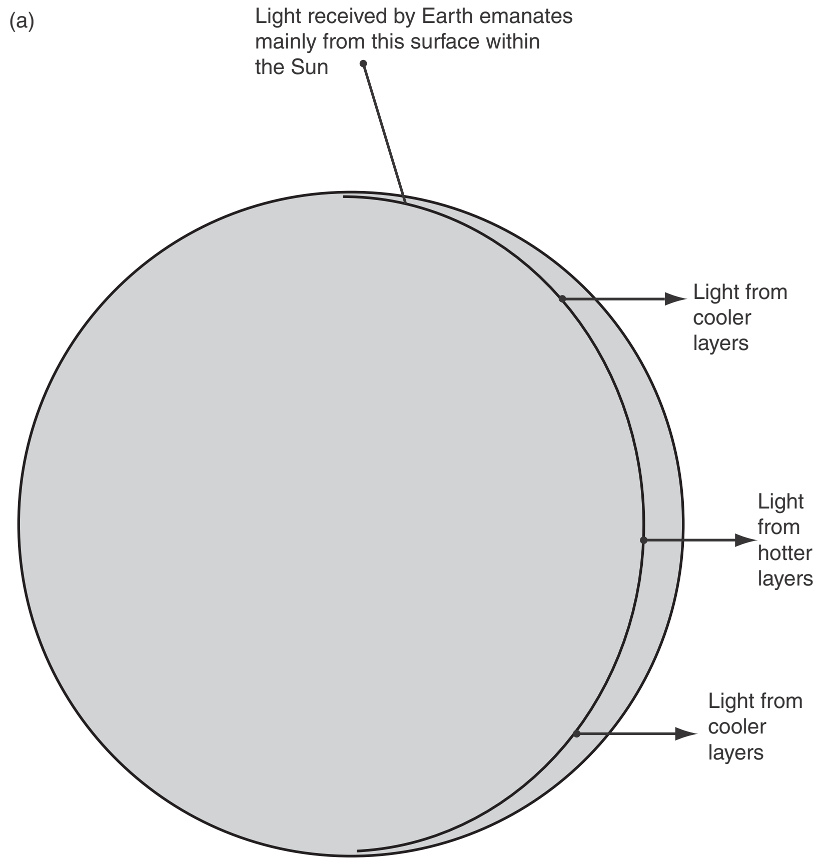


Figure 12.6 (a) A figurative illustration of the cause of limb darkening. Of course, in reality the depth to the surface from which we see most of the Sun's light would be far too small to show at this scale. It is here vastly exaggerated for the sake of making the explanation clear. Please refer to the main text for more detail.

The way the eye–brain combination works results in limb darkening being much less obvious when the Sun is observed by direct vision though the telescope (safely filtered, of course!). Incidentally, a few hundred kilometres is a tiny fraction of 1.4 million kilometres. So, despite the fact that the photosphere is really a thin layer of partially opaque plasma, the Sun's edge, or limb, still seems very sharply defined through the telescope, rather than fuzzy.

The best images reveal that the photosphere is not a smooth and uniform layer but is actually made up of a seething mass of turbulent cells (see Figure 12.7). These give the Sun a grainy appearance. These bright *granules* are typically around 1000 km across and are the tops of turbulent columns of material rising from the lower, hotter, layers. The solar material cools and mushrooms outwards, then falls between the rising columns. The best images clearly show the thin, darker, inter-granular lanes of descending matter that surround each granule. The average lifetime of a granule is around a quarter of an hour.

(b)

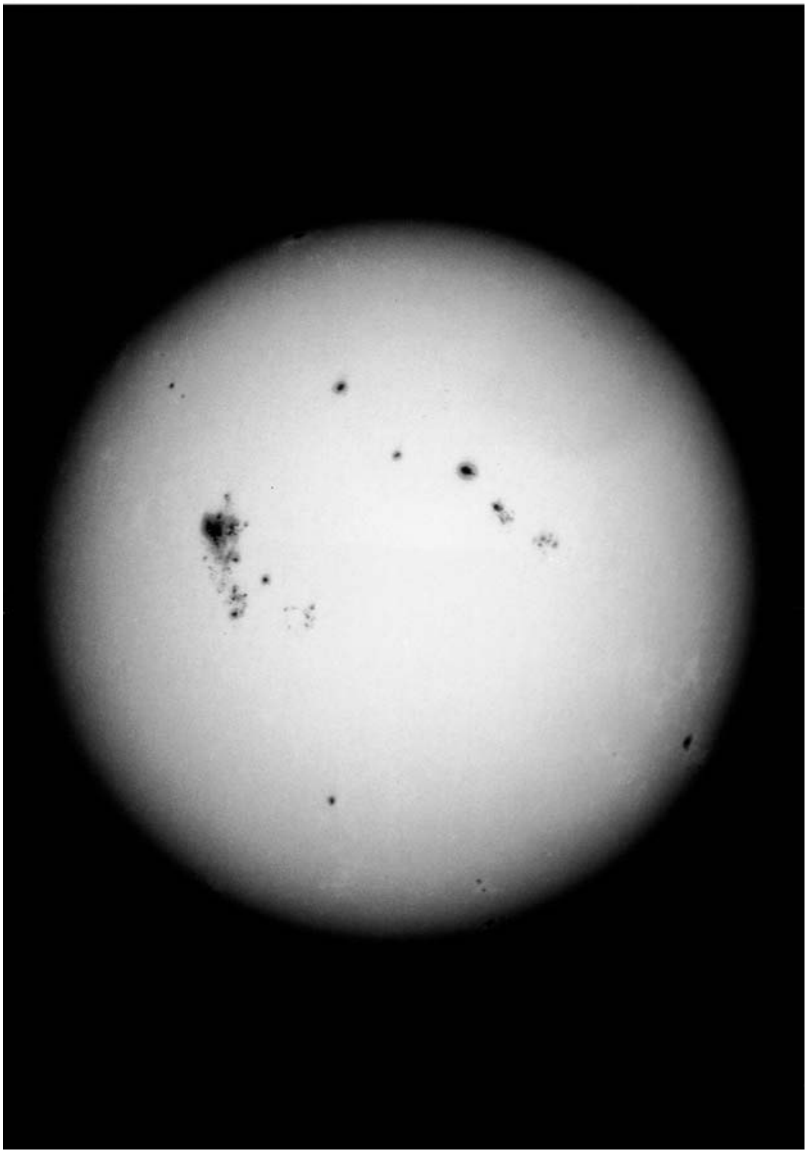


Figure 12.6 (*cont.*) (b) Limb darkening is well seen in this photograph of the Sun taken by Nick James on 1989 June 16^{d} 06^{h} 34^{m} UT. The telescope used was a 50 mm refractor stopped down to 35 mm, with an over-the-aperture Mylar filter. A 25 mm focal-length eyepiece was used to project the image to f/70. A 1/500 second exposure was made onto Kodak's now discontinued Technical Pan 2415 film. As well as the limb darkening, many sunspots are apparent. The Sun was near the height of its activity cycle. The large spot group visible produced a number of bright solar flares.

Larger-scaled convective motions produce *supergranules*, which are rather similar to granules but on average about thirty times larger. The chief flow of matter in supergranules is horizontal, spreading out from the centre of each cell. There is, however, an upward flow at the centre of the cell and a weak downward flow of matter at the cell boundaries. Individual cells last around half a day to a day. Conventional

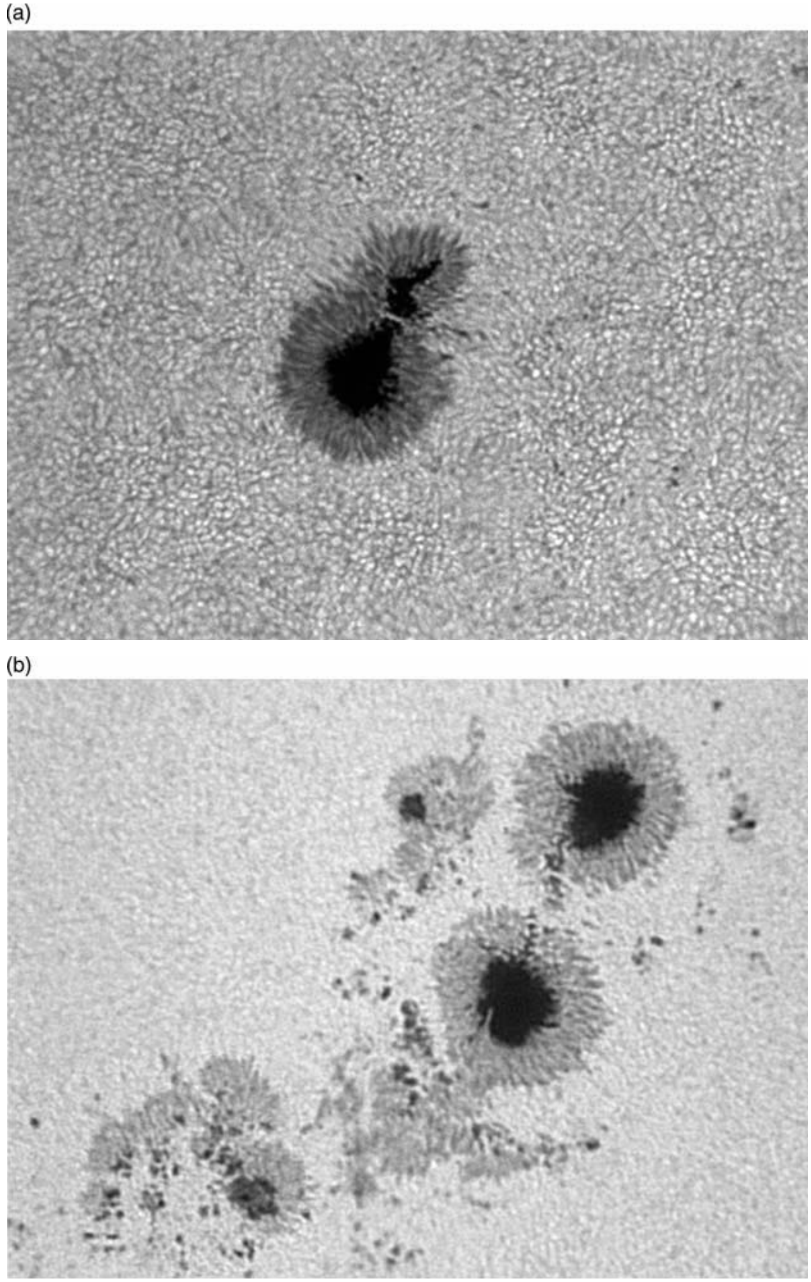


Figure 12.7 (a) Notice the solar granulation on the solar photosphere in this image of 'Active Region 0907' taken by Damian Peach on 2006 September 10^{d} 15^{h} 36^{m} UT using a 6-inch (152 mm) achromatic refractor working at an effective focal ratio of f/45, fitted with a Baader ND5 solar filter, and recorded with a Lumenera Lu075M camera. Image captured and processed using *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*. This remarkably good image well shows the structure in the penumbra of the large sunspot;
(b) Again the solar granulation is apparent in this close-up view of a complex sunspot group 'Active Region 0652' taken by Damian Peach on 2004 July 23^{d} 06^{h} 33^{m} UT using a Meade 5-inch (127 mm) semi-apochromatic refractor working at f/27, fitted with a Baader ND5 solar filter, and recorded with a Philips ToUcam Pro webcam. Image captured and processed using *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*.

photographs do not show up the supergranular cells, special techniques being needed to reveal them. Other large features are often to be seen on the Sun, particularly *sunspots* and the *faculae*, these being transient features intrinsically involved with the Sun's powerful magnetic field.

Figure 12.8 Notice the light areas of solar faculae, along with 'Active Region 0652' recorded on 2004 July 28^{d} 07^{h} 40^{m} UT. This is the same active area shown five days earlier in Figure 12.7(b). Notice the changes to the sunspots as the complex sunspot group has moved across the solar disk and now nears the Sun's limb. This time Damian Peach has used a Vixen FL80s (3.2 inches aperture) apochromatic refractor working at f/29 and fitted with a Baader ND5 solar filter. The image was recorded on a Philips ToUcam Pro webcam. Image captured and processed using *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*.

(Figures 12.6(b) and 12.7(a) and (b) show sunspots very well, though faculae less so. For a better look at faculae see Figure 12.8.

The *SOHO* space probe, as well as others including ESA's *Ulysses* and NASA's *TRACE* (*Transition Region And Coronal Explorer*), *STEREO* (*Solar Terrestrial Relations Observatory*), the Japanese probe *Hinode* and NASA's *Solar Dynamics Observatory* (*SDO*) – launched respectively in 1990, 1998, 2006, also 2006, and 2010 – have revealed much fine detail impossible to see from the Earth. The arsenals of remote-sensing equipment carried by each of these probes have revolutionised our investigations of the Sun, our quest for the fine details of how it operates, and its interactions with the rest of the Solar System. We now possess a vast wealth of detailed information. At the moment, though, our level of understanding of how it all works still lags far behind!

Since the early days of solar observing we have known that the Sun does not rotate on its axis in the same manner as a solid body. Its equatorial regions take 25 days to go once round, but this period increases to about 35 days near the poles. Since the Sun is almost entirely composed of the electrified gas we call plasma, any motion of its material gives rise to enormous electrical currents because electrical current is simply the movement of electrical charges. Further, an electrical current creates a magnetic field. The bigger the current, the bigger the magnetic-field strength.

The differential rotation of the Sun and the turbulent nature of its outer layers cause its magnetic field to be very strong and very complicated. The differential rotation tends to wind up the general north–south field into *flux tubes*, which approximately wrap around the Sun. These tend to break out of the photosphere in complicated loops and twists.

The smaller-scale seething motions of the plasma in the outer layers of the Sun add further to the small-scale complexity of the magnetic field. The value of magnetic-field strength in the polar regions is usually around 1×10^{-4} T (teslas), which is roughly twice the field strength at the surface of the Earth. Elsewhere, the magnetic field is very much stronger, reaching a value of over 0.3 T at the sites of sunspots (discussed in the next section). To complicate matters even further, the north–south polarity of the Sun reverses over a cycle of about 22 years.

If it strikes you as preposterous that we can know anything about the Sun's magnetic field, then I should explain that there is a phenomenon in physics called the *Zeeman effect*, which we can put to use. I won't take up pages describing the mechanism here as it is just the end result which is important to us. The presence of a magnetic field causes a splitting of the spectral lines produced by whatever is emitting the spectrum. This can be visible if the spectrograph used has a high enough resolution. Basically, the wider the split in the spectral lines, the stronger the magnetic field must be in the region emitting the light. So, we actually have an optical way of measuring magnetic fields on the Sun! It was George Ellery Hale that pioneered our investigations of the Sun's magnetosphere with equipment he designed and installed at the Mount Wilson Observatory.

I have already indicated some of the complex interrelations between magnetism and plasma. In fact these are crucial to understanding our daytime star, so they deserve expanding on. If you were to heat a glass pan of a liquid such as vegetable oil you will see movements within the oil due to convection. The plasma in the photosphere is similarly heated from below and is in constant convective turmoil. Plasma in motion generates a magnetic field. Yet a magnetic field constrains the movements of plasma – it wants to follow the field lines, rather than crossing them. There is a complex interplay.

Though the Sun's overall magnetosphere looks simple when viewed from afar, the picture close to the solar surface is incredibly complicated. All the features and phenomena that we observe on our Sun result from the intertwined and interdependent interactions of the magnetic fields and plasma.

12.5 SUNSPOTS, PORES, FACULAE AND PLAGE

The earliest records we have of small dark areas – sunspots – being seen on the Sun go back over 2000 years to the civilisation in ancient China. The observations were, of course, of the spots that were large enough to be seen with the naked eye when the disk was sufficiently dimmed by a thick haze or fog, especially near sunset and sunrise. Smaller sunspots were recorded from early in the seventeenth century by those using telescopes.

In the mid-nineteenth century the German astronomer Heinrich Swabe recognised that the number of sunspots appearing on the Sun's disk varied over a cycle of roughly eleven years. At the minimum of each cycle the Sun could go for long periods without a single spot being seen. At times of cycle maxima parts of the Sun's disk were often very heavily peppered with sunspots, some very large and complex in shape. As previously mentioned, George Ellery Hale pioneered our magnetic investigations of the Sun. In the process he discovered the strong magnetic-field concentrations associated with sunspots. He also linked the sunspot cycle to the Sun's overall magnetic cycle.

A typical sunspot consists of an irregularly shaped dark area, the *umbra*, surrounded by a lighter area, the *penumbra*. This is well shown in Figure 12.7(a). The penumbra can be round but it is most often very irregular in outline, again as is clearly seen in Figure 12.7(a). The umbra and penumbra are both darker than the photosphere because they are at lower temperatures. Remembering that the average photospheric temperature is 5800 K, the penumbra of a typical spot has a temperature of around 5500 K, while the umbra is usually not much hotter than 4000 K. Thus, a sunspot appears dark only by contrast. If it could be seen shining by itself it would appear very bright indeed. The very smallest sunspots appear as little more than small dots of dark umbrae without any associated penumbrae. These are generally termed *pores*.

Sunspots are carried round by the rotation of the Sun. They form, develop and change, and finally die away over a period of time. The larger spots can survive for two or three months. The smallest of them, such as the pores, might last just a few hours.

As mentioned earlier, the number of sunspots on the solar disk varies over a cycle of approximately eleven years. The latitudes where most of the spots occur also change over the cycle. At the beginning of an 11-year period sunspots mostly occur near latitudes of 35° north and south. By the end of the period they mostly occur just a few degrees north and south of the equator. As the incidence of these near-equatorial spots decline towards the end of one sunspot cycle, the next sunspot cycle begins with the occurrence of its first high-latitude spots.

Sunspots form where tight bundles of magnetic-field lines loop in and out of the solar surface. They can form as single spots but there is a strong tendency to form in pairs of opposite magnetic polarity. The spots are carried round by the rotation of the Sun. The spot that leads has the same magnetic polarity as the overall magnetic field in that hemisphere.

As to the whys and hows of sunspots, well, the story is complicated, added to which we do not yet have all the theory securely nailed down. Here I will give the explanation as best as we understand it at present.

First, where the bundles of magnetic-field lines pass below the solar surface they suppress convection. They also displace a little of the plasma, reducing the density of what is left. It is by convection that most of the energy reaches the photosphere from the deeper levels. So, by impeding convection, the magnetic-field lines impede the rate of flow of energy to any area of the solar surface where they are most concentrated. Hence, the temperature of the photosphere at that site drops until equilibrium is reached, when the energy radiated per unit area from the site is then equal to the energy per unit area being supplied to it from below. In this way the looping magnetic-field-line bundles create cooler patches in the photosphere at the sites where they pass in and out of the solar surface. These cooler patches are the sunspots.

The lowered density of the plasma in the sunspots makes them a little more transparent than the surrounding photosphere. When we observe sunspots near the limb of the Sun we are seeing them presented to us nearly edge-on. Due to their relative transparency we can see a little further in than the average photosphere and they often then appear to be crater-like depressions in the solar surface. This is called the *Wilson effect*.

The fact that the sunspot cycle is half the period for the magnetic reversal of the Sun is definitely not a mere coincidence. However, I must say that at present there are several different theoretical models all currently considered as strong candidates for explaining the sunspot cycle and global magnetic polarity change. Currently popular are those that relate the formation of sunspots to sub-surface flows of plasma in each hemisphere, which are collectively known as the *meridianal flow*.

I could spend very many pages discussing all these theories and their variants but this would not inform nor help your solar observing one jot (and I am already way over the publisher's page allocation for this book!). Also, the Sun's behaviour often defies the predictions made for it by this model and that model. The theorists then go back to their computers and try again. Such has been the case with the most recent solar minimum, which lasted much longer than expected. So, for now let us leave the theories to the theorists and concentrate on matters more relevant to our observing experience.

I have already referred to faculae and shown a good example in Figure 12.8. They are mainly associated with the sunspots but show up best when seen against the darker limb. They are actually small regions of higher temperature than the average for the photosphere.

Faculae often have associated with them clouds of hot material higher up in the chromosphere. These hot clouds are termed *plage*. Plage appear to be caused by local intensifications of the magnetic field and they are certainly areas of concentration of energy. Plage appear more soft-edged and cloud-like than faculae if they are visible at all. I almost never see them in white light but they are often visible when the Sun is observed in specific wavelengths of monochromatic light (more about that later).

An *active area* on the Sun is usually marked by clusters of sunspots. Here the magnetic field lines are concentrated in the sunspots and necessarily this leaves weaker magnetic fields in the immediately adjacent regions. These are the regions where faculae occur. In this case the local magnetic field creates a slightly dimmer and slightly more transparent small patch on the photosphere (you could think of this patch as a failed sunspot) and the brighter photospheric light shining sideways into this region illuminates its 'containing walls'. These bright walls we see as the faculae.

12.6 RECORDING THE SOLAR-DISK DETAILS YOU CAN SEE VISUALLY

Of the purely visual techniques, projecting the Sun's image allows for the two most straightforward ways to record accurately the positions of sunspots and any other visible features present. The easier of these two ways is to draw directly onto the focused image. However, this method does demand that the telescope and the projection board are particularly rigid. It is no good if every touch of the pencil causes the image of a sunspot to dissolve into jitters or to rapidly lurch back and forth like a dice in a shaker.

Years ago I successfully used the direct drawing method with the 8-inch (203 mm) refractor of the Jeremiah Horrocks Observatory in Lancashire, England. Mind you, that particular telescope is a mid-nineteenth century refractor of typical massive construction of the period. Few of the off-the-peg telescopes of today are anywhere near as rigid. When observing the Sun I stopped this large telescope down to 4 inches aperture. Figure 12.9 shows one of my observations with that telescope recorded on a standard BAA solar section report form (otherwise known as an *observation blank*).

The circle on the observation blank was exactly 6 inches (152 mm) in diameter. This size became the universal standard long ago. Your first task is to get the solar image to fit this circle exactly. Please see my earlier formula that will help you select the eyepiece and eyepiece–projection-screen distance to achieve this.

Next, you need to set the east–west orientation. This blank had the correct cardinal points already marked and labelled to suit an image projected through a refracting telescope with no star diagonal. Prior to use you should draw pencil lines to join the W–E and the N–S cardinal points. Having got the Sun's image to exactly fill the 152 mm diameter circle, move the telescope so that the extreme southern or northern limb of the Sun is just in contact with the W–E pencil line. Alternatively, use a

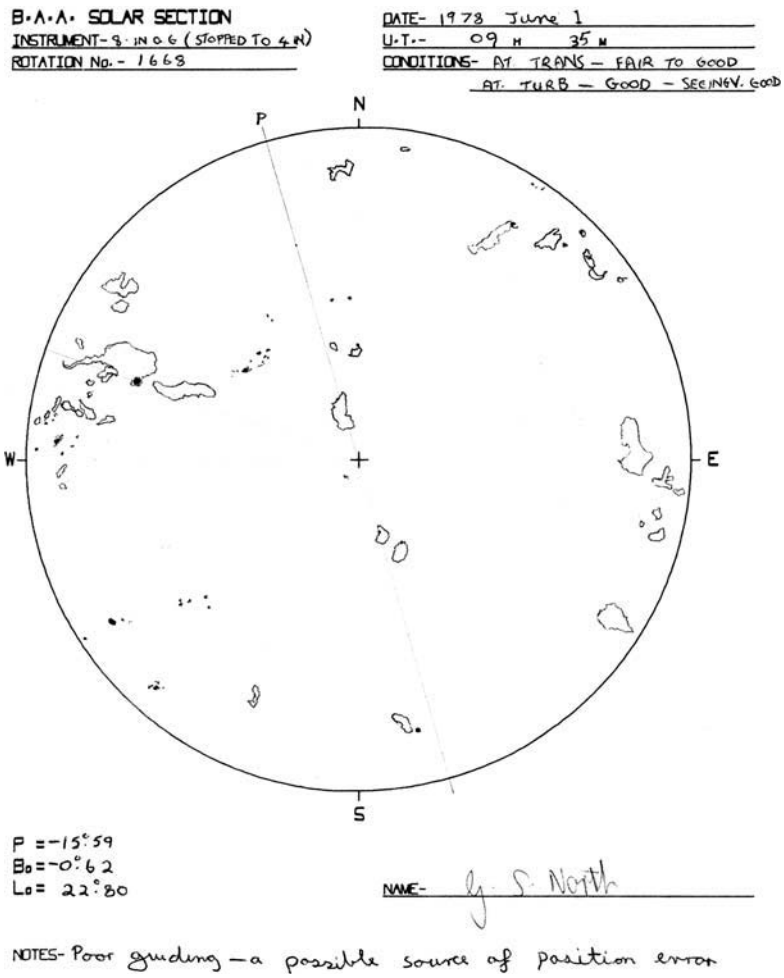


Figure 12.9 A solar observation made by the author on 1978 June 01^d 09^h 35^m UT. He used the 8-inch (203 mm) Cooke refractor at the Jeremiah Horrocks Observatory in Preston, Lancashire, UK. The telescope was stopped to 4-inch (102 mm) aperture and the image was projected directly onto a board carrying the report form blank. The solar-disk details were then traced directly onto this blank. Notice the large number of faculae recorded, together with several groups of small sunspots and several isolated pores.

small sunspot instead of the Sun's limb. With the telescope drive turned off the Sun's limb (or the selected sunspot) should just remain in contact with the W–E line as the Sun's image tracks across the observation blank. Adjust the orientation of the projection board and keep repeating until it passes this test.

Having got the orientation of the observation blank correct, switch on the telescope's drive and move the telescope to exactly re-centre the Sun's image in the blank. When all is correct you can proceed to draw in the details. Draw the sunspots as they appear. Any faculae, along with any instance of the rarely visible plage, can be represented by pencil outlines as shown in Figure 12.9. An older convention you might like to continue is to use a yellow pencil to draw the outlines of faculae and any plage present. Be prepared to repeatedly tweak the pointing of the telescope as necessary during the observation period in order to keep the Sun's image exactly within the drawn circle.

Various details should be added to your observational report form. Along with the date and time, a note of the equipment used and the observing conditions are essentials. It will also greatly help anyone wanting to analyse your observation to include three other items of data that you can obtain from an ephemeris. These are P, B_0 and L_0.

The parameter P is the apparent inclination of the Sun's rotation axis to the north–south line. If you look again at Figure 12.9 you will notice that P had the value of $-15°.59$ at the time of my observation. This means that the northern end of the rotation axis is inclined westwards by this angle (as measured from the centre of the Sun's disk). If the northern end of the rotation axis were tilted towards the east then P would have had a positive value. Remember, P is **positive** when the Sun's north rotation pole appears inclined to the **east**.

The parameter B_0 is the heliographic latitude of the centre of the Sun's image. The term 'heliographic' refers to co-ordinates on the surface of the Sun. It follows the usual convention of northerly latitudes being positive. At the time of my observation, B_0 had a value of $-0°.62$, as is shown on Figure 12.9. This means that the centre of the projected image actually coincided with a latitude of 0°.62 south on the Sun. In other words the southern rotation pole of the Sun was tilted by this small amount towards us – and of course the northern rotation pole of the Sun was tilted away from us by this amount.

Similarly, L_0 is the heliographic longitude that coincides with the centre of the Sun's image. It can have any value between 0° and 360°. As you will see from Figure 12.9, at the time of my observation a part of the Sun's surface with a latitude of 22°.80 happened to coincide with the centre of its image – and so also with the centre of my drawing.

Another useful piece of data is the *Carrington rotation number*. Originated by Richard Carrington in 1851, whenever the value of L_0 crosses from 360° to 0° the rotation number goes up by one. You will notice that the rotation number for the date and time of my observation was 1668. As I write these words the Sun has rotated more than 430 further times on its axis since that day in 1978. As is the case for the other data, the current Carrington rotation number can be found from an ephemeris.

It is instructive to draw a pencil line across the blank that represents the Sun's rotation axis. This is easily measured off from the centre of the disk using a protractor. It is usual for the line to be labelled P, as I have done in Figure 12.9.

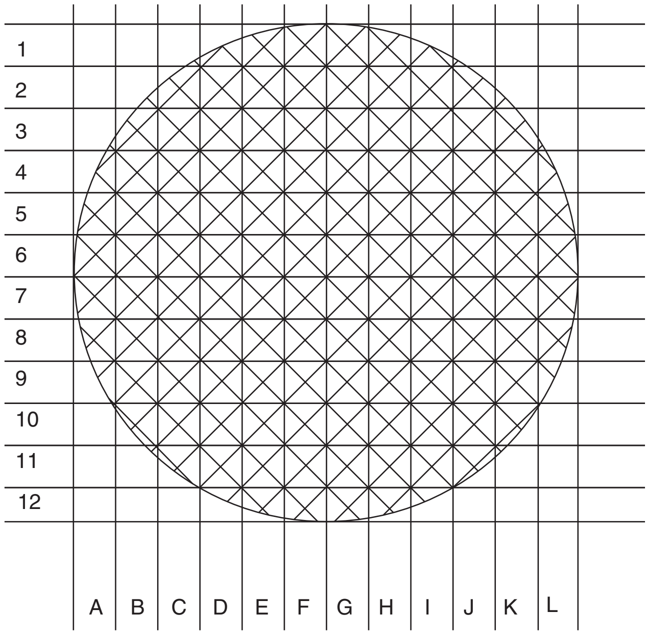


Figure 12.10 A grid like this is suitable for recording the positions of sunspots in a projected image. It is used on the telescope projection board and another copy under the observer's observation blank as described in the main text.

If the telescope and drawing board assembly are not rigid enough for direct drawing then, instead of a blank circle on the drawing board, a circle that is crossed with a grid of faint lines (see Figure 12.10) can be used. The squares of the grid lines are identified by numbers and letters drawn along the bottom and up the side of the circle, respectively. For instance, a square near the middle of the grid might be G7, and so on.

Place a sheet with a 152 mm circle and heavily marked grid lines underneath the report form, and carefully align the blank circle on the report form with the outline of the one underneath. The circle and grid underneath should faintly show through. Make sure that the centre line through the grid is aligned with the N–S line on the drawing. Carry out the same alignment and orientation procedure as before with the circle-grid on the projection board.

Provided you are always careful to preserve the alignments, features that appear on the solar image can be pencilled onto the corresponding positions on the observation blank. For example, a sunspot that appears exactly in the middle of the square D4 on the telescope's projection board is drawn as accurately as possible onto the observation blank over the middle of the square D4 as defined by the grid showing through. If you take the greatest care you can achieve millimetre accuracy in placing the solar features on the observation blank by estimating fractional positions within the squares.

The safely filtered direct view of the Sun through the telescope has the advantage that the lower contrasted and more delicate features are more easily seen than by projection. However, accurately recording the positions of the details on the disk is then problematic. A very laborious drift-timing technique was invented by the solar observing pioneer Richard Carrington in the mid 1800s. It involves using a crosswire eyepiece plugged into the telescope. The eyepiece is turned until one crosswire is orientated north–east to south–west. Of course, the other crosswire then lies south–east to north–west. The telescope is undriven and the solar features are timed as they cross each crosswire.

Then comes the really onerous bit – the reduction of the times you recorded in order to derive positions. I certainly do not have the space to go into this obsolete method here. If you are curious you could look up the excellent paper 'Carrington's method of determining sunspot positions,' by E. H. Teague in the April 1996 issue of the *Journal of the British Astronomical Association*.

If you have the necessary skills, you could draw selected very small areas of the solar surface showing the details seen. For your results to be scientifically worthwhile, though, your skill level must approach that of a professional artist-draughtsman. For most of us these days the best way of recording fine details on the Sun is by taking photographs.

12.7 PHOTOGRAPHING THE SUN IN 'WHITE' LIGHT

Beware! Any camera or other imaging equipment that is attached to an unfiltered telescope turned towards the Sun will be instantly ruined. Of course, the ND5 strength Mylar, Baader and Inconel filters for visually observing the Sun can certainly be used on telescopes in order to do solar photography in full safety for yourself and your camera equipment.

You can even get ND4 filters that allow 10 times as much light through as ND5 filters in order to reduce exposure times, which will give you a better chance of beating turbulent seeing and capturing a sharp image. The ND4 filters are still safe for your equipment but they let too much radiation through for direct vision. If you have one of these please take very special care that you never mistakenly put the wrong filter onto your telescope if you intend looking through it. You can potentially get very good images of the Sun even if you stick to using a visually safe ND5 filter, so that is what I recommend.

A CCD astrocamera with a large imaging area or a typical DSLR camera will allow you to obtain full-disk images of the Sun if the smallest dimension of the CCD is no less than the effective focal length of the telescope divided by 107. Please consult Chapter 3 for more about principal-focus photography, including how to gauge the potential image resolution obtainable.

Many DSLRs and other digital cameras will allow you to take video sequences. Subsequent processing in *AviStack* or *RegiStax* of short sequences (limited by the file size of the AVI) will allow you to obtain images with the maximum resolution possible. This resolution will probably be limited by the pixel size of the camera for photography at the principal focus. See Chapter 4 for more about that.

Enlarging the primary image (as described in Chapter 3) will allow you to increase the potential resolution. The practice of taking AVIs using a fast-frame-rate camera then really comes into its own (see Chapter 4) and many amateurs are achieving absolutely stunning results this way using relatively small-aperture telescopes. You can see what can be achieved by the images presented in this chapter. I should add that if you use the best techniques there is some advantage to using a larger aperture than you need for visual observing, maybe up to about 6 inches (152 mm), and perhaps even more under exceptionally good seeing conditions.

12.8 DERIVING THE POSITIONS OF FEATURES ON THE SUN FROM YOUR OBSERVATIONS

I mentioned in Section 12.6 the now-obsolete timing method invented by Carrington. This does have the advantage that accurate positions can be obtained even when using an undriven altazimuthly mounted telescope. However, the timing process and the subsequent mathematical reduction procedure are laborious, especially when there are many features to measure on the Sun.

The latitudes and longitudes of sunspots and other features on the Sun can be derived by making simple measurements of the drawings made by the projection technique (also described in Section 12.6) or from photographs (see Section 12.7) but again some laborious mathematical reductions are also required. I am sure that few, if any, observers now use this method but I have covered this procedure in full, including a worked example, in my book *Advanced Amateur Astronomy*, the second edition of which was published by Cambridge University Press in 1997. In addition, I should say that those who like to create their own computer programs can easily use the basic mathematics in a program to automate the reduction procedure.

Most observers who wish to derive the heliographic positions for their recorded solar features use an overlaid grid on a transparent sheet and some additional simple arithmetic to achieve acceptably accurate results. There are a number of variants of these grids. *Porter's disk* is a single grid which is used in conjunction with an auxiliary table. The other commonly used grids, the *Thompson/Ramaut/Ball disks*, the *Stoneyhurst disks*, and the *Ravenstone disks* each come in a pack of eight to cover the values of B_0 from 0° to 7°, and of course to −7° (see Figure 12.11). The observer selects the grid with the closest value of B_0 corresponding to that at the time of the observation to overlay the drawing or photograph. Your national astronomical society solar observing section director/co-ordinator ought to be able to supply you with a set of that observing group's preferred grids, or at least tell you where you can get them from. These should also come with instructions for their use.

If you can scan in your drawing or photograph (or maybe it is an image you already have in your computer) you can use the *WinJUPOS* program to analyse your observation for heliographic latitudes and longitudes (and do a variety of other analyses) in the same way as you can for the planets. There are also some other free downloadable programs which are easier to understand and use than *WinJUPOS*. In fact, for charting sunspots and determining latitudes and longitudes I recommend either *Tilting Sun*, at: www.atopics.co.uk/tiltsun.htm, or *Helio* on Peter Meadow's website at: www.petermeadows.com. The latter one has my special recommendation as it is particularly easy to use and includes a number of very useful features.

12.9 MEASURES OF SOLAR ACTIVITY

There are several measures of solar activity you can calculate from your own observations. First, the *Relative Daily Sunspot Number*, *R*, sometimes still known by its older name of *Wolf Number* is established by counting both the number of sunspot groups on the solar disk, *g*, and then counting up the total number of individual sunspots, *f*, observed on one day and using these figures in the following equation:

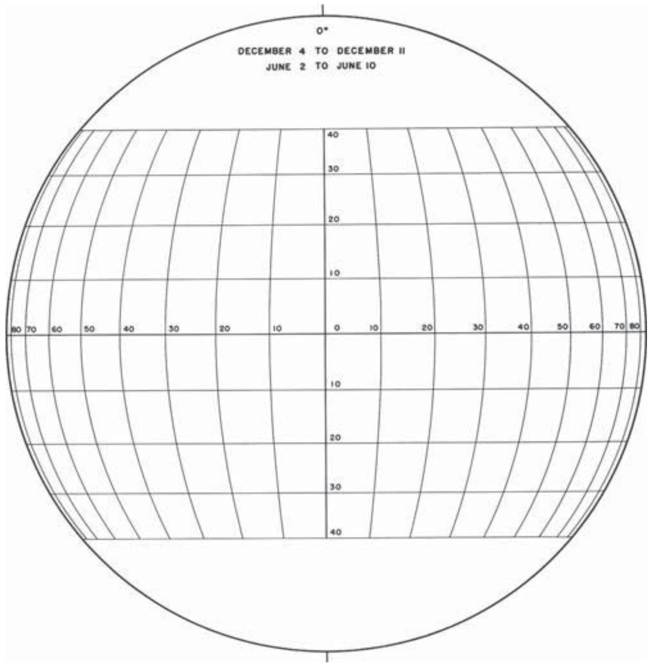
$$R = 10g + f$$

What counts as a sunspot group? Every individual sunspot, even the smallest pore, can count as a group all on its own provided it is at least 10° of latitude or longitude separated from its neighbour. If there is a collection of several spots or pores within a patch of the solar surface then, provided none strays beyond the 10° limit from its nearest neighbour, the whole collection is counted as just one group.

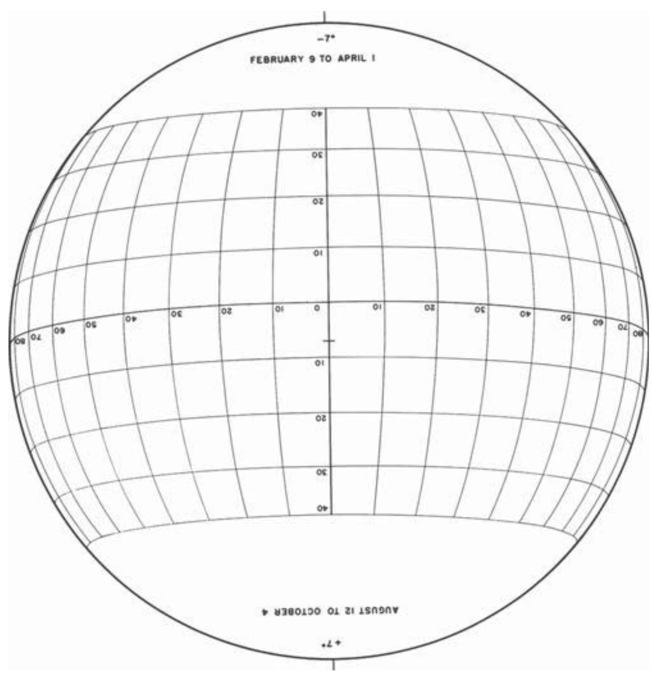
Next there is the *Mean Daily Frequency*, or *MDF*. This is found by first counting up the number of individual groups seen on every day the Sun is observed. Then these daily totals are added together for an entire month. Finally, this grand total is divided by the number of days the Sun was observed in that month. When you have collected enough

Figure 12.11
(a) A Stoneyhurst disk for a B_0 value of $0°$;
(b) A Stoneyhurst disk for a B_0 value of $-7°$.

(a)



(b)



observations you can plot either or both *R* and MDF against time (in months and years) to reveal how the Sun's level of activity changes throughout the solar cycle.

There are other measures of solar activity but I do not have the space available to explain them properly here. If you are interested, could I refer you to the December 1980 issue of the *Journal of the British Astronomical Association* for a paper entitled 'Measurement of areas on the solar disk'. Also, the November 1988 issue of *Sky & Telescope* magazine has an article 'Watching the premier star' in which one of the authors, Patrick McIntosh, describes his sunspot-group classification scheme. McIntosh's scheme, introduced in 1966, has become an accepted standard in professional solar research.

Perhaps the best tutorial on this scheme, and certainly the one most easily obtainable by you, is the illustrated paper 'The classification of sunspot groups' that Patrick McIntosh has written in Volume 125 (February 1990, pp. 251–267) of the professional publication *Solar Physics*. You will find this paper online at

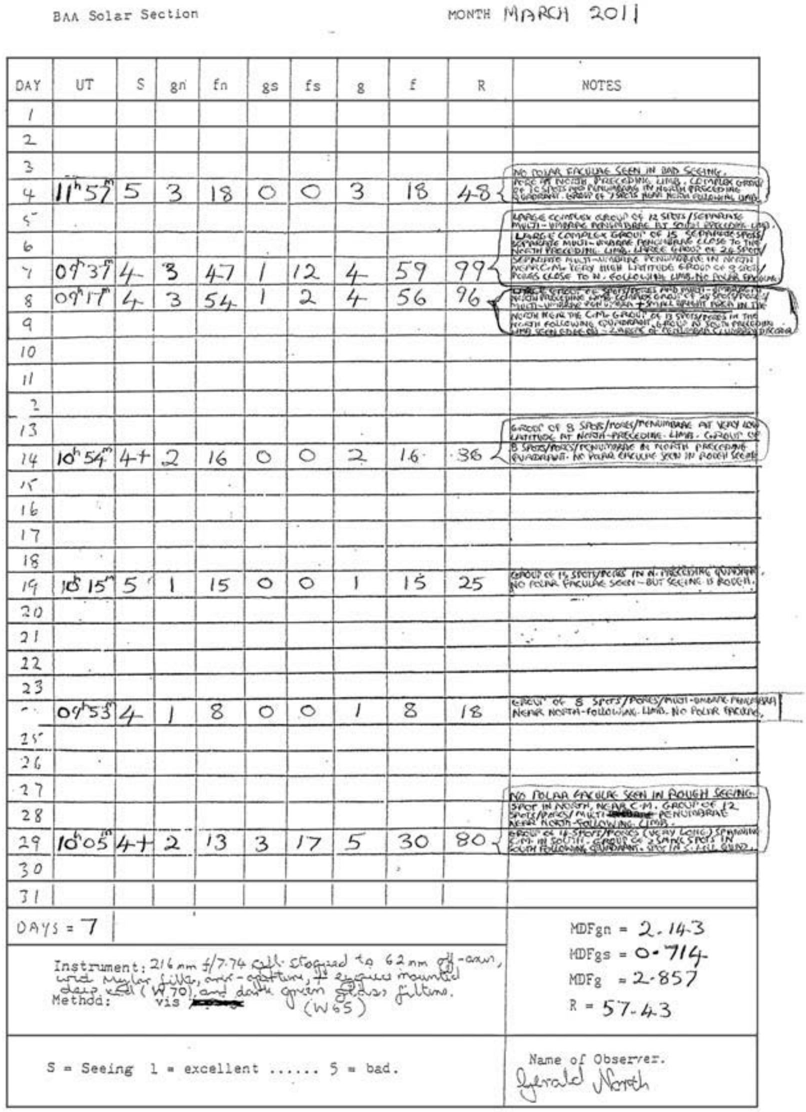
http://adsabs.harvard.edu/abs/1990SoPh...125...251M.

In essence, the scheme is fairly straightforward. There are three parts to the classification. The first is a capital letter from A to H (but with no G) that categorises the size appearance of the group as a whole. Next follows a choice of six lower-case letters (not in alphabetical sequence) that categorises the largest spot in the group. Finally, there is another choice of lower-case letters (also not in alphabetical sequence) that categorises the degree of interior crowding of the group.

However, please beware that accurately classifying sunspots and sunspot groups in practice is very far from easy. I consider this work to be the preserve of those who have gained a lot of experience and I do not propose to go into this any further here. Please do follow up the references I have given, if and when you become interested in sunspot classification.

There is also a so-called *Quality Number*, usually denoted *Q*, that uses the first letter of the McIntosh sunspot classification scheme, assigning particular numbers to these (A =1, B = 2, C = 3, D = 4, E = 5, F = 6; but H = 3). These numbers are added up for each day's observation to produce a daily value of *Q*. Currently very few amateur observers classify sunspots and produce daily Quality Numbers.

Even if all you can spare is a few minutes on each of a few sunny days each month for observing directly through your safely-filtered telescope, you can still produce scientifically valuable data simply by counting the number of sunspots and groups and filling in a form for each month such as that shown in Figure 12.12.


BAA Solar Section MONTH MARCH 2011

DAY	UT	S	gn	fn	gs	fs	g	f	R	NOTES
1										
2										
3										
4	11^h57^m	5	3	18	0	0	3	18	48	No polar faculae seen in bad seeing. [illegible]
5										
6										
7	09^h37^m	4	3	47	1	12	4	59	99	Large complex group of 12 spots/separate multi-umbrae penumbrae at south preceding limb. Large complex group of 15 separate spots/separate multi-umbrae penumbrae close to the north preceding limb. [illegible] No polar faculae.
8	09^h17^m	4	3	54	1	2	4	56	96	[illegible]
9										
10										
11										
12										
13										
14	10^h54^m	4+	2	16	0	0	2	16	36	Group of 8 spots/pores/penumbrae at very low latitude at north-preceding limb. Group of 8 spots/pores/penumbrae in north preceding quadrant. No polar faculae seen in rough seeing.
15										
16										
17										
18										
19	10^h15^m	5	1	15	0	0	1	15	25	Group of 15 spots/pores in N. preceding quadrant. No polar faculae seen – but seeing is rough.
20										
21										
22										
23										
24	09^h53^m	4	1	8	0	0	1	8	18	Group of 8 spots/pores/multi-umbrae penumbra near north-following limb. No polar faculae.
25										
26										
27										
28										
29	10^h05^m	4+	2	13	3	17	5	30	80	No polar faculae seen in rough seeing. Spot in north, near C.M. Group of 12 spots/pores/multi- penumbrae near north-following limb. [illegible]
30										
31										

DAYS = 7

Instrument: 216 mm f/7.74 OG stopped to 62 mm off-axis, and Mylar filter, anti-glare, equatorial mounted, drive. (W 70) and dark green glass filters. (W 65)
Method: vis

MDFgn = 2.143
MDFgs = 0.714
MDFg = 2.857
R = 57.43

S = Seeing 1 = excellent ...... 5 = bad.

Name of Observer.
Gerald North

Figure 12.12 A BAA solar report form filled in by the author for his observations of March 2011. This is necessarily much reduced in size here so you will not be able to read the small writing. This was a period where the Sun was just becoming active again after an unusually prolonged period of minimum activity.

12.10 OBSERVING THE SUN IN MONOCHROMATIC LIGHT

A useful unit for expressing wavelengths of light is the nanometre (nm). This is equal to one thousand millionth of a metre (1×10^{-9} m). However, if you read older astronomy books you will often come across wavelengths expressed in Ångstroms (Å). Ten Ångstroms are equal to one nanometre.

Images of the Sun formed in the full spread of wavelengths of visible light, known as 'white light' or more accurately *integrated light*, can show plenty of detail. However, if you select out an extremely narrow band of wavelength (so-called *monochromatic light*) centred at one of a small selection of specially defined wavelengths then you can see a fantastic amount of otherwise hidden detail. An especially good wavelength to choose is 656.3 nm in the red part of the spectrum. Alternatively represented as 6563Å, or 6.563×10^{-7} m, this is the wavelength at which de-exciting hydrogen gas emits most of its light. This special wavelength is often referred to as H-alpha light, sometimes written as Hα. This is the best wavelength to see details on the solar chromosphere, and to see the prominences extending from it (more about those features in the following sections).

An intricate piece of apparatus invented by George Ellery Hale in 1920s called a *spectroheliosc ope* allows the Sun to be studied in the light of just one wavelength. For historical accuracy I ought to say that versions of a related instrument were developed prior to that but Hale's invention was independently made and undoubtedly the most useful. I once had the pleasure of observing the Sun through the famous 'Sevenoaks Spectrohelioscope' the late Commander Henry Hatfield had built into the basement of his home. If you are interested you will find a detailed account of this instrument, written by Commander Hatfield in a paper 'The Sevenoaks Spectrohelioscope' in the December 1988 issue of the *Journal of the British Astronomical Association*.

The same objective can be met by use of a specially constructed filter and that is how it is mostly done these days. In fact, the modern H-alpha solar filter will normally produce images of much superior quality to those obtained using the spectrohelioscope. A handful of companies such as Coronado and Solarscope produce filter sets and, in some cases, complete H-alpha telescopes for the amateur market. The downside for amateurs working on a limited budget is that they are expensive.

Filter sets consist of a filter assembly that goes over the telescope objective and another filter assembly that plugs into the telescope before the eyepiece. Both are needed to produce a safe and effective H-alpha solar instrument. The designs vary but common to all is that the 'front-end' filter assembly includes a heat-rejection filter and at the very least a red filter with a fairly narrow passband centred on the H-alpha wavelength. Then the eyepiece filter stack includes a very precise piece of optical engineering based on a device called a *Fabry–Perot etalon*. This uses optical interference to cancel all but the selected wavelength to pass through the filter assembly. For it to work well the light rays that enter the etalon must be close to parallel, so an effective focal ratio of at least f/30 is needed for the best results with the etalon at the eyepiece end of the telescope.

In some cases, such as the filter kits made by Solarscope, it is the objective filter assembly that includes the etalon. This is more expensive but produces a superior result. The telescope can also have an effective focal ratio lower than the f/30 limit for an eyepiece-end etalon. The part of the kit mounted before the eyepiece is in that case referred to as a 'blocking filter'. The etalon has to be at one end of the telescope or the other. Simple filters cannot sufficiently isolate the required wavelength from those that bracket it.

Another variation is that you can have either a single etalon assembly or a double-stacked one. In most cases the single assembly produces a bandwidth of 0.7 Å. This is the minimum you will need to view the surface of the Sun in detail with an acceptable level of contrast. A double-stacked etalon produces a bandwidth of 0.5 Å and this allows the solar details to be viewed with better contrast. Of course a double-stacked unit costs more than a single etalon.

Usually the stack containing the etalon has some provision for slightly tuning it. This can be useful to optimise the view, especially for the 0.5 Å filter stacks. This feature can even allow one to follow material that erupts from the Sun, suffering a Doppler shift in its light as a result, which would otherwise move it out of the passband of the filter and render it invisible.

Coronado produce a mini version of an H-alpha solar telescope called a PST (the letters standing for Personal Solar Telescope) obtainable for about £500 in the UK and about $600 in the USA (2010 prices). Larger complete H-alpha telescopes and filter sets for your own telescope are going to cost you very much more. The bandwidth of the PST is 1Å and so the chromospheric details are only imperfectly seen against the solar disk. However, the flame-like prominences (see Section 12.12) are very well seen protruding from the limb of the Sun with this instrument.

A high-quality 50 mm aperture 0.7 Å H-alpha filter kit will probably cost you around £3000 in the UK and maybe around $4000 in the USA. You will have to spend nearly double that for one of around 70 mm aperture. At the time I am writing these words new products are coming onto the market, so here I will simply urge you to fully research what is available at the time you wish to go shopping for H-alpha equipment. As a start you could look up the Coronado company at www.coronadofilters.com and Solarscope at www.solarscope.co.uk. As always, also search out reviews and particularly customer comments that appear online. **Also be absolutely sure you know how to safely use any solar observing accessory you purchase**. I recommend you obtain the book by Philip Pugh, *Observing the Sun with Coronado Telescopes*, published by Springer-Verlag in 2007.

Another wavelength useful for observing certain solar features is 393.4 nm. This corresponds to the calcium K line of the solar spectrum and lies right at the boundary between the near-ultraviolet and deep-violet. The bright cloud-like features called plage (see Section 12.5) are best seen in the light of calcium K. A major problem is that many people can see images only very dimly at this wavelength and very many others cannot see anything at all. Older people have the greatest difficulty seeing light of this colour but those who have had cataract operations will find they can see calcium K light very much better than before. A small number of observers do obtain filter kits to observe visually at this wavelength – but many more choose to use a camera to do their calcium-light recording.

On the subject of cameras, you can record the Sun in the light of H-alpha or calcium K through suitable equipment, taking either whole-disk photos or close-up high-resolution images in the same way as you can in integrated light. Please refer back to Section 12.7 for details. Experiment with all the parameters, including camera gain, to find what works best with the equipment you use.

In the subsequent processing many like to colour their images obtained in calcium either blue or lilac. Those that image in H-alpha often colour the flame-like prominences protruding from the solar limb red while they colour the disk either orange or golden yellow, rather than the same red. Of course this is exercising artistic licence but it seems to have become accepted practice. Software such as *Adobe Photoshop* or freeware such as *Gimp* (downloadable from www.gimp.org) are the stock-in-trade for most astrophotographers.

I should also mention that the light from the disk of the Sun in H-alpha is brighter than that from the prominences, so separate exposures are normally made and the results combined in a software suite such as *Adobe Photoshop*. The overexposed disk is cropped out of the prominence image and this is laid onto the correctly exposed disk image and carefully aligned using the 'Move' tool. The images can be coloured by converting the monochrome image to 'RGB Colour' in *Adobe Photoshop*, selecting 'Curves' and adjusting the levels.

Try it for yourself and you will find it not as difficult as you might think. Having briefly mentioned certain features of the Sun that are revealed in H-alpha and calcium K light, we will properly examine them in the next few sections.

12.11 THE CHROMOSPHERE

The chromosphere is a low-density layer of gas on top of the photosphere. It is a few thousand kilometres thick and has a similar composition to the rest of the Sun. Its temperature rises from about 4300 K just above the photosphere to about half a million kelvins near the top of it. Then the temperature soars very rapidly with small gains in height in what is called the *transition region*. This marks the boundary of the chromosphere with the solar corona. More about the solar corona in Section 12.13. The density of the chromosphere drops dramatically with height, ranging from 1×10^{-5} to 1×10^{-10} kg/m^3 at the transition region. The height of the transition region varies over the solar globe but a rough average height for it is about 2000 km above the base of the chromosphere.

Thus the top of the chromosphere, though at a very high temperature, has little heat energy associated with it. If that seems wrong to you imagine using your unprotected hand to pick up a metal bar that has been heated to a couple of hundred degrees Celsius. You would suffer very serious burns. Yet you can let the sparks from a bonfire-night sparkler shower into your hand and barely even feel them, though the sparks have a temperature of around a thousand degrees. The reason the sparks do not burn you is that they have a very much lower density than the metal bar and so contain little heat energy, despite their high temperature.

The outer edges of the chromosphere can be glimpsed during total solar eclipses, momentarily showing as a thin red band round the limb of the Moon. An instrument called a solar spectroscope, invented in the nineteenth century, could do the same at other times. Later, the invention of the spectrohelioscope allowed the chromosphere to be seen across the full face of the Sun. In more recent times, the availability of H-alpha filter assemblies for telescopes has revolutionised the study of the Sun in the amateur arena.

Far from being a homogeneous layer, the chromosphere exhibits detailed structure and seething activity. The most obvious structures are the *spicules*. These are great jets of gas, rooted at the foot of the chromosphere. They rather resemble tall blades of grass sticking up on an otherwise threadbare lawn. A typical spicule consists of gas, at a temperature of about 15 000 K, rising upwards at 25 km/s to a height of 10 000 km. Any one spicule is a short-lived affair. A few minutes after its formation it disperses into the general chromosphere. The spicules are not evenly spread over the solar surface but are arranged around the edges of cells, rather in the same way that the metal in a chain-link fence surrounds the holes. Figure 12.13 illustrates this. These cells, forming the so-called *chromospheric network*, coincide with the photospheric supergranules.

Detailed studies show that the spicules follow the local, chaotic, magnetic-field lines. When they occur near sunspots the spicules become stretched out and more or less horizontal to the surface. They are then termed *fibrils*. To gain an impression of what spicules and fibrils look like, sprinkle some iron filings on a piece of card and bring up a magnet to the card's underside.

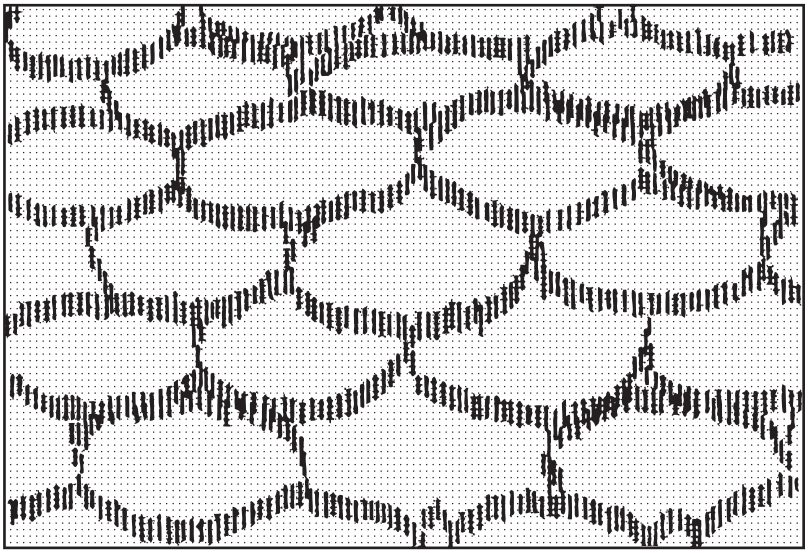


Figure 12.13 The cellular arrangement of spicules extending from the solar chromosphere.

A good H-alpha filter assembly will show solar granulation much more prominently than it appears in integrated light. Further, the narrower the bandwidth is, the better for observing chromospheric detail.

12.12 PROMINENCES AND FILAMENTS

Figure 12.14(a) is an image taken in hydrogen-alpha light of part of the limb of the Sun, with the bright light of the photosphere masked off. On it you will see several luminous flame-like, or cloud-like protrusions, looking like tongues and arches of flame, extending from the solar disk. These are known as *prominences*. They glow with the characteristic red colour of hydrogen gas and are readily seen when total solar eclipses occur. They can appear in many beautiful and dramatic forms. Figure 12.14(b) shows another example, this time with the separately exposed photosphere image layered into the prominence shot, as described in Section 12.10.

If the solar photosphere is imaged in hydrogen light using a suitable filter then the dark silhouettes of prominences can usually be seen visible on it. Some can be seen in Figure 12.15. These are called *filaments*, though they are exactly the same phenomena as the prominences. We just see them in a different way.

Prominences (and filaments) come in two varieties: quiescent and active. *Quiescent prominences* can survive with little structural change for several months. They often give the impression of upward surges of gas from the chromosphere, though they are really gas condensing from the more tenuous corona. In most cases the gas actually streams downwards towards the Sun, though upward gas motions are not unknown. The

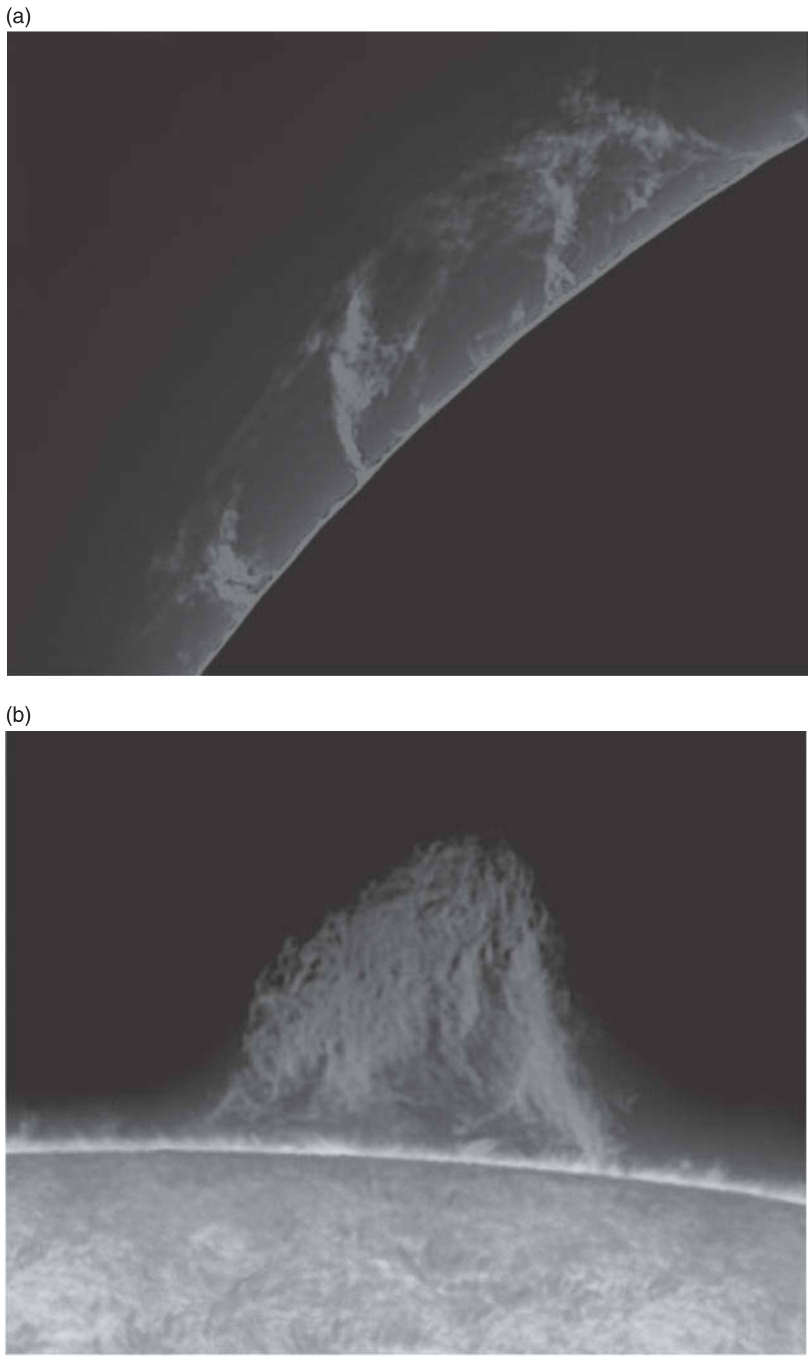


Figure 12.14 Solar prominences photographed in Hα light by Damian Peach. (a) For this image taken on 2006 December $16^{d}\ 10^{h}\ 23^{m}$ UT Damian used a Vixen 6-inch (152 mm) apochromatic refractor, working at f/40, fitted with a 5-inch (128 mm) energy rejection filter and a Daystar 0.6 Å ATM (the assembly fitted near the refractor's principal focus) and Lumenera Lu075M camera; (b) On 2006 October $8^{d}\ 10^{h}\ 25^{m}$ UT Damian took this image through a 4¼-inch (108 mm) achromatic refractor, working at f/40, with a Daystar full-aperture energy-rejection filter and a Daystar 0.6 Å ATM and Lumenera Lu075M camera. In both cases the images were captured and processed using *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*. [The images are also reproduced in colour as PLATE VIII between pages 304 and 305]

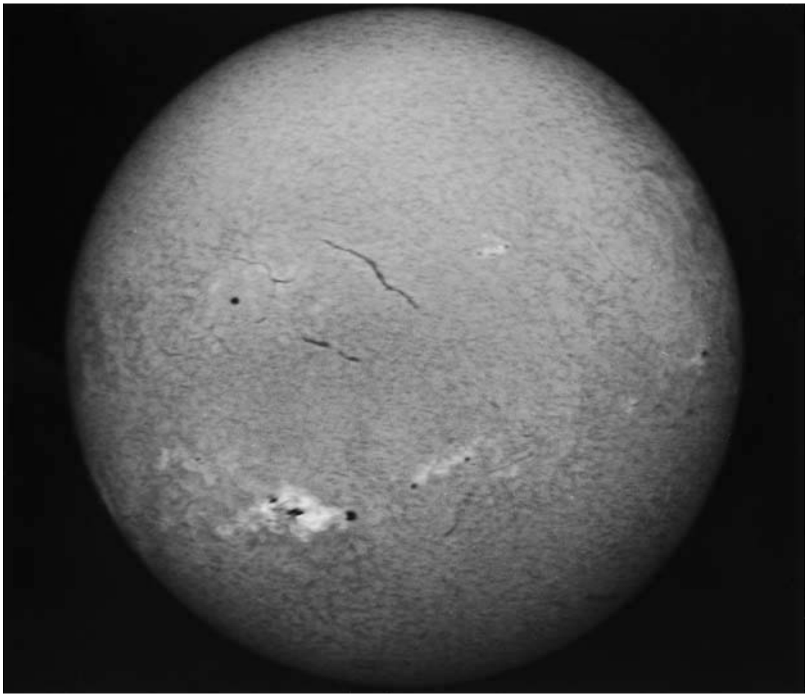


Figure 12.15 The Sun photographed in Hα light on 1981 October 12^{d} 12^{h} 00^{m} UT by the late Eric Strach, using his 8-inch (203 mm) Schmidt–Cassegrain telescope closed with a full-aperture cap in which was fitted an off-axis 60 mm aperture energy rejection filter. The eyepiece-end filter had a passband of 0.6 Å. A 1/30 second exposure was made on Kodak's now-discontinued Technical Pan 2415 film. Notice the bright faculae surrounding the sunspots, plus the solar granulation and the filaments seen as dark wavy lines in silhouette against the chromosphere.

Sun's complex magnetic field seems to support the condensed material, the downward flows of matter mostly following the field lines. They can show a variety of forms – loops, arches, complex filaments, etc., often extending to tens of thousands of metres in height. When they disappear they often do so with a violent eruption, which spatters much of the material into space.

Active prominences are much shorter-lived than the quiescent variety, and most of them are much smaller. They can change their forms rapidly, even over a period of just a few minutes. Some active prominences consist of falling material condensed from the solar corona, but many really are tremendous upward surges of material. In a few of the most violent events thousands of millions of tonnes of chromospheric material can be thrown upwards at greater than the Sun's escape velocity of 618 km/s.

As already mentioned, even a 1 Å bandwidth filter is good enough to show solar prominences and so a relatively cheap PST is enough to enable you to follow their forms visually, and to draw them if you have adequate drawing skills, and perhaps to photograph them. Mind you, prominences are always better seen using smaller-bandwidth filter assemblies. Further, you will find that the difference in brightness between the prominences and the bright disk of the Sun is lessened with decreasing bandwidth. This makes simultaneously observing disk details and prominences easier.

It has become accepted practice for observers to describe the forms prominences can take in rather imaginative, even florid, terms. Thus we have 'hedgerow', 'tree', 'mound', 'loops', 'spires', 'pillars', 'sprays' and 'flames'! The solar observing section director of your national astronomical society might welcome counts of prominences from you. If so, he/she will lay down particular criteria for you to follow, so I will not go into more detail here.

12.13 THE SOLAR CORONA

Visible as a pearly white glow at the time of a total solar eclipse, the *corona* is effectively the Sun's outer atmosphere. If it could be seen shining by itself, the corona would provide nearly as much illumination as the full Moon. However, the brilliance of the solar photosphere means that, aside from the times of eclipses, special equipment must be used to study it. Alas, affordable equipment that will work from typical amateur backyard observatories does not currently exist.

The corona is mostly fully ionised hydrogen and it extends to several times the Sun's diameter. Its density averages around 1×10^{-14} kg/m^3. When astronomers first made measurements of the radiations produced by the corona in order to determine its temperature they received a shock. They had expected the corona to be cooler than the photosphere. In fact, modern measurements indicate that the temperatures range from about 1 million to 5 million kelvins in different regions.

The corona's high temperature remained difficult to explain until recent observations turned in by the various space probes, particularly *Hinode*. It seems that various mechanisms are in operation. However, I must caution that we do not yet have the full picture. The relative importance of the various mechanisms has still to be pinned down and there may be other mechanisms still awaiting discovery.

To start with, vibrations in the form of waves in the magnetic fields in the Sun's photosphere and chromosphere, called *Alfvén waves*, have some solar plasma locked in with them. Their oscillations drive energy into their immediate environment causing matter to be ejected spaceward. In turn, this pumps energy further out into the solar corona. Also, there is a non-stop succession of relatively small explosions near the Sun's surface, caused by local rearrangements of the intense magnetic field. These explosions are relatively small but there are a lot of them and they happen continuously – so generating a significant flux of energy pouring into the corona and heating it. Acoustic (sound waves) from the Sun's churning and eruptive surface must also contribute to the energy flux into the corona.

Recent *Hinode* observations have revealed rapid-fire jets of extremely hot, X-ray-emitting, plasma squirting away from the sites of where magnetic fields break and are reconnected. This last mechanism seems to be a particularly important source of coronal heating and for generating and launching a vast outflow of matter from the Sun that spreads right out into, and through, the Solar System. More about that in the next section.

The solar corona displays considerable, and variable, structure. During times of minimum solar activity (i.e. when there are few sunspots visible) the corona is fairly regular in shape, but at times of maximum activity it becomes very irregular, with great streamer-like forms stretching into space above the prominences.

Ultraviolet and X-ray photographs of the corona often show dark patches, or *coronal holes*, in the otherwise mottled and translucent corona. These are cooler patches within the corona caused by the Sun's magnetic field being locally weaker and the fact that these field lines flow out into space. Elsewhere, the field lines form closed loops and arches with the Sun's surface.

Magnetically energised *coronal mass ejections* (*CME*s) sometimes occur, where billions of tonnes of plasma are shot into space. Some of these come our way and these are the main source of our terrestrial aurorae.

12.14 THE SOLAR WIND AND SOLAR FLARES

The Earth and the other planets are bathed in a breeze of electrified particles sent out from the Sun – the *solar wind*. At the orbit of the Earth the particle density is of the order of 2 per 100 000 cubic metres. The velocities of the particles average around 500 km/s, though the density and speed of them actually varies greatly. In fact, the solar wind is very gusty, especially at times of maximum solar activity. The particles are mainly electrons and protons, though heavier ions and nuclei are also present.

Near the Sun, where the magnetic field is strong, the solar wind streams radially outwards from it, co–revolving with the Sun. However, at greater distances, the magnetic field is weaker and the particles no longer corevolve. They form a spiral pattern as they move away from the Sun in the same manner as do water droplets from a lawn sprinkler. Since the solar wind is electrically conductive it is able to trap a magnetic field within it. Those solar magnetic-field lines, which are open-ended and leave the Sun are 'frozen into' the solar wind and take on its spiral pattern. As the particles from solar flares and coronal mass ejections sweep past the Earth, some can breach the protective terrestrial magnetosheath and drill into our upper atmosphere producing aurorae, as described in Chapter 1.

The three-dimensional structure and properties of the solar wind are currently being studied by the *Cluster* series of space probes. Between 1990 and 2009, the solar probe *Ulysses* also observed from a polar orbit. In

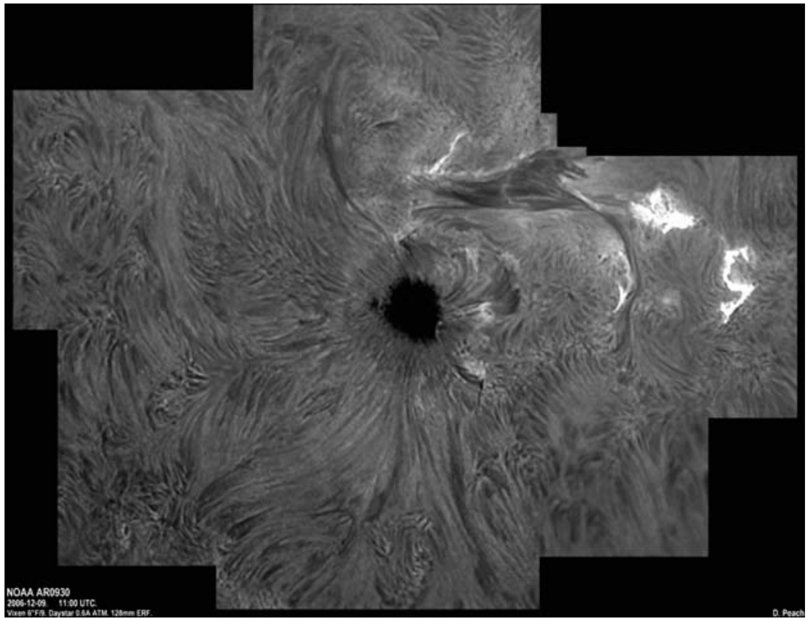


Figure 12.16 Damian Peach captured this image of a C-type solar flare erupting on the Sun using a Vixen 6-inch (152 mm) apochromatic refractor, working at f/40, fitted with a 5-inch (128 mm) energy rejection filter and a Daystar 0.6 Å ATM. The image was taken with a Lumenera Lu075M camera and captured and processed using *RegiStax*, *Adobe Photoshop* and *Paintshop Pro*.

addition, the nature and properties of the Sun's winds in the equatorial plane are currently being investigated by *SOHO*.

The solar wind emerges from the expanding corona. Primarily, the solar wind is generated from specific, often violently powerful, events involving complex mechanisms at the Sun's surface. The recently discovered small-scale and rapid-fire jets of extremely hot plasma that erupt from magnetic reconnection events near the Sun's surface (discussed in the last section) seem to a major cause of the solar wind. Solar-wind particles are also supplied from spicules and prominences and the edges of convection cells.

The solar wind escaping through coronal holes is particularly strong, and nearly twice as fast as elsewhere, because the particles can then ride the magnetic-field lines out unimpeded into the planetary system.

One phenomenon that can give rise to enormous gusts of highly energetic particles is the *solar flare*. The English astronomer Richard Carrington was the first to see and record a solar flare on 1 September 1859. It showed up as a small but brilliant patch visible on the photosphere when the Sun was projected onto a screen using a telescope. Such *white-light flares* are only very rarely observed, though less energetic events are more often seen in hydrogen light. You can often observe them if you have a good H-alpha filter kit installed on your telescope (see Figure 12.16). I have seen just the occasional white-light flare over the years. When seen, they appear as a short-lived brilliant white, or slightly bluish-white, patch nestled within an active area on the photosphere. Beware, less-brilliant white patches also can appear within active areas. These are energy concentrations but do not count as true flares.

Flares are violent eruptions on the photosphere where the temperature in a small region may rise to several thousands of degrees higher than that of the surrounding photosphere. The power involved in a flare can be as great as 1×10^{17} megawatts (MW), which is nearly a thousandth of the Sun's total power output! A major event usually lasts for around 20 minutes and during this time colossal numbers of atomic particles are sprayed into space, accompanied by a tremendous burst of high-energy electromagnetic radiations, particularly X-rays.

The *SOHO* probe was the first to show that waves, like the ripples that come after a stone is dropped into a pond, expand outwards from the site of a solar flare. These ripples can be tens of thousands of times as energetic as the worst earthquakes we have to endure!

The largest flares can cause intense auroral activity, magnetic storms and even radio blackouts here on Earth. The one that Carrington observed in 1859 was followed a day later by the most powerful auroral storm ever recorded. One can argue that modern astrophysics was born with this event. Certainly this was the first time that scientists associated transient magnetic and auroral phenomena on the Earth with anything happening on the Sun.

Solar flares pose a real hazard to astronauts in flight because they could be bathed in lethal doses of radiation when the particles reach Earth's vicinity, one or two days after the event. They are caused by immense releases of pent-up energy from highly stretched and twisted-up regions of the solar magnetic field. The release happens when magnetic-field lines shear or reconnect. Though they can be separate, solar flares and CMEs are often associated.

12.15 SOLAR ECLIPSES

In Chapter 5 I explained how the Moon could sometimes pass into the shadow cone in space formed by the Earth, so creating a lunar eclipse. Of course, it is also possible for the Moon to pass between the Sun and the Earth. We then see a solar eclipse.

Figure 12.17(a) is a very out-of-scale representation of how a solar eclipse occurs. It is a remarkable coincidence that the Sun and the Moon both appear the same apparent size as viewed from the Earth; the ratio of the diameter of the Moon to its mean distance from us just happens to be the same as the ratio of the Sun's diameter to its mean distance.

A solar eclipse can only occur at the time of the new Moon and when the Moon is also at the ascending node or the descending node

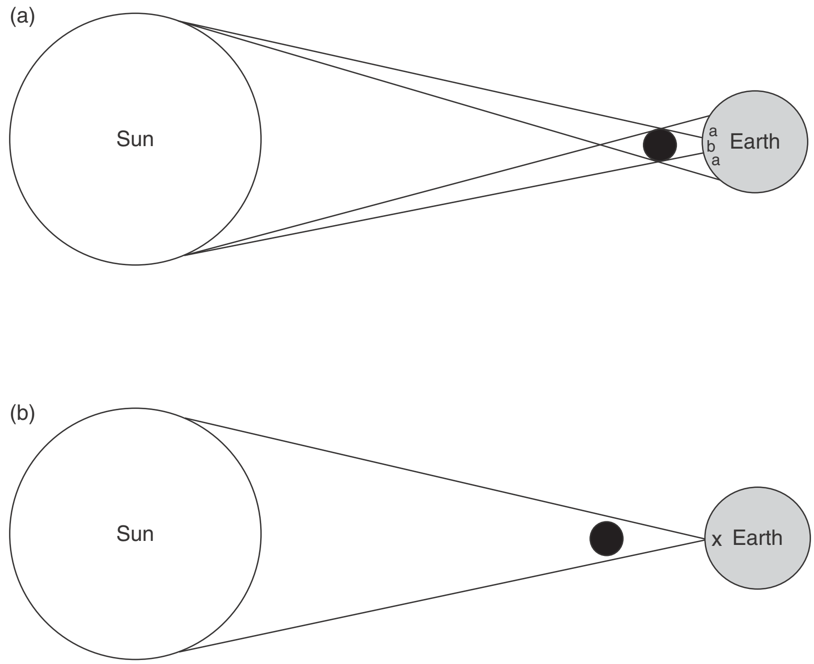


Figure 12.17 Solar eclipses. (a) An observer at **b** would see a total solar eclipse, while someone in the regions shown as **a** would see a partial eclipse; (b) A person at position x would see an annular eclipse. These diagrams are grossly out of scale for the sake of clarity.

in its orbit. Solar eclipses can be both *partial*, where the Moon appears not to cover the entire solar disk, or *total*, where the Sun's disk is completely covered. As can be seen from the diagram, a total solar eclipse can be seen only from a restricted region of the Earth's surface at any one moment during the eclipse's progress. All other regions see, at best, a partial eclipse. In fact, due to the rotation of the Earth as well as the relative motions of the Sun and the Moon, a narrow track is swept across the Earth's surface in which the eclipse can appear as total.

From any given location the eclipse can only have a limited duration, never exceeding 8 minutes. However, the duration of totality is usually much shorter than that. It varies from eclipse to eclipse. This is because the Earth and the Moon both move in elliptical orbits and so the apparent sizes of the Sun and the Moon both vary. A solar eclipse will have the longest possible duration if it occurs at a time when the Earth is at aphelion and the Moon is at perigee.

In the converse situation the apparent diameter of the Sun would be larger than that of the Moon. In that case an *annular eclipse* would be formed (see Figure 12.17(b)). This is so called because the Moon does not entirely cover the Sun but leaves, at mid-eclipse, a bright ring of sunlight surrounding the disk of the Moon.

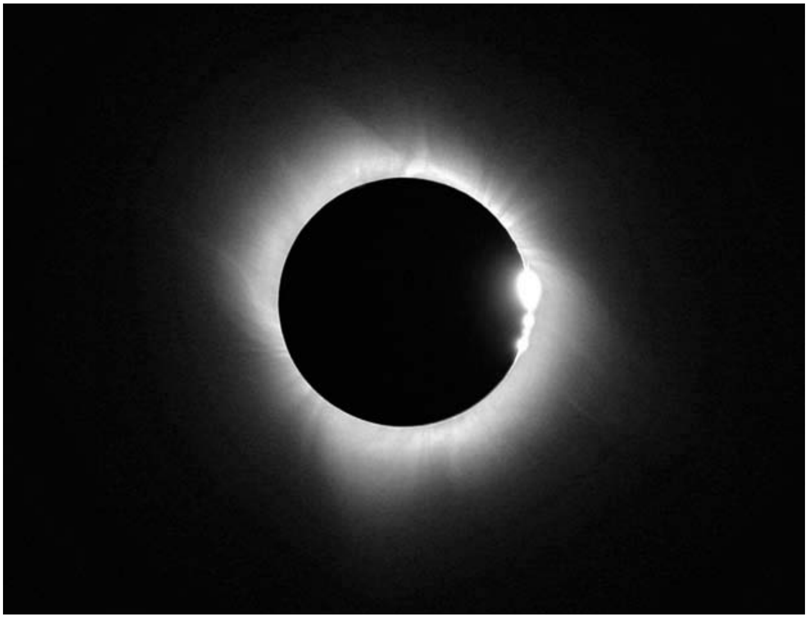


Figure 12.18 Martin Mobberley travelled to the South Pacific island of Hao to photograph the total solar eclipse of 2010 July 11. He used his Canon 300D camera, set to ISO 400, plugged into his 355 mm focal length, 60 mm aperture, Takahashi F560c refractor. This image is a combination of two sequences. The second contact (last part of the Sun's photosphere disappearing) photograph was taken at $18^h\ 41^m\ 24^s$ UT, with a single exposure of 1/2000 second. The image of the corona was taken as a series of exposures varying from 1/400 to 1/60 second during the interval $18^h\ 42^m\ 00^s$ to $18^h\ 43^m\ 22^s$ UT. Martin subsequently combined all these shots into this one image.

A total solar eclipse is an impressive spectacle (see Figure 12.18). The partial phase lasts about an hour, with progressively more and more of the Sun being covered by the Moon. At the point where only a very thin crescent remains the observer's surroundings rapidly darken until the last bright chink of direct sunlight vanishes. The sky then becomes dark enough to see the brightest stars and any bright planets, such as Mercury and Venus.

From around the silhouetted Moon's limb springs the pearly white glow of the solar corona, and the little red tongues of 'flame' which are the solar prominences. After a brief few minutes of this spectacle a sliver of bright sunlight suddenly explodes into view as the rays from the Sun find their way through some depression in the lunar limb to form the famous 'diamond ring' effect. Totality is over, and during the course of the next hour more and more of the solar disk is uncovered and the eclipse becomes only a memory for those lucky enough to have witnessed it.

Eclipse chasing

Solar eclipses happen somewhere on Earth on average a couple of times a year. The chances are that most years you will be able to see at least one partial eclipse from your location. You can buy 'eclipses glasses' from reputable astronomical suppliers that can safely dim the view. Of course you can employ your telescope using any of the safe observing methods I described earlier in this chapter.

Many *eclipse chasers* like to travel to the sites where the narrow path of totality is predicted to sweep across and experience the full spectacle for themselves. If you wish to do this, it is as well to seek advice from those who are experienced in order that you get the best out of the event and come home with the best photographs and videos – and most importantly to do it all safely. I can especially recommend two books: *Totality – Eclipses of the Sun*, by Mark Litterman, Fred Espenak and Ken Willcox (third edition published by Oxford University Press in 2008) and *Total Solar Eclipses and How to Observe Them*, by Martin Mobberley (published by Springer-Verlag in 2007). At this point I will also mention a book on general solar observing you might find useful: *The Sun and How to Observe It*, by Jamey L. Jenkins (published by Springer-Verlag in 2009).

To finish this chapter I will just say, enjoy your solar observing, however you do it – but please, **please**, **PLEASE** ensure that you put your safety before everything. Your eyesight is too precious to lose. **If you can't do it with 100 per cent safety DON'T DO IT!**

This is also the end of the main section of the book – but please don't forget there is some more useful material in the appendices that follow. We have covered a lot of ground in our exploration of the Solar System. We started with space-borne phenomena that intrude into our home planet's atmosphere. We then surveyed everything from the hot and fiercely lit innermost worlds to the frigid outermost bodies of our Solar System. Planets, moons, asteroids and comets have come under our gaze and we have finished by looking (safely!) towards the brilliant orb at our Solar System's heart.

We have considered the equipment and methods we humble amateurs can use to study all these bodies. The good news is that you can always do something no matter how small your budget. If you feel inclined, you can make a genuine contribution to mankind's ongoing researches into the worlds and phenomena around us. I very much hope that you will join at least one national astronomical society and contribute your own observations. Even if you do not want to do that, I most of all hope that you experience for yourself the same sense of magic and wonder I do every time I see details on any distant celestial body through the eyepiece of my telescope.

APPENDIX 1: TELESCOPE COLLIMATION

A telescope's optical performance can be severely impaired if its optics are even slightly out of alignment. Some observers insist that every time you go out to your telescope you should re-collimate it. That is not what I do. I leave my permanently stationed telescopes for many months on end without even checking them. In my defence, I find that it is extremely rare for me to have to ever make even the slightest of adjustments. It all depends what materials the telescope is made from and how robust it is. For instance, a telescope homemade from wood is likely to need frequent adjustments owing to the unstable nature of that material.

Of course, it is important to check any portable equipment each time it is set up anew. So, if you are forced to use portable equipment then checking the collimation of your telescope becomes a necessarily frequent chore. The following notes, concerned with the main types of telescope, may be of help. In all cases I must leave you to become familiar with the types of adjustments provided (perhaps push-pull screws, or nuts and springs, or nuts and lock nuts) and their locations on your own telescope.

COLLIMATING A NEWTONIAN REFLECTOR OF FOCAL RATIO F/6 OR LARGER

The first step is to make or buy a 'dummy eyepiece'. This is really no more than a plug which fits into the telescope drawtube and which has a small hole drilled exactly centre in the top of it. The best size for the hole is about 3 mm. This plug is inserted into the drawtube, replacing the eyepiece, and the function of the small hole is to ensure that your eye is steered onto the axis of the drawtube. When the collimation is successfully completed this axis will also coincide with the optical axis of the telescope.

You could make the dummy eyepiece from an old 35 mm film canister but do make sure that the hole you drill in its base is exactly centred. Alternatively if you have an old high-power eyepiece that is no longer used you could remove its lenses and use that.

We will begin by assuming that the axis of the drawtube is exactly perpendicular to the side wall of the telescope tube. It certainly should be if the telescope has been commercially manufactured. How to check for this and correct any error is covered later.

Start by pointing the telescope at the daytime sky or at a light-coloured wall, or an illuminated screen, wall, or curtained window if you are working at night. The secondary mirror mounting should have some provision for adjustments that will allow it to rotate and to move laterally up and down the axis of the telescope tube. Use these adjustments until you see, when looking through the dummy eyepiece, that the outer edge of the secondary mirror appears concentric with the inner edge of the bottom of the drawtube. The view you see should look rather like that illustrated in Figure A1(a).

If you rack out the drawtube this will make the secondary mirror appear to nearly fill your view of the bottom of the drawtube and so will help you to be more exact in your judgement of concentricity.

Once you have successfully got the secondary mirror looking concentric with the drawtube you can make any fine adjustments to the tilt and the rotation of the secondary mirror cell until you see the reflection of the primary mirror appearing concentric within the inner edge of the secondary mirror (see Figure A1(b)). As before you can rack the drawtube in or out in order to get the reflection of the primary mirror nearly filling the secondary mirror. Even small inaccuracies will then easily show up.

All that is left is to adjust the tilt of the primary mirror cell until the reflection of the secondary mirror is nicely centred within it (as in Figure A1(c)). I always find the secondary support vanes of help here. Any slight error in the tilt of the primary mirror makes the reflections of the vanes very obviously unequal, as seen through the dummy eyepiece.

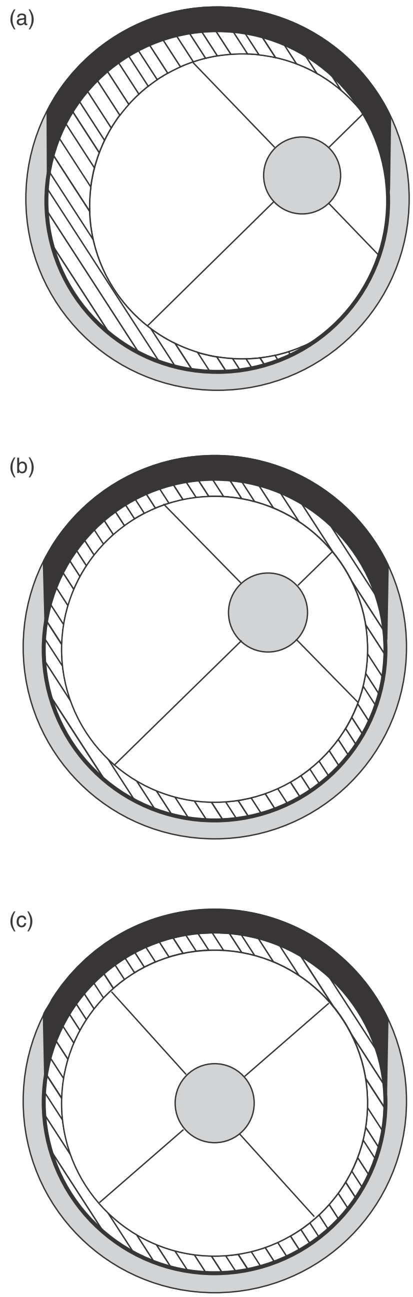
You could visually check through everything again, refining your adjustments if necessary. Your telescope is now adequately collimated.

COLLIMATING A NEWTONIAN REFLECTOR OF FOCAL RATIO LESS THAN F/6

The lower the focal ratio of the primary mirror, the more critical is the collimation of the telescope. So, if we are to get the best results, we should use a refined technique to achieve the best possible collimation.

Added to the foregoing, there is another slight complication we encounter with low-focal-ratio Newtonian reflectors. We can collimate our telescope with the secondary mirror concentric, as before. However, the area of the field of view where the image is unvignetted (fully illuminated by all the rays arriving from the primary mirror) will be a little offset from the centre of the field of view.

Figure A1 Collimating a Newtonian reflector.
(a) The view through the dummy eyepiece after adjusting the position of the secondary mirror, making the visible edge of the secondary mirror concentric with the edge of the drawtube.
(b) The view after fine-adjusting the tilt and rotation of the secondary mirror, to make the reflection of the outer edge of the primary mirror concentric within it.
(c) The view after adjusting the tilt of the primary mirror, to make the reflection of the secondary mirror-mount concentric.



To counter this, the secondary mirror ought to be offset a little away from the eyepiece and an equal distance towards the primary mirror. However, with focal ratios of more than f/3.5 for a 300 mm aperture, more than f/4 for a 400 mm aperture, and more than f/5 for a 500 mm aperture the adjustments will be less than 7 mm in each direction. The fall-off in image brightness due to the vignetting will be quite small, especially if the secondary mirror is large enough to fully illuminate a patch at least a couple of centimetres across. In that case, if you have any provision for making the offset adjustment (or if you are building your own telescope, or modifying it yourself to minimise outfield vignetting) I would say do not bother offsetting.

However, if you are using a commercial large reflector of low focal ratio then the manufacturer may well have set the secondary mirror off-centre within the telescope tube, leaving you with no choice. You must ensure that the secondary mirror is also offset the correct distance down the axis of the telescope tube in order that the axial rays from the centre of the primary mirror are turned through exactly 90° and passed exactly along the axis of the drawtube.

Of course, you will realise that the rays can still be turned through 90° with the secondary mirror offset away from the eyepiece but not equally offset down the telescope tube. This simply depends on having the secondary mirror set at exactly 45° to the optical axis of the primary mirror. **However, the normal collimation procedure will produce an error in that case: the mirrors will appear collimated to you but only when the secondary is actually tilted by less than 45°. The primary mirror will also be incorrectly tilted and the end result will be that the optical axis will pass at an angle through the drawtube**. Hence the need for the dual offset.

So, carefully measure the position of the secondary mirror to see if it is centred in the telescope tube, or if it is offset and by how much. If it is offset, then you must ensure that the mirror is offset by an equal distance down the telescope tube.

How do you do this? There are various ways. In my view the best method is by direct measurement. Measure the minor-axis diameter of the secondary mirror (so you can determine where its centre is), the diameter of the bottom end of the drawtube and the distance this is from the sky end of the telescope tube (rack the focuser inwards so you can make the measurement). From this you can determine the distance of the exact centre of the axis of the drawtube from the top of the telescope tube. Putting a straight edge across the top of the telescope tube you can measure down to the top edge of the secondary mirror. When the mirror is correctly set at 45° its centre will be this distance plus the minor-axis radius from the top of the telescope tube.

If you want the secondary mirror centred with the axis of the drawtube simply make the distances from the top of the telescope tube to the centre of the secondary mirror, and to the centre of the drawtube, exactly the same. If you want, say, a 4 mm offset then move the secondary mirror a further 4 mm down towards the primary mirror. **Remember, the secondary mirror's offset towards the primary mirror must be equal to the measured offset in the direction away from the eyepiece**.

Having sorted out the correct positioning of the secondary mirror we can now make the, hopefully very small, adjustments to bring the telescope into proper collimation. We have a choice. We can, in daylight, run through the same procedure as outlined in the last section and then take our telescope out under the stars and check for any remaining inaccuracy based on what we see through the eyepiece, making the very fine adjustments that may be needed to finish the job. The second option is to first run through the same procedure as before and then, still in daylight or using an illuminated screen or wall, apply another piece of kit to bring the collimation to a higher degree of accuracy.

The first option may sound straightforward but making mechanical adjustments to the telescope at night is tricky. Also you want to be observing, rather than fiddling with the telescope at this time (unless, of course, it is a portable telescope set up at the beginning of your observing session, in which case you have no choice). In the next section I cover star-testing a Cassegrain telescope and refining the alignments this way. You can follow the same procedure for fine-tuning your Newtonian telescope.

The second option is usually much preferable but does require you to have placed a mark on the primary mirror (something you may feel nervous about doing – but you may be lucky and have a mirror the manufacturer has centre-marked for you). Here we go with the second option . . .

Carefully measure the exact centre of your telescope's primary mirror and mark a small spot at this point. It has to be correctly placed to ±1 mm (albeit you are relying on the manufacturer getting the optical centre of the mirror at this same point). A spirit marker will suffice to make the mark. **Do please keep your fingers, palms, sleeves and cuffs away from the mirror surface. As well as the obvious hazards of scratches and dust, the oils, moisture, and salt from your skin will badly affect the reflective coating**.

While you are taking on this invasive procedure you might as well check to see that the primary mirror is properly centred within the telescope tube to better than ±2 mm. If it is not and there are no provisions for adjustment then all you can do is to bear this fact in mind when deciding about any offsets for the secondary mirror. Improve the centring of the primary mirror if there is any way of doing it. Perhaps there are provided radial adjusting screws or bolts? You might consider using shims but do not squeeze the glass of the mirror or you will see the star images distorted as a result.

Next, go through the collimation procedure as described in the last section. You can be fairly quick about it this time and no dummy eyepiece will be needed for this rough set-up. Then insert a carefully made ‘sighting tube’. This is a tube about 18 cm long which fits snugly into the drawtube. One end is closed with an accurately made dummy eyepiece. The other end (this end is inserted into the drawtube) is open but is crossed with wires. The wires are mutually at right-angles and cross at the exact centre of the tube. Sighting tubes can be purchased commercially. If you make your own, you must ensure that the sight hole and the crosswires are accurately positioned.

Using the sighting tube, make any fine adjustments to the secondary mirror’s tilt and rotation so that the refection of the spot on the primary mirror appears exactly under the intersection of the crosswires.

For the next adjustment you may need to use a lamp to throw some light into the telescope tube so that the crosswires are illuminated enough to be seen via reflection in the telescope mirrors. Fine-adjust the tilt of the primary mirror until the reflection of the crosswires you see exactly coincides with the ones at the end of the sighting tube (and so that the intersection of the reflected crosswires also coincides with the centre spot on the primary mirror). Finally, check through the procedure again. If you were to star-test your telescope now any viewed errors remaining would likely be the fault of the optical manufacturer.

COLLIMATING A CASSEGRAIN REFLECTOR

As before, it is a good idea to check that both the primary and the secondary mirrors are properly centred within the telescope tube. It is true that both could be off-centre, even by different amounts, as long as both mirrors can be tilted enough to bring their optical axes into coincidence. However, in that case the focuser drawtube would also have to be tilted by an amount and direction to suit. If the two mirrors are properly concentric to start with the drawtube can then be perpendicular to the base-plate and all will be well (assuming it is also mounted properly centred on the base-plate). Cassegrain telescopes are often provided with adjusters for this purpose. If so, do your best to get all the components concentric with the telescope tube to ± 1 mm.

Next, point the telescope at a light-coloured wall and insert a sighting tube into the drawtube. Looking through it, adjust the tilt of the secondary mirror until the reflection of the primary mirror in it appears exactly centred. Then adjust the primary mirror until the reflection of the secondary mirror in it is also exactly centred.

If the secondary support vanes are four in number and are equally spaced (as will normally be the case) then you can use the crosswires on the sighting tube to achieve a little extra precision. Simply rotate the sighting tube until the crosswires are brought into near coincidence with the secondary support vanes. By tinkering up the adjustments you should be able to get the crosswires to exactly coincide with the reflection of the support vanes.

Now your telescope will be very close to its optimal collimation. Nonetheless, a Cassegrain reflector is rather more finicky than most other types of telescope and it is as well to be prepared for some **very** slight further adjustments when you actually try it out under a clear sky.

Here is how to go about the final refinements to the collimation. Plug in an eyepiece that will deliver a magnification of several hundred after pointing the telescope at a test star. The star ought to have as high an altitude as possible so that it is not too badly affected by atmospheric turbulence. If the telescope drive is rather erratic (as many are) you should choose the star Polaris for this test.

Once the test star is centred defocus it slightly while watching for any asymmetry. If the expanding disk of light becomes oval and is less bright in one direction, the telescope is still very slightly misaligned. You should be aware that this test assumes the optics are of excellent quality. If the mirrors are even slightly astigmatic then the images will display a distortion which will be rather hard to tell from misalignment.

Now comes the really tricky bit – made easier if you have a willing assistant. With the telescope still pointed at the test star adjust the tilt of the secondary mirror until the star moves a little in the direction that the out-of-focus image is at its faintest and most distended. This will be an adjustment so slight that tightening the one screw without slackening the other two may even suffice, depending on the robustness of the mounting of the secondary. Next, adjust the tilt of the primary mirror by just enough to bring the star image back into the centre of the field of view. For this to work the telescope must not have been joggled out of its alignment with the test star while the adjustment to the secondary was made – an incredibly difficult thing to achieve in practice.

If all has gone well the slightly out-of-focus star disk will now appear rather more circular and evenly illuminated. Continue this tricky procedure until you achieve the most circular and evenly illuminated star disk you can manage. Check that it remains so for all positions of the focuser.

COLLIMATING A REFRACTOR

If the manufacturer has not provided any adjustments for the squaring on of the object glass then it is still worth checking the alignment but you will either have to put up with any misalignments or return the instrument to the manufacturer. If any adjustments are provided then the procedure is rather similar to that for the fine-tuning of the Cassegrain reflector.

Select a good test star as before. Centre it in the field of a high-power eyepiece. Slightly defocus it and watch for any expanding asymmetry in the expanding disk of light. Try to ignore the different colours you will see as the disk of light expands. This is quite normal behaviour for a refractor's object glass. All you are interested in detecting is any non-circularity and uneven distribution of light. Alter the tilt of the object glass until the re-centred star image looks as symmetrical as possible both a little inside and a little outside the best focus position.

COLLIMATING MAKSUTOV AND SCHMIDT–CASSEGRAIN TELESCOPES

Fortunately, the modern ones usually come with instructions on how to collimate them. They do vary in design. Sometimes only one of the optical components is adjustable. The classical Maksutov has an aluminised spot on the centre of the inside surface of the correcting plate. The Rumak version of the Maksutov has a separately mounted secondary mirror between the corrector plate and the primary mirror, the mount of which is often bonded to the centre of the corrector plate. This latter arrangement is also the norm for the Schmidt–Cassegrain telescope.

My advice is to always follow the manufacturer's instructions. If you have acquired an instrument without any instructions then, after inserting a dummy eyepiece, alter the tilt of whichever component is adjustable until the reflection of the primary appears concentric within the secondary. If both the primary mirror and the secondary mirrors are adjustable then treat the unit in the same way as for a Cassegrain telescope. To finish, fine-tune as I have previously described for the Cassegrain reflector.

COLLIMATING A SCHMIDT–NEWTONIAN TELESCOPE

Meade's Schmidt–Newtonian telescopes come with full instructions on monitoring and adjusting the collimation. In brief, the procedure is the same as for a Newtonian telescope except that the secondary mirror is not readily accessible to you for adjustment. The Meade instruments come complete with a factory-made collimation spot at the centre of the primary mirror. The only optical adjustments you should normally make are to the tilt of the primary mirror. It is a good idea to star-test and, if necessary, fine-adjust the collimation in the field.

COLLIMATING A MAKSUTOV–NEWTONIAN TELESCOPE

Normally these telescopes have factory-fixed corrector plates with the Newtonian-style secondary mirror in its holder fitted to the centre of it. So, only the primary mirror is adjustable. Treat the collimation as you would for the latter stages of a classical Newtonian telescope.

'SQUARING ON' THE EYEPIECE FOCUSING MOUNT

If the drawtube is not aligned to the optical axis of the telescope, the focal planes of the eyepiece and the telescope will be tilted with respect to each other. The action of focusing the telescope can then only achieve coincidence of these planes along one line. Star images will be in sharp focus anywhere along this line but will become increasingly out-of-focus with increasing distance from it.

With Cassegrain, Schmidt–Cassegrain and Maksutov telescopes drawtube alignment is easily checked using a sighting tube. Look through it and check that the crosswires appear centred against the secondary mirror in each case. For checking a refractor make a cap for the object glass with a small hole drilled exactly central. Does the intersection of the crosswires coincide with this hole?

Mechanically checking a Newtonian telescope's focuser is more difficult. It involves removing the secondary mirror and cell and marking a small spot on the far wall of the telescope tube **exactly** opposite the centre of the drawtube. The position of this spot can only be determined by very careful measurement. With the sighting tube inserted, do the crosswires line up exactly with this spot?

Drawtube misalignment is perhaps best checked by star-testing. First, centre the test star and focus it as carefully as possible. Try watching as you rack the focuser from fully in to fully out. As the disk of light changes its size does it also appear to shift across the field of view? If so, try to determine (by waggling the end of the drawtube if necessary) whether this is merely 'slop' in the sliding fit or if there is a progressive lateral shift of the image, which can only be due to misalignment.

I should say here that commercial Maksutov and Schmidt–Cassegrain telescopes achieve focusing by moving the primary mirror slightly along the optical axis. You will experience a cyclical to-and-fro motion of the image as you change focus due to the inevitable slight mechanical imperfections of the mechanism. It is not easy to do anything about any drawtube misalignment if you do find any.

Investigate further by moving the telescope in order to place the star at different positions in the field of view. Do you notice any change in the appearance of the star as it is moved across the field of view? Do bear in mind that it will be normal to see some image degradation radially away from the centre of the image. This will be especially evident close to the edge of the field of view. However, is this degradation symmetrical about the centre of the image?

In recent years, Cassegrain telescopes have virtually disappeared from the marketplace. If you obtain one of these rare beasts you will likely find that it has provision for adjusting the focuser alignment. Most other telescopes do not, so you will either have to put up with the defect or resort to packing the mounting of the focuser with shims in order to achieve proper alignment.

COLLIMATING A STAR DIAGONAL

At one time scorned by many, star diagonals have now become almost mandatory with today's marketed refractors, Maksutovs and Schmidt–Cassegrain telescopes. The best examples of these units have some provision for adjusting the tilt of the mirror or prism.

The test for proper alignment is simple but should only be made after the telescope is properly collimated (including drawtube alignment). Centre a star in a high-power eyepiece (better still if it has fitted cross-wires) and carefully focus. Check again that the star really is properly centred. Replace the eyepiece with the star diagonal and put in the same eyepiece. Refocus. Does the star still appear centred? If not, adjust the tilt of the mirror/prism until swapping between diagonal plus eyepiece and eyepiece alone produces no apparent image shift.

OTHER AIDS TO COLLIMATION

You do not really need anything more than I have described in the foregoing notes. However, there are some devices to further help you in collimating your telescope that you can purchase if you really want to.

For instance there is the *Cheshire eyepiece* and the *Autocollimating eyepiece*. Their principles of operation are too involved for me to describe here but you can rest assured that their manufacturers always provide full instructions with them. If you want to know more about them, let me point you to an article in the March 1988 issue of *Sky & Telescope* magazine.

The *laser collimator* is a very popular device these days. It is inserted into the drawtube and produces a thin beam of laser light, which is passed through the optical system of the telescope. The idea is that the secondary mirror is adjusted until the spot of laser light falls exactly onto the centre of the primary mirror (on the centre spot if there is one). The primary mirror tilt is then adjusted until the laser light passes back into the device, where some of it is passed through a partially reflective mirror and appears on a 'target', which you view from the side. Supposedly, this means that the laser beam has passed back exactly along its outgoing path and so ensures that the telescope is properly collimated.

Unfortunately there are hazards. One is the slight but very real physical hazard of catching a dose of laser light in your eye. The second is that a drawtube misalignment, or a secondary-mirror misalignment, can produce a situation whereby you adjust until the spot of light hits the target but the beam has **not** actually passed back along its outward path. You will then have actually set your telescope with a definite misalignment between the axes of the secondary and primary mirrors! I would say, get your telescope as nearly collimated as you can using the procedures I describe in the foregoing notes and limit your use of the laser collimator to the final fine-tuning.

A better approach to using a laser collimator with a Newtonian reflector is described by Nils Olof Carlin in the January 2003 issue of *Sky & Telescope*. The first stages are carried out as previously described. His innovation is for fine-adjusting the tilt of the primary mirror. For this final stage he suggests inserting the laser into a Barlow lens and plugging this into the telescope drawtube. The bottom of the Barlow lens is closed with a disk having a small central hole in it (to allow the diverging laser light to emerge into the telescope). Instead of a central spot on the primary mirror is a small central ring (a self-sticky 'reinforcement ring' used normally for sheets of paper to go into a ring-file might do very well).

When the telescope is correctly collimated a silhouette, in laser light, of this small ring appears concentric with the hole in the disk at the bottom of the Barlow lens (if it is too far up inside the focuser for you to see it use a small mirror hand-held inside the mouth of the telescope tube). The clever thing about Carlin's innovation is that the broadness of the cone of light makes the system insensitive to secondary-mirror offset and drawtube misalignment, while still being very sensitive to primary-mirror misalignment. Hence the situation of an inaccurately offset secondary mirror is not made far worse by introducing a tilt to the primary mirror in order to bring the laser spot to target as it would in the usual way of using the device.

With Cassegrain, Schmidt–Cassegrain and Maksutov telescopes the laser can only be used to ensure that the optical axis of the secondary mirror is coaxial with the drawtube, since the reflected thin beam is then simply fired back through the hole in the primary mirror and is not reflected from it.

One problem that might afflict the laser used on any type of telescope is slop in the telescope drawtube or a loose fitting of the collimator in the drawtube. Either may cause the laser beam to go a little off line, particularly so when tightening any fixing screws. Also, is the beam emerging from the laser truly coaxial with the cylindrical body of it? To be sure, try rotating the laser in the drawtube and look to see if the red spot(s) remain on target. As you can see, the laser collimator is a tool to be used with caution. Blind reliance on it may very well lead to inaccurate collimation.

APPENDIX 2: FIELD-TESTING A TELESCOPE'S OPTICS

The majority of today's amateur astronomers do not make their own telescope optics. Nonetheless, most of us are aware of the basic procedures involved and are familiar with the basic principles of the Foucault and Ronchi grating optical tests. I would, however, wager that very few telescope users realise that simple versions of these tests can be used to evaluate the overall accuracy of both figuring and alignment of the assembled telescope's optics with much greater ease than the toiling mirror maker can assess the individual components in his/her workshop.

The easiest method involves using a Ronchi grating. Many optical firms, especially those dealing in telescope optics and telescope-making materials, sell these gratings. They are very cheap to buy. If a choice is given select a grating of at least four lines per millimetre (100 lines per inch), with more lines per millimetre providing a more sensitive test.

Simply mount a small piece of the grating over the central hole in a dummy eyepiece (a collimation tool described in Appendix 1) and you have all you need to make the evaluation.

I mounted my own grating in place of the eyelens of a cheap discarded eyepiece – all the lenses first being removed from it. I store the unit in a container, to keep it clean and so it is always ready for use at a moment's notice.

Using this device could not be easier. Simply set the telescope on a fairly bright star in the normal way. Centre it accurately in the field of view. Then replace the normal eyepiece with the grating device. Peering through the grating you will see the primary mirror/objective of the telescope flooded with light from the star but crossed with dark stripes. These stripes are effectively the highly magnified image of part of the grating.

You will find that rotating the grating produces a consequent rotation of the pattern. Adjusting the focuser causes a dramatic change in the apparent magnification of the pattern and so a change in the apparent broadness of the dark bands and the number of them crossing your view of the telescope's objective/primary mirror. The closer to the telescope's focal plane the grating is, the smaller the number of stripes visible.

For this test I recommend adjusting the focuser until four dark stripes are seen to cross the image, the grating being just intrafocal (inside the focal plane – in other words, with the focuser racked inwards such that further inwards adjustment increases the number of stripes visible).

Assuming the grating is not faulty or dirty, the image of the stripes you see should be straight and like that shown in Figure A2(a). Grains of dust trapped in the grating will show up as a jaggedness along the edges of the stripes. Any faults in the figuring of the optics or their alignment will be immediately apparent as shown in the other views in Figure A2 and described in the caption accompanying it. Rotating the grating through 90° in several steps will allow all of the optics' radial zones to be evaluated.

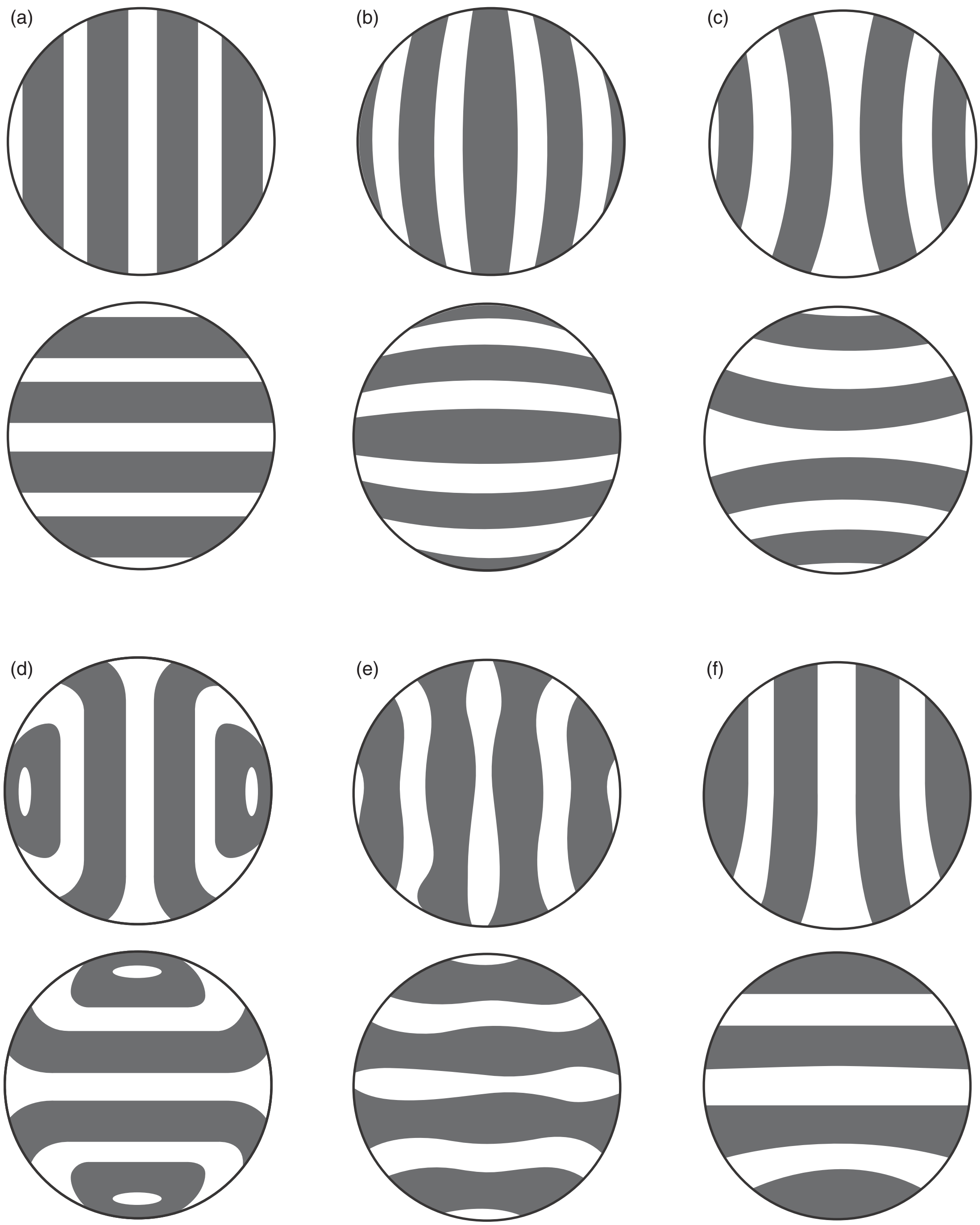
The beauty of this test is that the complete optical system of the telescope is tested in field conditions – and this is surely what really counts. Also, this test is applicable to **all** telescopes. Even better, this is a *null test*. In other words, the appearance of the stripes is straight and regular when all is well. This is because the star is at infinity and the grating is then close to the principle focal plane, unlike the much more complicated situation for the mirror maker who works with the light source and the grating both close to the centre of curvature and who has to assess curved stripes.

Mounting a razor blade to half cover the hole in a dummy eyepiece enables a version of the Foucault test to be carried out. Set up in the same way as for the Ronchi test. With your eye close to the hole and peering past the edge of the razor blade you will see the telescope objective/primary mirror flooded with light from the test star. If you move the telescope **very** slightly so that the blade begins to cut off the light you will see a black shadow sweep across the pool of light.

Adjust the focuser until moving the telescope causes the shadow's edge to become more blurred. Keep adjusting the focuser until moving the telescope causes the whole of the mirror to darken evenly. In other words, at the correct position you will not be able to decide whether the shadow sweeps across the image from the right or from the left when you move the telescope.

The razor blade is now coincident with the focal plane of the telescope. Any figuring errors or misalignment of the optics are hugely magnified and are thrown into a 'pseudo 3D relief' and become very obvious at the position where the pool of light is half extinguished. If all is well with the telescope the disk of light will appear perfectly smooth and flat and an even shade of grey. However, you will also see superimposed on the ideal image a moving set of swirls and corrugations caused by atmospheric turbulence and the convection of air over the telescope's

Figure A2 Ronchi patterns for a telescope field tested on a star.
(a) The pattern that would be seen for good optics in accurate collimation.
(b) The pattern that would be obtained for a spherically overcorrected system. For instance, a pattern like this might result from the primary mirror of a reflecting telescope being ground too deep at its centre, or perhaps the change is temporary and is caused by the mirror cooling rapidly, in which case the error will slowly lessen as the mirror approaches thermal equilibrium.
(c) This pattern is produced by a spherically undercorrected system (in this case if the mirror is cooler than the ambient air temperature, that fact ought to be evident because it will soon be covered in dew!
(d) This pattern is produced by the 'turned edge', a very common manufacturing fault in telescope primary mirrors.
(e) This pattern results from a telescope afflicted by zonal errors. An almost infinite number of variations of this are possible.
(f) This pattern illustrates astigmatism but a similar result would be generated from misalignment of the optics.


(a)
(b)
(c)
(d)
(e)
(f)

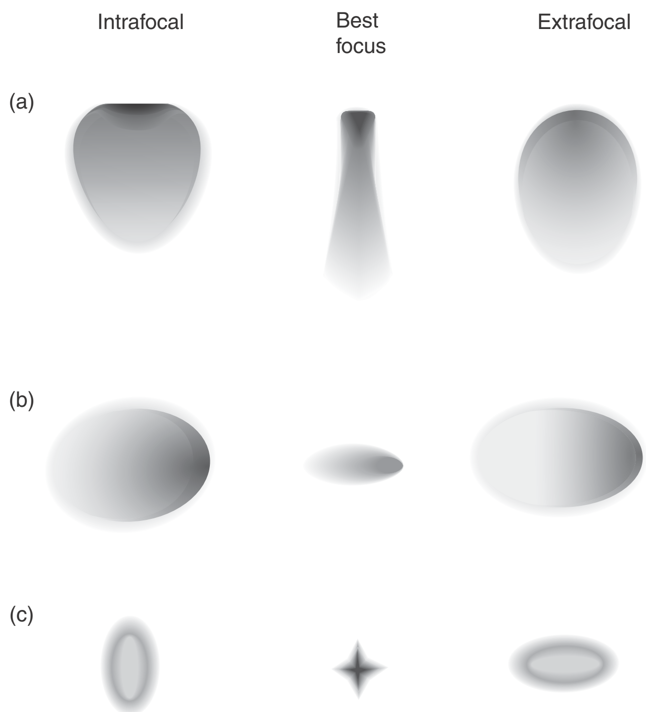


Figure A3 Depictions of the telescopic appearances of a star at high magnification, for different focal positions, with each of the following problems:
(a) tube currents;
(b) misalignment of the optics (note that the orientation of the cometic image does not change either side of the best focus);
(c) astigmatism.

optical surfaces. You will have to do your best to see past these moving waves and just judge the static underlying image.

The knife-edge test performed in the field using a star as the light source has the same advantage of ease of interpretation as the Ronchi test, over that made in the mirror-maker's workshop. The Foucault test is potentially more sensitive than the Ronchi test but it is also a lot more tricky to perform. Most people will prefer to use the Ronchi test, which is much more forgiving of less-than-firmly mounted telescopes.

Finally, one can inspect the focused, intrafocal and extrafocal (the eyepiece racked outwards from the best-focus position) star images when a high-powered eyepiece is plugged into the telescope. Choose a star of medium brightness as seen through the instrument, and one which is as high in the sky as possible, so that the effects of atmospheric turbulence are minimised.

The precise analysis of the appearance of the intrafocal, focal and extrafocal star images is a complex business. Also, this technique is of most use for telescopes smaller than 250 mm aperture because in larger ones the effects of atmospheric turbulence would overwhelm the effects of all but the most serious errors on most nights. However, Figure A3 shows the star-test appearances for the effects of astigmatism, misalignment, and tube currents as these are the most common troubles and are by far the easiest to recognise.

APPENDIX 3: POLAR ALIGNMENT

The first thing to say is that if you are using an equatorial mount that comes with the manufacturer's instructions, then refer to those. For instance 'GOTO' mounts will have their own elaborate set-up procedures that should be followed for the best results. The notes I give here will be useful in the absence of instructions, particularly for the simpler models of equatorial mounting.

Good telescope mountings will have provisions for making fine adjustments to the elevation and azimuth (east–west pointing) of the polar axis. Sometimes they also have polar-alignment telescopes built into the polar axes. The eyepieces of these are fitted with a graticule of specially marked lines, and/or circles, and divisions. Using these and a chart of the area around the celestial pole (or following other supplied instructions) one can achieve a polar alignment to within a fraction of a degree accuracy.

How accurately does your telescope mount have to be aligned? The answer to that depends on what you intend doing with it. Simple visual observation is made all the easier if the polar axis is aligned within a couple of degrees of the true pole. Adjustments made in response to a squint along the polar axis may well be good enough in that case, especially if the mount is fitted with a declination slow motion. Of course, observing is made more convenient, and hence more pleasurable, if the alignment is better than that. Photography involving exposures of a small fraction of a second is also uncritical of polar alignment. Longer exposures demand much greater precision. In addition, if you are going to set an equatorial mount permanently into position you will surely want to bother to get the polar alignment of your telescope as true as possible. In those cases you could follow the following procedure.

Once again, begin with your best go at a rough alignment (squinting along the polar axis, or using a compass and setting the polar elevation scale, if there is one, to your latitude, etc.). Then the idea is to make small corrections until the apparent north–south drift of the image of a star that is being tracked over a period of time is reduced to zero. This is done with the telescope pointing in at least two different directions.

First, set the telescope on a star that is close to the meridian (due south if you live in the northern hemisphere) and the celestial equator (i.e. with a declination close to zero degrees). Then lock the declination axis. With the telescope drive engaged, monitor the apparent north–south drift of the star. Ignore any east–west drift. If you are at all unsure as to the orientation of the image, momentarily move the telescope in declination a very small amount in the direction of Polaris. The direction in which the star appears to move in the eyepiece defines **south** in the field of view. Move the telescope to re-centre the star once more and continue.

If the telescope has no right-ascension (sidereal) drive then simply move the telescope every few minutes to bring the star back into the field of view. Does it come back to the **centre** of the field of view?

If the star appears to drift **southwards** over a period of time the polar axis is pointing a little **east** of the true celestial pole. An opposite error will produce an opposite direction of drift. Correct as necessary and repeat until the drift is as small as you wish to make it. I recommend you use a crosswire eyepiece or a graticule eyepiece to help you be precise.

Remember, though, to ignore east–west drift. It is only the north–south drift of the star's image that tells you of the azimuth misalignment of the polar axis.

The other adjustment – the altitude of the polar axis – is more difficult to achieve accurately by this method. For this you should select a star that is about 6^h (that is about 90°) east of the meridian and is preferably within 20° of the celestial equator. In other words, the star will be ideally due east and rather low in the sky. Centre the telescope on it and follow the same procedure as before. This time a star-image drift to the **south** indicates that the elevation of the polar axis is too **low**. As before, the opposite drift indicates the opposite error. Adjust as necessary.

The fact that the star is low over the eastern horizon means it will be affected by refraction (causing it to appear higher in the sky than it really is), the effect of which will decrease rapidly as the star rises. Neither can you select a star at 6^h east of the meridian and at zero degrees declination (the theoretical ideal) as this star would be right on the horizon and virtually unobservable even if you had an uncommonly clear horizon from your observing site. The consequence is that a small error in the elevation of the polar axis will remain even if you reduce the apparent star drift to zero.

If you have the time you could set the telescope on a star about 6^h west of the meridian and repeat the procedure once more. This time the required corrections are opposite to before (a star-image drift to the south now means the polar axis is pointing too high). If you find any apparent error this time, after you had thought you had corrected it before, then adjust the polar-axis altitude to a compromise setting.

If you are reading these words in the Earth's southern hemisphere then please reverse all the foregoing directions and corrections.

Once you are sure that the polar alignment of your telescope is correct then, and only then, should you consider fine-adjusting the tracking rate of its right-ascension (sidereal) drive if there happens to be any provision for adjustment. This is because a polar-alignment error will also produce east–west drifts of varying amounts dependent on where the telescope is pointing.

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