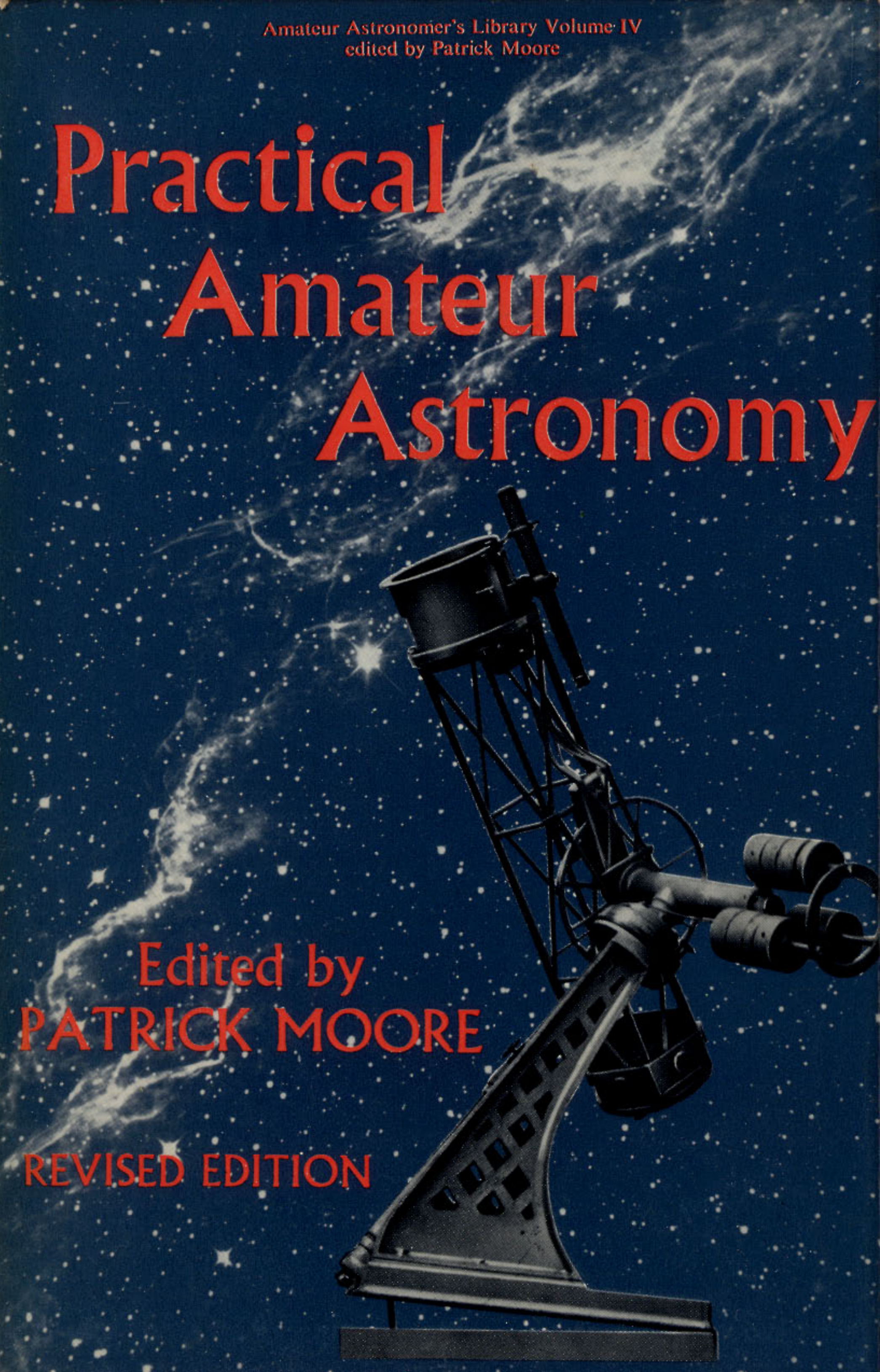
Practical
Amateur
Astronomy

Edited by
PATRICK
MOORE

REVISED
EDITION



Amateur Astronomer's Library Volume IV
edited by Patrick Moore

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Volume IV
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Most keen amateur astronomers possess books giving the theoretical background to astronomical science, and there are also many popular books devoted to observation. What is not so generally realized is that in spite of giant telescopes, artificial satellites, high altitude balloons, manned rockets and other highly sophisticated professional equipment, astronomy is one of the few sciences in which the amateur may make contributions of real value; and it is for the serious amateur that this book has been written.

Making casual, haphazard observations provides interest and enjoyment, but nothing more. If the observer has a moderate telescope, or even no telescope at all, he can, however, undertake useful work; it may be studies of the surface features of Jupiter, it may be naked-eye observations of auroræ, it may be tracking and recording Earth Satellites visually or by means of photography. Up to now, there has been no comprehensive book giving the amateur the necessary instructions for turning a pleasant hobby into a valuable branch of scientific research.

In *Practical Amateur Astronomy*, each chapter is devoted to some specific branch of observation, and each is written by an expert in his particular field. Sections are included dealing with equipment, observatories, photography, and radio astronomy, as well as with details of the observational programmes connected with the Sun, Moon, planets, comets, meteors, auroræ, and variable stars. The book is, in fact, an essential guide to the amateur who has made up his mind to perform useful work without having to spend large sums of money on complex equipment; it contains information which provides an overall picture, and will fill a long-standing gap in the literature of astronomy.

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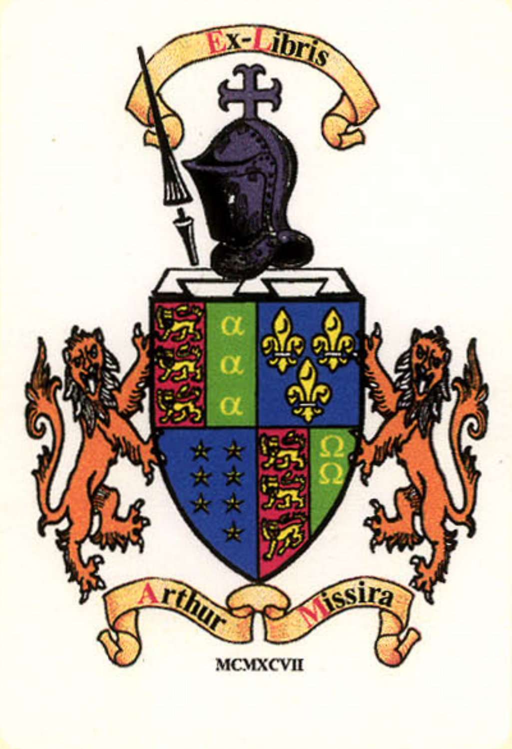

PRACTICAL AMATEUR ASTRONOMY

The Amateur Astronomer's Library

VOL I	*The Amateur Astronomer* *by Patrick Moore*
VOL IV	*Practical Amateur Astronomy* *Edited by Patrick Moore*
VOL V	*Naked-Eye Astronomy* *by Patrick Moore*
VOL VI	*The Amateur Astronomer's Glossary* *by Patrick Moore*
VOL VII	*The Amateur Astronomer's Photographic Lunar Atlas* *by Henry Hatfield*

PRACTICAL AMATEUR ASTRONOMY

edited by

PATRICK MOORE

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The source of the majority of the plates is acknowledged in the captions, but the publishers particularly wish to thank Henry Brinton for the trouble he took to obtain a suitable photograph of his telescope for reproduction on the jacket.

The line illustrations are all prepared from material supplied by the contributors, but special acknowledgement must be made to David A. Hardy, F.R.A.S. for drawing Figs. 13, 18, 19, 35, 38 and 48–52, to B. McInnes, whose drawings were used as references for Fig. 30 a – h, and the late M. B. B. Heath, F.R.A.S. for permission to reproduce Fig. 17.

FOREWORD TO THE SECOND EDITION

SINCE THIS BOOK first appeared, six years ago, there have been striking developments in astronomy, and inevitably this has meant some re-casting of the text. In most cases the original authors have brought the chapters up to date, but unfortunately we have lost, by death, both Mr. M. B. B. Heath and Mr. B. M. Peek—a fact which has been deeply regretted by their many friends and colleagues all over the world. I have therefore taken on the responsibility of overhauling these chapters. Mr. F. W. Hyde was also unable to undertake revisions, and the radio astronomy chapter has been re-written by Mr. J. R. Smith. To all these contributors, to the original authors and to the publishers I am most grateful.

Selsey, June 1969. *Patrick Moore*

FOREWORD TO THE THIRD EDITION

THE NEED FOR a third edition of this book has called for some extra revisions. So far as the Moon is concerned, so much has happened that it has seemed best to re-cast the chapter, and minor amendments have been made elsewhere.

It is with great regret that we must note the death of W. M. Baxter, the great amateur observer of the Sun. His contributions to solar research were outstanding, and show that the work of a skilled amateur is of immense value.

Selsey, January 1973. *Patrick Moore*

FOREWORD TO THE FOURTH EDITION

MINOR CHANGES HAVE again been made for this new edition—chiefly because the various space-probes have sent us back new information about some of the planets. However, the text remains essentially the same as in the third edition.

Once again we must record, with deep regret, the death of one of our contributors: James Paton of Edinburgh, one of the world's greatest authorities on auroræ. He is much missed by his many friends in many countries.

Selsey, August 1974. *Patrick Moore*

Introduction

MANY BOOKS ON astronomy have been produced in recent years. They may be divided into several types. There are popular accounts, aimed at the beginner; technical books, too complex (and usually too mathematical) for the layman, and dealing with specific branches of research; and a few works which may be termed "semi-popular", written principally for students. The latter are, of course, mainly theoretical.

The aim of the present book is entirely different, and is an attempt to fill a notable gap in the literature. It sets out to provide an observational guide to the serious amateur astronomer —not the casual "star-gazer", but the enthusiast who really wants to carry out useful work. Basic knowledge is, therefore, assumed. The reader should know something about astronomical science, though he need not be a mathematician.

A few general points seem to be worth making at the outset. Astronomy is still one of the sciences to which the serious amateur can make really valuable contributions. Professional work is concerned largely with the really important matters—that is to say, the stellar universe; giant telescopes are not intended to be used for, say, physical observation of Jupiter. Such work can be undertaken with relatively modest equipment, and this is where the amateur comes in.

His field is not as wide as it used to be; the development of space research has swung the attention of at least some professional astronomers back to the Moon and planets, which is a welcome development—and no amateur can hope to assist in programmes such as planetary spectroscopy, since the necessary equipment is too complex and too expensive. But the amateur still has a rôle, and even in stellar astronomy he can contribute by making estimates of variable stars of the types not so intensively studied at the official observatories. The value of amateur work is fully recognized by all eminent professional astronomers, and by most (though not all!) of those who are not so eminent. On the other hand, the amateur must recognize his limitations, and be well aware of the things he can and cannot do.

Sporadic observations are of comparatively little value; patience is essential, and it is always worth remembering that a single good observation is worth many hundreds of careless ones. Indeed, careless work is not only useless, but is actually harmful if it is published. Fortunately there are various societies which correlate the best of amateur work, and make it available; in Britain, for instance, there is the British Astronomical Association, which has a record of observational achievement second to none, and there are various observational societies in the U.S.A. In Australia there is an active branch of the B.A.A. in New South Wales, and the main New Zealand society is the Royal Astronomical Society of New Zealand with its secretarial address at the Carter Observatory, Wellington. The Royal Astronomical Society of Canada has a large amateur membership, and several major branches. The International Union of Amateur Astronomers was formed in 1971; the current President is Dr. Luigi Baldinelli of Bologna, Italy, while the secretary for the American continent is K. Chilton of Hamilton, Canada.

The serious amateur will naturally specialize in one particular branch of observation, and in compiling a book of the present kind it seemed essential to have each chapter written by such a specialist. This has been done, and it is hoped that the work will be really useful. Of those who have contributed, most are amateurs, while the remainder have strong sympathies with, and strong associations with, amateur work. Their willing co-operation, plus the great help given by the publishers, has made my editorial task both easy and pleasant.

Patrick Moore

Chapter One

THE SELECTION OF TELESCOPIC EQUIPMENT

G. A. Hole

Ideally, selection or construction of observatory equipment is governed by the aspect of astronomy that the user intends to pursue. It is often possible, by choosing wisely, to approach closely the ideal for several purposes. Nearly always the amateur's pocket has a lot to say about it, and it is fortunate that the cheaper reflecting telescope compares very favourably with the more costly refractor in nearly all the fields likely to interest a serious amateur.

Types of Telescope. Each type has its drawbacks and its advantages. In its own particular field of positional astronomy, where the stability of the optical axis is of prime importance, the refractor is the ideal instrument. Its long relative focal length, generally fifteen to twenty times its aperture, gives an image scale that requires eyepieces of only moderately short focal lengths to reach the higher powers, and the occasional opportunity for the use of the highest powers is within the reach of the really short focus eyepieces.

Refractors up to six inches aperture are often met with in amateur hands, and occasionally appear in the "for sale" columns of technical journals. If equatorially mounted they are capable of valuable research. Smaller sizes, generally on portable tripod stands, may be met with much more often. Indeed, the three-inch refractor is almost an institution. Above six inches in aperture the type is not so common, as the cost increases tremendously with aperture.

Fortunately the case is somewhat different with reflectors. These are less expensive to build, this fact resulting in a much larger telescope being available for an equal expenditure.

The image yielded by a properly wrought mirror is actually superior, on axis, to that of a refractor, as it is formed without the separation and recombination of the various colours, and is thus free from uncorrected colour. Except in very specialized and expensive objectives, it is not possible to do this for the refractor, some colour remaining uncombined and showing as a purple halo around bright objects. The reflector image, free from all false colour, has coincidence of focus for all colours; the visual and actinic focus is the same, and the reflector is therefore ideal for photography. The usable field of the reflector is limited by the image quality, which decreases as the distance from the axis increases.

Normally a reflector is much shorter in focal length than a refractor of similar aperture, thus making it less inherently powerful when magnification is considered. This is because it is not satisfactory to make the focal length of a refractor objective less than twelve times its aperture, for optical reasons. More often the figure is at least fifteen. The concave mirror of a reflector can reach equal, or even superior, quality with a focal length of eight times the aperture, and with the image being formed by one surface only. The mirror need only be of glass of normal quality. The refractor has a double lens, making four surfaces, each unit of extremely fine quality glass. Hence the difference in the cost.

The mechanical and optical layout of the two types also influences the cost. In the refractor the observer is at the lower end of the instrument, which makes a tall mounting unavoidable; its tallness dictates a degree of rigidity expensive to attain, and increasing the size of the observatory housing it. This applies to compound reflectors as well, which also have the observer at the lower end of the telescope. The Newtonian reflector, with its eyepiece at the top of the tube and with the weight concentrated low down, lends itself to a quite compact construction, making it possible to house a much larger instrument in a given space.

Aperture. These are factors to consider when choosing an instrument, but the decisive one is that the reflector provides a much larger aperture, and aperture is what matters in a telescope, as the resolving power, or ability to separate close images, is a function of this alone. It can be ascertained for any telescope by dividing the constant 4·56 by the aperture in

inches. The answer is the resolving power expressed in seconds of arc, and is thus easily ascertained owing to the work of Dawes, an observer who went into the question very thoroughly over a long period. The resulting Dawes' limit, while empirical, agrees closely with the purely mathematical Rayleigh limit, and is, as a matter of fact, slightly more stringent.

Therefore, a telescope that is 4·56 inches in aperture will just divide two points one second of arc apart. Reduce the aperture by masking it, and the two points can only be seen as one. Assuming the telescope to be optically perfect, no refocusing can divide the single point, which is larger than either of the original two, although it will be quite sharp. This divorces the function of resolution from that of definition, with which it is often confused.

A properly focused image of a point (star) will consist of one disk of light, surrounded by one or more rings of light due to diffraction. An image of a line object may be considered as a line of these dot and ring point images, and an image of an extended object is obviously composed of an array of dot and ring images covering the entire field, with the rings of one dot superimposed on the adjacent dot, and so on. It is therefore legitimate to regard the image yielded by telescope objectives as being composed of units of a diameter given by Dawes' limit. Thus a larger aperture will build its picture of smaller units, absolutely independent of sharpness of definition, which, given equal excellence optically, will be the same for all. If we compare the image with a picture made in mosaic, the tiles of which are one inch squares, it follows that no detail finer than one inch can be shown, to achieve which, requires the use of a smaller tile. So with the telescope. The larger apertures give the smaller image building unit, and hence can reach finer detail. It is clear that merely magnifying the coarser mosaic cannot expose detail which it does not contain. If, as an illustration, we take as an object one of the lunar seas, and examine it with a three-inch telescope, parts will appear perfectly smooth and devoid of detail, while the general picture is sharp and well defined. The same surface examined with a six-inch telescope will show the formerly smooth, structureless surface exhibiting detail, owing to the higher resolving power of the six-inch. So with every increase of aperture, more detail comes into the image, irrespective of magnifying power or definition. Greater aperture also means more light in the image, which will therefore permit fainter objects to be observed.

The Focal Length. This has a direct influence on the magnifying power of a telescope. It is not generally realized that the objective, as well as forming and illuminating the image, also plays some part in magnifying it. The image is enlarged by a factor of one for each ten inches of focal length. The distance of ten inches is taken, by universal consent, as the least distance of distinct vision for a normal eye, and the angular size of an object so seen is unity, or magnified once. An objective of 100-inches focal length presents an image ten times as large as that seen by the unaided, normal eye. This image can be further magnified with an eyepiece, which also is measured by reference to the ten-inch standard. Thus an eyepiece of one-inch focal length allows us to view at one-tenth of this standard distance, and therefore see the object enlarged to the same extent. It follows that a one-inch eyepiece will have a magnifying power of ten. If this is used to view the image from the 100-inch focal length objective, the resulting power is × 100. This step by step analysis of the process of magnification is contained in the expression "Magnification = F.L. objective divided by focal length of eyepiece", but only when dealing with a normal eye. Should the observer be short-sighted, so that his distance of distinct vision is less than the standard ten inches, then he is getting more magnification from a given set of optics, and conversely if he is long sighted. If the eye is brought to normal with spectacles, then the textbook figures apply.

The reflecting telescope uses a concave mirror to converge the light to a focus. If this mirror were spherical in figure, it could not bring all the light to the same focus. This fault is overcome by making the mirror so that its surface becomes, in section, part of a parabola. The difficulty of producing this figure on the mirror puts a lower limit to the focal length of, for normal use, about four times the aperture. The increasing length of the instrument, bearing in mind that the image is produced at the top of the tube and the observer has to get up to it, applies an upper limit. Whatever the focal length, the main mirror forms the image and the problem is to get that

image into the observer's eye. For instruments up to about twelve inches aperture, and focal lengths to about ten feet, the Newtonian solution is generally used, in which the upper part of the cone of rays from the mirror is diverted out through the side of the tube, where it can be examined with the eyepiece. A small optical flat mirror, set at an angle of 45°, is used to accomplish this; the flat, or to give it its correct name the diagonal, obstructs only a small amount of the incoming light. This construction, the simple reflector, was the earliest practical form of reflector and the invention of Sir Isaac Newton.

The problem of viewing the image, solved in the Newtonian telescope by the diagonal or prism, is avoided in two other types of reflecting telescope, which divert the cone of rays, not out of the side, but axially down the tube. At the same time its angle is modified so that it reaches a secondary focus outside the lower end of the tube. To pass this, the main mirror is usually perforated, the hole involving no loss in efficiency or light grasp as it occupies a dead spot, permanently masked by the secondary mirror.

The Gregorian telescope uses a small concave mirror, elliptical in section, placed outside the focus of the main mirror; being elliptical, it has two foci. The position of this secondary is adjusted until the focal plane of the main mirror coincides with one of these foci, the shorter one, when any image in that focal plane is reproduced in the second focus of the elliptical mirror. This secondary image is enlarged in direct ratio to the geometry of the ellipse, and is right way up, or erect. The work done by the concave secondary, from outside focus, can be done by a convex secondary inside focus, which arrangement constitutes the Cassegrain telescope. It is the shortest of all telescopes, and the image is telescopically normal; that is to say inverted. In both these compound telescopes the secondary mirrors are really transfer devices, and the resulting enlargement of the primary image is merely the price paid for bringing the image to the bottom of the tube. The enlargement, itself, is not always an advantage. Here these mirrors differ from their refracting counterpart, the Barlow lens, whose function is solely that of amplification.

Modern Improvements. Image formation by lens or mirror was the basis of telescope design until about thirty years ago, the drawbacks of each being recognized and accepted. The defective colour correction of the refractor, and the nasty images off-axis, in the reflector, were regarded as unavoidable. In 1930, Bernard Schmidt produced an instrument that has since resulted in a new class of telescope, using a mirror to form the image, and a lens to correct it. The lens is placed at twice the focal length in front of the mirror, and modifies the light passing through it. This modified or corrected light then passes to the mirror, which forms an image in the normal way. As the mirror has only to converge the light to focus, and not to correct it, it can have a spherical figure. Rays that pass through the corrector lens at an angle to the axis, also receive the appropriate correction; and as the mirror is spherical, it can be made larger to receive them. This system can accurately image extremely large fields, amounting to 20°. As the 100-inch Mount Wilson reflector has a field free from coma of only 7 minutes of arc, and the 200-inch, only 3 minutes, the importance of this development can be readily realized.

The fact that, in the Schmidt, the corrector plate is at twice its focal length in front of the mirror means that the telescope is twice as long as normal. This consequence of the design results in steep curves of short radius being used on the main mirror to keep the overall length down. With its inherent ability to accept extremely large fields, its large aperture, and its short focal length, the Schmidt design produces an instrument that is more a camera than a telescope, and it is as such that it is mostly used. Subsequent developments in the system have produced variants shorter than the focal length of the mirror, while retaining the extremely wide aperture.

The compound principle has been applied to the lens-mirror telescope in the form of the Maksutov Cassegrain, where the very steeply curved corrector plate is inside the focal point of the main mirror, with a central patch of its inner surface silvered or aluminized and used as a secondary mirror. All surfaces being spherical in a Maksutov (on paper, at all events), the use of a spherical secondary does not contribute to bad off-axis images, as the correction of these images is the function of the corrector plate itself, not just the part used as the secondary mirror.

When telescopes were invented, and for nearly 200 years after, the mirrors were made of metal, as the process of coating glass with silver to make it highly reflective had not been invented. Today, telescope mirrors are made of glass, or, for special purposes, of fused quartz, and coated with either silver or aluminium. Silver for general use is dying out, as it is not so tough as the aluminium and requires a certain amount of care taken if its life is to be a useful one. It has, however, certain advantages for the amateur, and is inexpensive to apply.

The glass on which this film rests may be either ordinary plate, or low expansion glass, of which Pyrex is typical. For very long focus mirrors, or for those intended for solar use in a cœlostat or solar telescope, the higher expansion of normal glass may result in temporary changes in focal length or figure. The lower expansion materials are justified here, but for visual observation mirrors of normal glass are quite satisfactory, if properly figured.

The Eyepiece. Eyepieces used with any telescope are important. They must function without harming the image formed by the objective. They must receive as large an area of the objective's field as can be contrived, and present images in this area to the eye with as little distortion as possible and the minimum of false colour.

The function of the eyepiece is to receive rays diverging from the image and render them parallel, or closely so, for the eye can only function when the light rays entering it are close to parallel. Hence the ten-inch least distance of distinct vision. Light from an object closer than this is so divergent that it focuses long, or behind the retina. Only a shortsighted eye can deal with this, and the light emerging from the focus *is* diverging.

The eyepiece, placed so that its focus coincides with that of the objective, rectifies this condition and permits normal vision at the much closer distance of its own focal length. For objects on axis this is perfectly satisfactory, but it becomes increasingly difficult for objects away from it. Many forms have been developed in order to yield larger fields and more accurate images. None can fulfil all requirements, some suffering internal reflections that give rise to ghost images which are confusing when other faint objects are present. The ghosts can be identified by the direction of their movement when the telescope is moved slightly. They oppose the direction of movement, and vanish when the object causing them is brought to the centre of the field. The use of anti-reflection coating on the lenses greatly reduces them, but, with some designs, cannot eliminate them completely.

The single concave lens used as the eyepiece in the Galilean telescope may be eliminated, as it restricts the field to an extent that renders it useless before any real power is reached.

The Huyghenian eyepiece, consisting of two plano-convex lenses of focal length ratio one to three at a spacing of half the sum of the focal lengths, functions very well with telescopes of aperture to focal length ratios of fifteen and over. It is probably the best known of them all, but does not deal with the wider cones from reflectors at all well. Having four air/glass surfaces, it is prone to ghosting. Its focal plane is that of the eye-lens, and is thus inside the eyepiece in the plane of the field diaphragm. Because of this, it is called a negative eyepiece. It cannot be used with external cross wires or micrometer webs, but can be fitted with such webs across the diaphragm for special purposes where distortion of the wires can be tolerated.

The Ramsden is also a two-lens eyepiece, composed of plano-convex lenses of equal focal length, placed their own focal length apart, flat sides out. In practice they are spaced slightly closer, to avoid dust and surface defects on the field lens being in sharp focus, and to increase the eye distance. In this condition the eyepiece has an external focal plane, and qualifies for the title "positive". Apart from a tendency to ghosting, the Ramsden, with less spherical aberration than the Huyghenian, is an excellent eyepiece, suitable for use with micrometer webs. The eye-lens is sometimes achromatized by making it a doublet. When the leading lens is made as a crossed lens, in which form the spherical aberration of a single lens is at its lowest value, and assembled with an achromatized eye-lens, the combination is known as a Kellner eyepiece. It makes an excellent low-power with a large flat field. As now made with bloomed surfaces, the ghosting is much reduced.

A modern development of the Kellner, and therefore of the Ramsden, is the family of eyepieces known as orthoscopics. Originally designed by Mitenzwey, the eye-lens is single and

the field-lens becomes a doublet or triplet combination, with its aberrations opposed to those of the eye-lens, thus cancelling them out. Many variations on this theme exist, all giving wide flat fields and much reduced spherical aberration and colour. These eyepieces can work well with extremely wide angle cones of rays, and so are the obvious choice for large, short focus reflectors.

Another whole family of highly corrected eyepieces have been developed from the old Coddington lens. They retain the advantages of solid construction (elimination of inter-lens air spaces), and cemented combinations have resulted in almost complete elimination of chromatic and spherical aberrations. These solid eyepieces are noted for their freedom from ghosts and scattered light. The resulting pure fields are rather smaller than those yielded by the orthoscopics, but are comparable in the finest designs of the type. Examples are the Tolles solid ocular, the cemented doublet and triplet eyepieces, and the king of all eyepieces, the monocentric. This design, in which all curves are practically struck from a common centre, has proved itself to be almost perfect. Most of the famous makers have their own version of this eyepiece, all characterized by delightfully flat, pure fields and practically complete freedom from the various aberrations.

The device known as the Barlow lens, while not an eyepiece, cannot be omitted from any discussion of them. It consists of an achromatic doublet lens of negative focus. This is placed inside the prime focus of a telescope to reduce the convergence of the rays from its objective. The image formed by this modified cone is enlarged in direct proportion to the distance the Barlow lens is placed inside the original focus. The limit to this is reached when the Barlow is its own negative focal length inside. Then the convergence of the original cone is cancelled, the rays emerging are parallel, and no image is formed—at least, where we can get at it. Being able to alter the focal length by installing a small inexpensive accessory means that each eyepiece is able to deliver several different powers, and provides an enlarged image for photography. It is necessary that the Barlow be large enough in aperture to prevent it acting as a stop when at its extreme inside position. The combination of a Barlow and an eyepiece into one unit, forming a variable power eyepiece, offers a remarkably flexible, compact assembly, and has been perfected by H. E. Dall, of Luton, whose optical work is known wherever telescopes are seriously used.

Mountings. Good optics cannot be used to the best advantage unless they are adequately mounted.* Beware the spindly, light stand; it will emulate the jelly, and make observation a trial. Certain requirements must be met, and certain basic mountings have evolved to meet them. Any mounting must permit two motions of rotation at right-angles to each other. If the axis of rotation is vertical, then the telescope will trace out a line parallel to a level horizon, and constant use of the axis of elevation will be needed. This type is called altazimuth, and suffices for casual work. Tilt the axis of rotation until it is parallel to the axis of the Earth and it becomes a polar axis, so that the telescope will follow a celestial object without a change in elevation. Such mountings are termed equatorial, and the most likely to be met with is the German mounting, where the telescope is at one side of the polar axis, with a counterweight at the other. Both refractors and reflectors are usable on this mounting, the mounting head being on top of a tall pier or column for the refractor, while the lower centre of gravity of the reflector allows the pier to be much shorter. Being an overhang-mounting, it calls for massive construction to secure rigidity. Eliminate the overhang, and bring all the weight inboard, and it becomes easier to attain the desired rigidity. This is achieved in the type of equatorial known as the parallactic ladder, of which the mounting of the 200-inch reflector is a modified version. A ladder mounting carries the telescope swinging in elevation, inside a rotatable frame. The frame is carried in bearings at either end, and is the polar axis. Being at an angle, the top bearing is on a pier or other support. All weight is inside the spread of the base, and no dead weight, in the shape of counterweights, is carried. The upper bearing of the frame is the main drawback to this mounting, since its presence prevents the telescope from reaching the pole and adjacent areas. Even if the ladder is long enough to allow the telescope to swing clear through, the telescope is unusable for these regions. This will not, however, bother the observer whose main work lies along the ecliptic. Two solutions exist. In the type named the English mount, the ladder is merely a prolongation of the polar axis; the telescope is on one side and a counterweight on the other. It resembles a German mounting with its polar axis extended and supported. The second solution is that used in the 200-inch reflector. Here, the offending upper bearing has been expanded into a ring, and the top section of the ring cut away to let the telescope have an unobstructed view down to the pole. Smaller versions of this have been built, but the amateur is not likely to find them on the market. He can, however, build one himself.

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* See Plate 1.

The mounting offering most to the instrument of moderate size, if it be a reflector, is without doubt the fork. Here the telescope is carried in a fork mounted on the upper end of the polar axis, which needs to be very rigidly constructed. Meeting this requirement, however, frees the mounting from almost all the drawbacks of the other types. It is a universal mount, the telescope never needing reversal. This reversal of the telescope from side to side, with its simultaneous turnover in altitude, presents only inconvenience for visual work, but for photography it stops work altogether, as the plate is turned over with the telescope. It is to be avoided, and, short of a cranked, overhung pier, the fork seems the best solution.

Drive. Whatever the mounting, the question of a drive for its polar axis has to be settled. For star gazing, and where no long exposure photography is intended, a manual drive is satisfactory. The actual power is nearly always applied to the polar axis by means of gearing. The smoothest gear, and that offering the greatest speed reduction, is worm or screw gearing. A good telescope mounting has on its polar axis a large wormwheel, the larger the better. The diameter of this wheel is important, as while a smaller wheel, when driven at the required speed, would certainly drive the telescope, the rotation so obtained lacks the steadiness given by the longer leverage exerted by the larger driving wheel. So one thing to look for when selecting an instrument is the size of its driving wheel.

On some of the larger, older mountings the drive is obtained with a sector of a very large wormwheel, which means that when the end of the sector is reached the driving worm must be disengaged, the sector unclamped and moved back, and the worm re-engaged. The disengaging driving worm is necessary but unsound. Mountings with this feature should be very carefully examined to see that the teeth on the worm sector are not too badly damaged.

Whatever the type of wheel, the worm is the actual power input. It can be turned by hand with an extending rod ending in a universal joint to permit drive at odd angles, a thing not always easy to do, as the tube sometimes takes extreme positions. Mountings, using manual drives, should be able to accept the drive rod from either end of the worm, for this reason.

More often the worm is rotated by some form of clock or mechanical power. Older instruments used the power of a falling weight, hauling a wire cable over pulleys to turn a drum. The rotation of the drum was controlled by gearing up to a flying governor, very similar to the governor fitted to clockwork gramophone motors. When in good condition this kind of drive can be adjusted to give good following.

The electric motor has superseded gravity as a motive force, the main problem being one of speed control. The most general form is some variety of the Gerrish system. In this, the motor speed is constantly monitored by a pendulum operating a switch. The motor also operates a second switch in time with the pendulum, and receives current during a part only of the swing. A fly-wheel preserves its rotation during the dead period. Should the motor get out of step with the pendulum, the switching ensures that the motor receives current for the required part of each swing until it has again attained the correct speed—a device so excellent that it became almost universal, and it also added a new verb to the language, "to Gerrish", i.e. to function correctly.

The combination of alternating current and the synchronous motor makes a prime mover of high accuracy. These motors run at a speed determined by the frequency of the mains, and each one using it has the accuracy of the highly accurate master clocks that control it. With suitable gear reduction the synchronous motor is a simple, compact drive. When using mains current the speed cannot be altered, so some way of superimposing the output from a second motor is needed for control purposes, this being usually effected through a differential gear somewhere in the gear train. The second motor is reversible,

and is controlled from a reversing switch on a wander lead. A suitable gear reduction for use with a synchronous motor running at 1,500 r.p.m. is 2,154,750 to 1, obtained by using a 608 wormwheel on the polar axis, its worm rotated by a 443 wormwheel, and this worm in turn rotated by an 8 to 1 gear, which can be normal spur. This results in a reduction of 2,154,752 to 1, the error being 2 motor revs in a sidereal day (at 1,500 per minute). These figures incorporate a refraction allowance of 26 seconds, the sidereal day plus 26 seconds being taken as target. Conceiving this gear-train passed quite a few spells of my sentry-go during the war! It has since been fitted to several largish telescopes, with no complaints.

The national A.C. supply of 230 volts 50 cycles provides an energy source consistent enough for most purposes, but the ultimate in synchronous drives is one in which the frequency of the current is controlled by electronic means. Such drives are the last word in accuracy, but are of the order of special equipment, and are not likely to be found on normal commercial instruments.

Circles. These are normal fittings on commercial instruments, but their absence should not preclude the acquisition of an otherwise satisfactory telescope, as they are easily added and need not be finely divided. While the majority of observations do not demand their use, when thoroughly used to them they become so automatic that I have heard a well-known observer rather sheepishly admit that he found himself setting them when he wanted to look at the Moon. Like driving wheels, the larger the better. As the only function of circles on an equatorial is to put an object inside the field of a low-power eyepiece, 2-minute divisions on the R.A. circle, and half degree ones on the declination circle, suffice. They can be interpolated to half this easily, and need no verniers. The R.A. circle is sometimes solid with the polar axis, and sometimes a friction fit on it. If solid, it is read against a single fixed index and the hour angle has to be worked out for each object. A friction slip circle reads from one index fixed to the mount, and a second one fixed to the polar axis. The hour angle is set off on the circle at the start of the evening, and, providing the drive is not stopped, that is the end of it.

Finder. Very few objects cannot be traced with the finder, which is standard equipment on any telescope. It consists of a low-power wide field telescope of about 2 inches aperture with cross wires in the focal plane of its eyepiece. It is desirable to fit more than one finder on a Newtonian, as the telescope gets into awkward positions sometimes. More often than not a finder is improvised from any small refractor that the owner can obtain or construct, and it may be awkward to provide for the objective to be separately focused on the cross wires, as is the case in standard finders. Here the wires can be pre-set to the focus of the eyepiece, and the assembly moved as a whole to bring the objectives focal plane on to them. Human hair makes a good wire, if a little on the thick side, and is easily secured with normal adhesives.

Chapter Two

ASTRONOMICAL PHOTOGRAPHY FOR AMATEURS

H. E. Dall

A VERY SIGNIFICANT difference between the work of amateurs and professionals in the field of astronomical photography is that the professional is primarily interested in highly accurate positional, luminosity, and spectroscopic measurements. For this reason he almost invariably uses glass plates of a special grade of flatness, and for Schmidt camera work they are very thin and circular to enable them to be deformed to fit a spherical focal surface.

It is true that a few advanced amateurs have built and used Schmidt instruments, but in the main even these few have not attempted to emulate the prime photographic function of the professional. This is surely a matter for self-congratulation for the amateur, because he finds it more rewarding to concentrate his efforts in fields which the professional seldom fully covers, that is, on the ever changing aspects of the Solar System: the Sun itself, the planets and satellites, comets and meteors.

The standard of photographic work of the professional is extraordinarily high when applied to the photography of deep space and the spectra of its enormous population of stars and galaxies. Large instruments really score in this field because light grasp is the crucial requirement. The light grasp of the Palomar 200-inch is at least 600 times greater than that of the average keen amateur's telescope. This overwhelming advantage of the big instrument is very evident when comparing photographs of star-fields from the two sources; distant galaxies showing intricate detail are seen on the one which are absolutely invisible on the other. On the other hand, when it comes to comparing photographs of lunar and planetary detail (the domain of high resolution photography), the best that has been achieved with the Palomar 200-inch is barely twice as well resolved as the best taken by a keen amateur's telescope. A lunar crater-pit two miles in diameter is as well shown on the amateur's photograph as one a mile across in the best Palomar photograph. The obvious inference is that the amateur is much more likely to achieve the satisfaction of an astronomically useful photograph by concentrating on high resolution work—mainly of the Solar System. Aesthetic personal satisfaction is another matter. An ordinary camera set on a stand and pointing towards the celestial pole is a common introduction to astronomical photography. With the shutter open for an hour or two, the resultant circular star-trails is sure to thrill the beginner and whet his appetite for progressively more useful work. This same simple set-up can be used for recording the trails of earth's artificial satellites, with a chance of a useful contribution if the timing record is well organized.

Personal satisfaction is also achieved by the amateur in the mere contemplation of his first nebular photograph—probably that of the relatively bright Orion Nebula. It will be a poor thing by comparison with those taken with the large American telescopes for the reason already given, but it will nevertheless show more detail of the structures of the luminous cloud than the eye at the same telescope perceived.

There is one possible branch of stellar astronomy upon which amateurs would find it worth while to concentrate, even if occasions to practise it are quite infrequent. That field is the photography of novæ, as closely following discovery as possible. On the law of averages a spectacular nova or even a supernova is due at any time now, and the occasion may favour the amateur having dark unclouded skies when the professional is unable to do anything about it. It is too much to expect an amateur to discover a nova photographically by casual star-field exposures. The professional engaged in systematic photographic searches for comets or asteroids is much more likely to do so, especially as he has the aid of his powerful tool, the "blink" microscope. Even this technique is not beyond the scope of the amateur, and the reward of a discovery is particularly great in this field, more so if the nova is waxing rather than waning. A blink microscope is simply a stereoscope of the same general type as used to examine air photographs, and the pair of photographs examined are those of identical tracts of sky taken at

suitable intervals. Any object missing from one, or not equally impressed on both of the photographs, shows up prominently in the same way that a speck of dirt on any one of a stereoscopic pair of photographs is painfully obvious.

Our climate, with its greater than 70 per cent cloud cover, mitigates against the chances of success, but I do not think this method of discovery of comets, asteroids, or novæ has been properly exploited by the amateur. The thrill and good chance of success is more likely if a moderately wide field of 30°–40° is covered with good definition. The technique is attractively simple with an aircraft camera using roll film, and fixed on a clock-driven equatorial mount, if the film and processing costs are not major obstacles.

A moderate-sized Schmidt camera working at about *f*/2·5 would be ideal for the purpose, but would need many more exposures to cover the same area, because of the smaller field of about 10 degrees. Several exposures per hour are possible with this aperture, and many distant galaxies would be recorded. No prints are made, as the negatives are examined in the blink microscope.

Having now briefly covered the possible amateur incursions into "deep sky" photography, a more systematic discussion of ways and means of this and Solar System photography follows.

Cameras. A decision on the type and size of camera is one of the first considerations; whether it is to be home-made, or of a standard type available in photographic shops.

The size chosen must depend on the type of work intended and the price one is prepared to pay for materials. For high resolution photography of the Moon and planets with amateur size telescopes, there is much to be said in favour of 35 mm film, easily available in many types. It is possible to use a 35 mm camera either with its lens or without it. If the camera is of the modern reflex type, removal of the lens is advisable. This reflex type with focal plane shutter, which permits focusing and framing on a ground glass screen up to the moment of exposure, is undoubtedly the best for this class of photography. At least a dozen makes are available (including the Leica with reflex housing), and some can probably be purchased without the lens if desired.

The camera must be coupled coaxially with the eyepiece tube of the telescope and preferably with adjustable distance (or separate adapter lengths) between eyepiece and camera flange. With a telescope of focal ratio around *f*/8, a distance of five or six inches is desirable to give a useful magnification by a medium power eyepiece without straining the coverage angle required from it. With a Cassegrain type of telescope, a suitable magnification of the primary image can be arranged by using an appropriate secondary without using an eyepiece at all. Naturally, the fewer the number of optical elements between primary mirror and the film, the less is the loss of light and, in general, the better is the quality of the image. Light is nearly always at a premium: except for the Sun and for Venus, more light would be appreciated for focusing and for keeping the length of exposure down. If the camera is *not* of the reflex type, nor fitted with a reflex attachment, perfectly good astronomical photographs may still be taken, though not with the same facility. In this case a quick attachment of camera to eyepiece with minimum risk of shaking the telescope is desirable. The camera would be used complete with its lens set to infinity focus, and a "between lens" shutter or focal plane shutter is equally suitable. The procedure is to use the telescope in the ordinary way with its eyepiece. The object is framed, (i.e. the most important part is placed centrally) and focused through the eyepiece with the eye at the normal "rest" condition focused on a distant object. If this is done correctly, parallel bundles of light issuing from all parts of the field of the eyepiece converge on the "exit pupil" or "Ramsden disk", usually situated about half the focal length of the eyepiece on the camera side. The camera is attached quickly and gently, with the camera lens as close to the eyepiece as possible. Ideally the exit pupil should come midway between the camera lens components, where the iris is situated. The angular field of the eyepiece then becomes the coverage angle of the camera lens, and the increase in size of the image on the film compared with the image at the eyepiece is equal to the ratio of the camera lens focus to that of the eyepiece. Thus if a magnification of 8 is desired, and the camera lens is 2-inch focus, an eyepiece of ¼-inch focus is necessary. To avoid such a short focus eyepiece the primary image can be enlarged with a Barlow lens, or by a positive erecting lens. Although excellent astronomical photographs have been taken with this "infinity to infinity" focusing system, there are several sources of uncertainty in results which do not occur with the reflex focusing systems. One is that the amount of accommodation of the human eye (especially for the flexible eye of youth) makes eyepiece "infinity" focusing rather indefinite. Practice by quickly transferring the gaze from eyepiece to a distant object is helpful here; so too is the much reduced accommodation of older people. Another difficulty is the possible shift of image when transferring camera to eyepiece after framing and focusing.

The shutter should of course be set, and the film advanced, before focusing, and the shutter should be released for exposure by means of a cable or pneumatic release, preferably several feet long. Very few telescopes are so rigidly mounted that camera body release buttons can be operated without serious risk of shake. The loss of light through the camera lens is not at all excessive if it is coated, and for this duty a 3 or 4 element lens working at *f*/3·5 is as good if not better than an *f*/2 lens. The iris should be fully opened.

Home-built Cameras. An amateur contemplating the building of his own camera will no doubt want to exploit his own particular ideas. Much variety is possible. T. W. Rackham (*B.A.A. Jnl.*, vol. 66, p. 61, 1956) built a 35 mm film camera in which focusing was through a small hole in the back with a fixed high-power magnifier set by trial to focus on the film plane. Accommodation troubles are lessened by using a very short focus magnifier, e.g. ¼-inch focus which would be satisfactory providing that the image viewed is not longer in focus than *f*/20 or so. Rackham's camera, which has done excellent work, used a retractable tube carrying a prism for the purpose of framing, and a large aperture between-lens type shutter for exposing. Much simpler cameras can be used, without shutter or means of framing. These omissions may be overcome by exposing with a moving card screen across, but not contacting, the mouth of the telescope tube, and the framing can be done with an accurately set finder or guide telescope.

Plate 2A shows a reflex type 35 mm camera home built by the author (except for the shutter). The latter is a "between lens" everset type of 1½-inch clear aperture and speed range from 1 second to 1/100. This is operated pneumatically, and the cylinder and piston is visible at bottom centre. At top centre is the ×8 magnifier focused on a very finely ground screen with ⅛-inch diameter clear spot in the centre. The reflex mirror is click-stopped in or out of position by the small knob below the viewing tube. The film feed knob can be seen at left centre. This is also click-stopped to advance the film by either one, two, three or four film perforations, depending on the size of the planetary or lunar image on the film. For a small planetary image, e.g. of Mars, four exposures can thus be made in the space of a normal frame. Owing to atmospheric turbulence a whole series of exposures on the one object is made, on the theory that brief intervals of good seeing may occur. Sometimes there is little to choose between the resulting images. More often perhaps 1 in 10 will be markedly better than the rest, and only the best is subsequently enlarged by about 6 diameters, so that the full frame enlarges to halfplate size (6½×4¾ in.) which is well suited for visual use. Contact prints from the film are suitable for 2×2 in. slide projection.

Limits of Resolution. The amount of detail which *can* be packed into one frame of a 35 mm film is equivalent to that on a television screen of at least 1000 lines, i.e. twice as many as the present screen shows. Whether this amount is actually achieved will depend on the state of the atmosphere, the accuracy of focusing and clock drive, and on the quality of the optics. The 1000-lines limit is that imposed by the grain of the film of medium speed type.

The texture of the image detail is, or should be, much finer than this at prime focus. An *f*/8 primary image has a texture (limited by diffraction) five or six times finer than the above film could register. A double star at Dawes' Limit has a separation less than 1/5000 inch in this case. This suggests that if the primary image is enlarged five or six times before reaching the film, the blurring effects of grain and diffraction would be equal and give optimum possibilities for high resolution photography. This degree of enlargement would indeed give very good results for lunar or planetary work, but there is usually sufficient light to focus the final image with an even

greater enlargement, say ×10 on *f*/8, giving a final image of *f*/80. This will reduce the harmful effects of film grain and squarely place the limiting factors on the state of the atmosphere, assuming that the technique is otherwise good.

Choice of Film. For high resolution work the exposure time should never exceed a few seconds. It is better to aim at one second or less, to minimize atmospheric or clock-drive troubles. It so happens that there is barely enough light to focus by if the required exposure exceeds three or four seconds.

Ilford FP4 Series 2 film is probably as good a choice as can be made for this type of high resolution photography, but for feebly illuminated objects, such as Saturn or Uranus, faster film, e.g. Ilford HP3 or HPS, is desirable. There is a fairly wide choice of film material available for 35 mm cameras, and simple theory would indicate that a factor of merit to compare them would be the product of the relative speed and the square of the film resolving power. These figures are available from manufacturers' lists, and appear to show that the higher speed films have the highest factor of merit. However, many practical tests with the various materials available has convinced me that actual relative merits are much closer than this theory shows, presumably due to the indeterminate nature of film resolving power. Films differing in speed by a factor of 20 or more, yield final results which are not easy to distinguish when the enlargement of the primary image is adjusted to give a similar exposure time for each type. The fastest films are much more prone to stress marks and blemishes than those of medium speed, hence the choice of FP4II or Kodak Plus X used on a final image of about *f*/80.

Clock Drive. A tacit assumption of a clock drive for the telescope has been made in the preceding pages. If there is no clock drive it is possible (though difficult) to "pan" the telescope by means of a smoothly operating slow motion. Alternatively, the exposure time should be reduced to a small fraction of a second, providing the object brilliancy permits. Quite good lunar and planetary photographs have been taken without a clock drive, but to achieve maximum resolution the shutter speed must be comparable with the time taken by the diurnal movement of the image to equal the resolving power of the telescope. For a 6-inch telescope this time interval is 1/20 second, and for a 12-inch telescope it is 1/40 second. Venus is the only planet sufficiently brilliant to yield a correctly exposed picture in 1/20 second with an *f*/80 image, (i.e. 480 inches final focus for 6-inch aperture) on FP4 film. Thus with this planet, and of course the Sun, it is quite possible to photograph detail to the resolving power limit without a clock drive, atmosphere permitting. For the Moon and the other planets this satisfactory state of affairs will not be possible until much finer grain high-speed films become available, of which there is little sign. It may yet happen, but progress in this direction has been disappointingly slow over the last half century, even more so for photographic emulsions suitable for exposures of long duration for deep-sky photography.

Enlarging the Primary Image. Using a reflex type of camera without a lens, the telescope eyepiece may be used to provide the amplification required, the image from the eyepiece being projected directly on to the film. The distance between eyepiece and film should be equal to $(M+1)$ times the focal length of the eyepiece, where M is the magnification. For example, if the primary image, initially *f*/8, is to be magnified × 10 to give a final *f*/80. Also if the eyepiece is 0·60 inches focus, the distance from the centre of the eyepiece to the film should be $11 \times 0{\cdot}60 = 6{\cdot}6$ inches. With an eyepiece of one-inch focus the distance would be a somewhat awkward 11 inches. Several other methods of enlarging the primary image have already been mentioned in connection with "infinity to infinity" focusing systems. The Cassegrain secondary method was also quoted as a method involving no lenses at all between primary and film, though the addition of a Barlow or erecting lens would enable the magnification to be varied over a useful range. If the Cassegrain secondary gives a secondary image above *f*/25, the optical corrections required for the subsequent amplification are easily met with simple non-achromatic lenses if achromats are not available. Achromats are certainly desirable for direct amplification of the primary image if this is *f*/8 or smaller. Badly designed or badly made Huyghenian eyepieces used for enlarging the primary image will give final images visibly defective on the screen of the reflex camera. An achromatic (e.g. orthoscopic) eyepiece is a good acquisition for visual purposes or for enlarging, and it can serve as a criterion in comparing the final image with that from other eyepieces.

Atmospheric Dispersion. With objects photographed at altitudes of less than 30°, the colour fringes on planetary and lunar images as seen on the reflex screen are quite noticeable, and will cause perceptible degradation of the quality of the final photograph. Colour filters may be used to reduce or eliminate the trouble if the available light permits, as it generally will for Venus. Similarly and additionally, the secondary spectrum from refractors may be eliminated by using an Ilford "Astral" green filter which absorbs light at both ends of the spectrum, but necessarily at the expense of light in the final image. A method of eliminating (or rather of neutralizing) atmospheric dispersion without loss of valuable light is described in the *B.A.A. Journal*, vol. 71, p. 75, 1961, and is based on the decentring of a lens element.

Developing and Printing. The operations follow quite normal photographic practice, but special precautions to minimize grain and its effects are well worth taking in view of the considerable enlargement to which the small pictures will be subjected. The fine grain developer "Promicrol" appears to give as fine a grain as any alternative tried, while retaining the normal film speed. Other fine-grain developers may be similar, but it is always wise to get thoroughly accustomed to one developer and indeed one type of film. If the exposures are known to be on the short side, due to hazy skies or other reasons, full or a little extra development is desirable even though grain may be somewhat increased. For astronomical work, the harm from the coarser grain is often less than that from too little density in the image. When printing, grain can be reduced in at least two ways: first, by deliberately defocusing during the enlarging. When the image is critically focused and the enlarger lens iris set to the operating aperture, close scrutiny, if necessary with a magnifier, will reveal the grain. The focus is then changed *just* sufficiently to blur the grain into invisibility, and the exposure made. The second method is to use almost a pinhole aperture stop (1 mm to 1·5 mm in diameter) in the enlarging lens after focusing at normal apertures. By this method the grain is blurred into invisibility by diffraction, though the exposure time may amount to a minute or two. These methods of grain blurring have no effect on the picture detail, but give a more pleasing effect—very similar to the more complicated way of grain suppression in which six or eight negatives of the same object are printed in exact superimposition: a rather difficult operation.

Colour Photography of the Planets. With the advent of very high speed 35 mm colour film, it is technically no more difficult to take high resolution astronomical photographs in colour than in black and white, although the exposure latitude for correct colour rendering is relatively small. Jupiter and Mars are the only planets with pronounced tints, and very pleasing colour transparencies of these have been taken by amateurs, showing the pinkish colour of the Red Spot on Jupiter and the brownish tinge of the belts very well; also the orange tint of Mars, and by contrast the greenish maria. The highest speed colour films have very coarse grain, and it is possible that the less rapid material with longer exposure will yield better results.

Solar Photography. Although this is systematically treated by some large observatories, amateurs have achieved remarkably good pictures of sunspots, faculæ and the "rice grain" surface. Slow speed fine grain film or plates are quite suitable, with exposures 1/100 second or less, depending on the transparency of the atmosphere and the scale of final image on the film; *f*/80 is quite suitable. Solar prominence photography was until recently considered almost the preserve of the professional, but Klaus and others have now demonstrated that good results are possible with Lyot coronascope type refractors about three inches aperture. In these a relatively inexpensive interference filter made to pass the Hα line of hydrogen with a half intensity width of about 120 Ångströms, (e.g. Schott and Gen P.I.L. Type) gives sufficient contrast between the prominences and the background in a reasonably clear blue sky. Spectroheliographs or polarizing monochromators with a half-intensity width of 5 Ångströms or less have been used by some very advanced amateurs, but they are likely to remain outside the reach of the vast majority.

Sunspot photography is a very suitable field for amateurs preferably using refractors from 3 to 6 in. aperture. As explained before, a clock drive is by no means essential except perhaps for prominence photography using highly selective Hα interference filters. The use of an ordinary colour filter is desirable for sunspot photography to eliminate secondary spectrum, and green is the best choice. Sometimes reflecting telescopes are used, in which case a closed tube design is best and it is possible to close the tube of an ordinary Newtonian or Cassegrain with a filter-mirror, i.e. an optical quality plano-parallel disk of the same aperture as the telescope, coated *in vacuo* with gold or other metal, of thickness that will transmit only one or two per cent of the light. This conveniently cuts down the illumination while eliminating trouble from scattered light in the tube and the heat in the solar image.

Successful photographs of sunspots showing considerable "rice grain" detail can be taken with apertures below three inches, but larger aperture will score under favourable seeing conditions. The primary image is enlarged by eyepiece or Barlow in the same way as described for planetary photography. An alternative method is to project the solar image on a white screen and photograph this image using an ordinary 35 mm camera at a distance of several feet. This method needs the use of a darkened room or light protected enclosure, and it can be used for the photography of Mercury or Venus in transit across the sun's disk. Pl. 2*B* shows Mercury in transit nearing the edge of the solar disk in the transit of 1960. It was taken with an ordinary Leica camera by W. A. Dovaston of the image projected on a screen by the author's camera obscura, under rather unsteady atmospheric conditions.*

Mercury. An elusive planet indeed, especially in our beclouded skies owing to the low altitude, small size, low brilliance, and proximity to the Sun. It presents a challenge to the professional or the amateur photographer. Twilight skies give the best opportunity, and an orange filter enhances contrast and cuts

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*W. M. Baxter describes his technique of solar photography in Chapter 5. See also Pl. 12 and 13.

out most of the atmospheric dispersion. Under these conditions an exposure at *f*/80 of about 1 second on FP4II film is suitable. Plate 2*C* is an example taken in April 1963 of the crescent phase, at an altitude of only 8° and a diameter of only 8 seconds of arc.

Venus. Much finer results are possible here, because of the high brilliancy and good altitude as well as the greatly enhanced diameter when approaching or receding from the Earth, near inferior conjunction. The intrinsic brilliancy of Venus is about ten times that of Mercury, and the diameter at an average crescent phase is some six times greater. Daylight or twilight is best for photography, and here again an orange filter is desirable, with an exposure of about 1/10 second. The author has succeeded in photographing the almost hairline crescent at noon within three or four days of inferior conjunction and with the Sun shining full on the mirror of the telescope. Photographs of Venus never appear to show any definite or permanent features as do those of Mars. There is, however, the normal fall-off of illumination as the shadow terminator is approached, (e.g. see Plate 3*C* of Venus in 1961), much as would be expected from a cloud-covered body. This shading is accentuated with photographs in ultraviolet using a Wood's glass filter, and gives a strong impression of being a permanent feature of the surface, whereas in fact ultraviolet light has little if any chance of piercing the cloud cover.

Mars. The disk is either gibbous or full, and the full disk at opposition diameter varies between about 14 seconds for a February opposition to about 23 seconds for one in August. The smaller diameter does not give the amateur much expectation of revealing intricate detail, but the polar caps are well shown, and the photographic record of the contraction in size as the Martian summer advances is well worth acquiring. The larger disk is unfortunately accompanied by low altitude for observers in Britain; nevertheless, quite a fair amount of detail can be recorded—together with dust clouds, and there is always the chance of seizing a moment of superlative seeing. Mars is fairly bright, and exposures even with an orange filter (desirable to enhance the contrast of surface features other than the polar caps) range about half a second at *f*/80 using FP4II film.

Jupiter. Photographically one of the most satisfying planets, because of the large diameter of about 45 seconds and the unpredictable changes in the belt detail from month to month. The diameter of Jupiter's image on the film at *f*/80 will be about 1/60 of the diameter of the mirror or object glass, and even the shadows of the satellites, which add interest to the picture when they occur, have an appreciable diameter. The diameter of the image of any planet or satellite on the film at *f*/80 can be readily calculated using the formula: Image diameter in millimetres $= \frac{SD}{100}$, where S is the diameter in seconds, obtained from *Whitaker's Almanac* or from the *B.A.A. Handbook*, and D is the diameter of the mirror or object glass in *inches*. At the adopted final image size of *f*/80, the exposure for Jupiter will be about one second on FP4II. Under-exposure leads to such a rapid fall-off in density at the limb of the planet that the limb itself is lost in the print; many amateur and professional photographs of Jupiter suffer from this defect, which can be avoided with more generous exposure and development. Owing to the predominantly brownish or pinkish tint of the belts, contrast in the photograph can be increased by using blue sensitive ordinary or orthochromatic film, or by using a light blue filter. However, the resulting prints are likely to be too harshly black and white, which does not correspond to the visual appearance. Colour photography, as already mentioned, can be suitably applied to Jupiter and Mars, and grain suppression improves the appearance with black and white prints. Plate 3*A* and *B* are typical pictures of Jupiter taken with moderate apertures.

Saturn. No planet gives a more pleasing photograph than Saturn, especially if the rings are fairly well opened and enable Cassini's division to be seen in the photograph, even if not very prominently. Unfortunately the Sun's illumination of the planet is low owing to its distance, and an exposure of at least four times that given to Jupiter is necessary for the best results. There is no pronounced tint to see visually—perhaps because the low luminosity reduces the colour-sensitivity of the eye. Colour photographs at *f*/80 would need an exposure of four or five seconds, an exposure which may lead to some falsity of rendering of colour from variation of reciprocity failure in the various emulsion layers. Only one belt is normally registered on amateur's photographs.

Uranus. Attempts have been made to register the disk of Uranus with amateur size telescopes. This is even harder to achieve than getting a recognizable disk from Jupiter's satellites.

Comets. This is a field which makes a special appeal to a select band of amateurs provided with good telescopes and slow motions which permit the rather delicate and feeble cometary image being followed for a period which might exceed an hour. This hardly comes within the category of high resolution photography, because errors of following can easily amount to 20 or 30 seconds of arc, but is adequate for such ill-defined objects. Owing to the long exposures, fast panchromatic emulsions are not so suitable as "slower" films or plates suffering less from "reciprocity failure", for example Ilford's Astro-Zenith plates. This "slower" description only applies for the photography of bright objects at snapshot speeds. Comets vary greatly in luminosity, and they often cover several degrees in length. The telescope is not often used for the photograph of the comet, but becomes a "guide" telescope which carries a camera fitted with an anastigmat lens from 5 to 30 inches in focal length and with an aperture of from *f*/2·5 to *f*/6. These lenses cover an adequate field of view with a suitable quality of definition. The accuracy of guiding the telescope to follow the comet's movement among the stars is shown by the straightness of the short star-trails in the same field as the comet. This is evidence of the skill of the observer who is attempting to keep an ill-defined nucleus of the comet centrally on a cross-wire for what must seem an inordinately long time.

Meteors or artificial satellites. Ordinary cameras with rapid lenses are again used but not necessarily fixed to telescopes. The object for meteors is to point the camera towards a part of the sky which contains a radiant point of the expected meteor shower. The lens is kept open for an hour or two or until the light from the night sky builds up to appreciable fogging. Plates or films of considerable speed, but suffering from

"reciprocity failure", (i.e. slow in speed for feeble illumination and only fast for brief exposure to strong light), are the most suitable for this duty, because the primary need is to get a strong trail of a fast-moving meteor among slow-moving star-trails. If two cameras are operated in liaison but separated by at least ten miles, triangulation can enable the height and trajectory of the meteor to be found, especially if supplemented by visual observation of the same meteor. There may be many blank plates before a successful result is achieved, but persistent work is sometimes rewarded by a spectacular exploding meteor.

The difference of technique for satellites is obvious.

Double stars. Amateurs rarely try their skill at high resolution photography on double stars. Perhaps too few doubles are bright enough to give good images in the few seconds limit imposed by unsteady atmosphere, etc. Without doubt, this field does provide a challenge, and has been successfully tackled by a limited few professional observatories. These have shown Castor easily, and other doubles down to well under one second of arc. By using cascaded image tubes of 100-fold light amplification, the famous Pic du Midi Observatory claims to have photographed doubles close to quarter-second separation. Such photographs would enable much more accurate measures of angle and separation than is possible with micrometer eyepieces.

Lunar Photography. This is the last heading under the category of high-resolution photography for amateurs, and is the most popular subject of all.* The Moon gives far more opportunities than do the planets, and with an even greater variety in subject matter and illumination. An *f*/80 final image is very suitable, and results in exposure times varying from one-fifth of a second near full phase to one or two seconds for the crescent phase under clear atmospheric conditions with FP4. As the movement of the Moon is over three per cent slower than diurnal, longer exposures than one second should demand an adjustment of the clock drive to suit. No two photographs of the lunar landscape are ever precisely alike, because of varying phase and libration. This adds considerable zest to the pleasurable effort to seize every opportunity to acquire as complete a series as

* See Plates 4 and 5.

possible—even spread over many years. Perhaps only one superlative exposure occurs among many hundreds; with luck it may show resolution up to half the aperture of the telescope used, and show crater-pits down to a mile in diameter.

With many exposures to choose from, stereoscopic pairs of individual craters or mountainous areas may be selected, using libration to provide the differing direction of view. (Stereoscopic pairs of Jupiter or Mars may also be made in a single session of photography using the planetary rotation to provide the necessary difference of view. A time difference of 10 to 15 minutes is suitable for Jupiter and 30 to 40 minutes for Mars, and the result will show the rotundity of the planet well, providing seeing has been good enough to show a high standard of resolution.)

Deep Sky Photography. Nearly eighty years ago Isaac Roberts, using a 20-inch Newtonian reflector in his private observatory, obtained a unique series of photographs of star clusters, galactic and extra-galactic nebulæ, which gained world renown and awards from astronomical societies. In spite of the advances in photographic materials and technique since that date, it is by no means easy to get much better pictures with the same aperture today. One well-known amateur who has emulated Roberts' work is E. C. Silva of Lisbon, who, by patient efforts with the best modern materials and the same aperture telescope, has considerably improved on the early work and has derived much satisfaction from doing so. Amateurs throughout the world, using much smaller telescopes, are also being rewarded with the pride of achievement in the same field—this in spite of the knowledge that the giant observatory telescopes produce far superior results. Exposures may run into hours for these subjects; hence plates or films of the Astro-Zenith type are best, and guide telescopes of fairly high power are used to monitor and correct the clock drive. Prime focus photography is common, because of the low intensity of the light and the wider fields to be covered. Both of these factors are greatly helped by using Schmidt type coma-free telescopes which, at some expense in resolution and difficulty in technique, cut down the required exposure drastically, enabling such feeble objects as the Zodiacal Light or auroræ to be registered in seconds.

Chapter Three

OBSERVATORIES AND OBSERVATORY EQUIPMENT

Henry Brinton

For the amateur observer with a small or medium-sized telescope, the problem of providing an observatory may be almost as important as obtaining the telescope itself. The first question to be decided is whether an observatory is necessary, and, if so, what type it shall be.

It is clear that some sort of covering is required for almost any instrument which is not sufficiently portable to be put away in the dry after each occasion on which it has been used. Most refractors of 4-inch aperture and upwards, and reflectors of 6 inches and upwards, are too heavy and cumbersome to be moved about easily. When I had a 6-inch reflector I could and did move it often; but it was not easy, and there were occasions when I was tempted to take a risk in apparently good weather and leave it out uncovered. Assuming, therefore, that you own a telescope which is too large to move freely, and which needs some efficient form of covering, the immediate need is to decide what form that covering shall take.

Loose Covers. The simplest answer, of course, is some type of material such as a plastic sheet or car cover, but in my view this is most unsatisfactory. Plastic sheets always tend to tear; they lead to condensation, and, no matter how one lashes them, they appear to possess a fiendish capacity for coming loose in any strong wind. Moreover, a loose covering of such a kind will not cost much less than the materials needed for a really satisfactory form of cover. This means, in effect, building an observatory, and the two most common forms are the run-off shed and the dome.

Run-off Sheds. By and large, I believe that the run-off shed is the best sort of observatory for medium-sized instruments (say reflectors of from 6–to 18-inch aperture). It is easy to make; it can be pushed off or replaced over the telescope in a matter of seconds; and it gives perfect protection against the weather. The materials for making it cost very little, and the time taken in assembling it is negligible compared with the work necessary in building a dome.

As I have described elsewhere*, a run-off shed consists of a fairly light structure—hardboard is a suitable material, with a wooden framework—set upon rails. It can be made in halves which slide in opposite directions, as shown in Plate 6*B & C*, which covers a 12½-inch reflector. This pattern has some advantages, but also serious disadvantages. Unless it is extremely well made, there will tend to be a leak where the two halves join, and the separate halves of the shed will cumber the ground round the telescope in two places instead of one.

In my view, the more convenient form is the one which I have used, and which is shown in Plate 6*A*; it covers my 12-inch reflector at Selsey. It has a door at one end, which can easily be lifted off and moved out of the way, after which the entire shed is pushed off on its rails.

The idea of making rails daunts some of those who are not handymen by nature. In fact, there is nothing difficult about it at all. The rails can be made of ordinary angle-iron, which can be bought from any blacksmith or large ironmonger's shop. All that is needed is that the two rails should be well anchored in the ground and, of course, kept exactly parallel to one another.

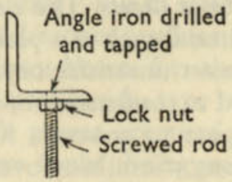

Fig. 1

The first problem can be dealt with either by screwing rods into holes bored on the underside of the angle-iron, as shown in Fig. 1, or by getting a blacksmith to weld short twisted rods underneath. If the ground into which the rails are to be set is soft, it is advisable to set the supporting rods in concrete. This can be bought ready-mixed, and is very little trouble to use. If the ground is heavy clay, then concrete is not necessary. My own rails, which are without concrete, show no signs at all of

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*Brinton, H., 'Construction of a Run-off Shed' *1963 Yearbook of Astronomy*, Eyre & Spottiswoode 1962.

moving. The question of keeping the rails parallel is easily solved by cutting a length of wood to act as a gauge. Suitable wheels, 4 to 5 inches in diameter, can be obtained from most large builders' merchants, about an inch in width, and which will run nicely in inch and a half angle-iron. Plates for attaching them, as shown in Fig. 2, can be made by a blacksmith for a few shillings.

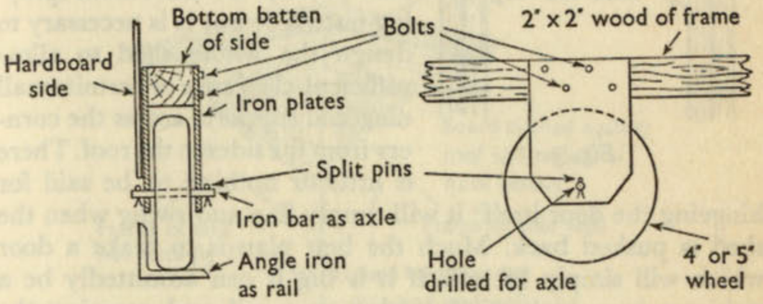

Fig. 2

The shed itself consists essentially of three fixed walls, a roof and a door (assuming that we have decided upon the "one-piece" construction, as opposed to the two halves moving off in opposite directions). The board should be fixed on 2″ × 2″ sawn joinery softwood along all the edges, crossed if necessary with 2″ × 1″ for extra rigidity. (For smaller telescopes, below 12-inch aperture, 2″ × 1″ may be strong enough throughout.) It may be wise to creosote the wood after cutting, but before joining and screwing on. As the wood is liable to rot first at the joins, treating at this stage will protect the most vital parts. There is no need for professionally neat joins; a simple joint for joining the top and end supports can be made by cutting out half the thickness of the batten at each end, and then nailing, or preferably screwing, one over the other to fit flush. Note that the roof should be sloped to allow the rain to run off.

The simplest way of going about the construction is to make and erect the three fixed walls first. The side walls slope towards the back, to allow for the pitch of the roof, and the end wall can be fastened to the sides in a number of different ways. One is to make the battens of the end wall fit snugly into the battens of the two sides, and then bolt or nail the two sets together as in Fig. 3. For larger sheds, small diagonal pieces can then be fixed across the corners at top and bottom.

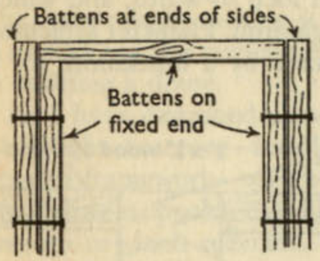

Fig. 3

The open end, where the door is to be hung, is slightly more tricky, since it can obviously have no support across the bottom. Luckily the rails prevent the sides from splaying outward, but it is necessary to design the whole shed to allow sufficient clearance to permit small diagonal supports across the corners from the sides to the roof. There is little or nothing to be said for hingeing the door itself; it will simply flap and swing when the shed is pushed back. Much the best plan is to make a door which will simply lift off. If it is big it can admittedly be a nuisance in a high wind, acting as a sail and carrying the observer off. On the other hand, few of us have telescopes rigid enough to be of much use in a gale.

A lift-off door can be made like the lid of a box. The top and side battens of the shed can be flush with the board, and the door can have battens which fit outside these. Better, I feel, is to let the boards of the shed stick out beyond the battens and let the door fit inside, with its own battens lying up against the battens of the shed. Any form of fastening can then be made.

The roof is a critical part of the construction, since it must be absolutely waterproof both in itself and where it joins the walls. If it is to be more than 4 feet wide, the joint should be most carefully made, and the board nailed closely over well-applied sealing compound. Unless the shed is very large, the board can be fastened straight to the battens running along the tops of the three fixed walls of the shed, with its own battens cut to fit closely inside these. A couple of inches at least of overlap of the roof board should be left all round. When it has been fixed, flat pieces of board, 3″ × 1″ or 2½″ × ¾″, should be pushed up tight against the overlap of the roof and nailed on to the battens of the sides with sealing compound in the joint (Fig. 4).

One last point may need to be watched. If the shed is narrow in relation to its height and length, there may be a danger of its

blowing over in a high side wind. There are many easy ways of coping with this problem, but the first consideration is that any fastening should be quick to release. One method is to sink a metal rod, with a loop or ring on top, in the ground on each side. If hooks are then fastened to the sides of the shed, they can be so arranged that they will slide into the rings automatically, and so anchor the shed without the need for any action. And finally, though tempered hardboard will stand up to the weather, I thought it better to paint my shed with bituminous aluminium paint, particularly since my garden adjoins the beach and is exposed to violent and salt-laden gales. The result has been most satisfactory. Alternatively marine ply can be used.

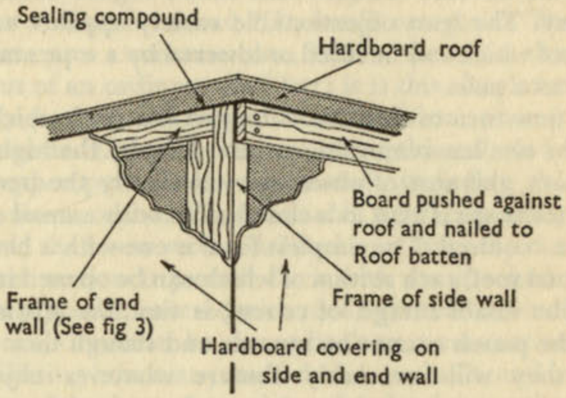

Fig. 4

Fixed Observatories. Some people will prefer a fixed structure which has, at least, the advantage of giving some protection against the wind when the telescope is being used. First, there is the building with a roof which may either be slid back, hinged back, or else removed completely.

In my opinion there is nothing at all to be said for the latter type. It offers no advantage, or no substantial advantage, over the run-off shed, but it has serious drawbacks. Unless the instrument is very small (in which case it will presumably be portable), a roof which has to be taken off is horribly cumbersome. One type of building has a roof which hinges back on itself; another has a roof which is lifted off like the lid of a dustbin. A variation, which is slightly better, is to make the roof slide back on to a support. I do not propose to describe any of these in detail, if for no other reason than that I regard them as unsatisfactory. The least objectionable variety appears to be the hinged roof which can be lifted or lowered by a rope and pulley attached to a pole.

Let us now turn to the observatory with a roof, which either revolves or else has removable panels. Despite the high cost of construction, this sort of observatory is clearly the best of all, since the telescope is kept in a closed room with a small opening only when required. The simplest form is one with a hexagonal or octagonal roof, each section of which can be opened independently. The disadvantage, of course, is that the struts which support the panels cannot be moved; and though they may be slender, they will invariably obscure whatever object one wishes to observe, precisely at the moment when one wants to look at it! It seems, then, that if this kind of observatory is contemplated, it will be worth while to be slightly more ambitious and have an observatory which has a revolving dome.

It is, of course, possible to have an observatory which has one removable panel, and which is completely revolvable. It can be built of wood on a central pivot set in concrete, with wheels around the periphery running on a concrete track, after the manner of certain summerhouses. It may even be possible to buy such a summerhouse and adapt it. Once again, however, I would advise against anything of the sort. Pushing the whole arrangement around is not easy, and the observatory is too apt to jam at the crucial moment.

We are left, then, with the proper rotating dome, as is used in almost all professional observatories. I do not propose to describe this in as much detail as I have done for the run-off shed; those who are rich enough to have one built, or sufficiently experienced to make one for themselves, will not need design instructions, and few others will have telescopes big enough to warrant such an ambitious observatory. However, a few notes may be useful, and two typical amateur domes are shown in Plate 7. The one belonging to W. M. Baxter is

wooden, and houses a 4-inch refractor used by its owner for his studies of the Sun. It is octagonal, and the viewing panel hinges back against the roof itself. It was constructed by a professional builder at moderate cost—but this was a good many years ago, when labour was much cheaper than it is now.

The other is the dome covering one of Patrick Moore's reflectors at East Grinstead.* It, too, is octagonal. The wooden walls rest upon a concrete base. Inside, there is a circular rail, made out of an ordinary steel bar; it is this circular rail which probably presents the most difficult problem, since it must be very accurate. Eight bearings run along this rail, and the whole of the upper part of the observatory, including the window section, moves round. The removable panel is in two parts, and is hinged; the lower section is lifted over from the outside, and the upper section is pushed back with an attached rod. The roof is of plywood, covered with roofing felt. The window below the slit can, of course, be swung back on a conventional hinge.

Considering how many small domes are built, and how excellent some of them are, I may have dismissed them too cursorily; yet those who feel that such an observatory is not beyond their skill or their pocket will be well advised to have one, with the qualification that it is better to be without it than to make it too small.

Equipment. Leaving the question of construction, we now turn to the matter of equipment. The most important item to most people will be the provision of a seat which can be so adjusted as to bring the eye to the desired height. There is no one arrangement which will meet every case, but a most ingenious and adaptable model has been described by the late F. J. Sellers†. Sellers' arrangement consists in essence of a self-locking seat which slides up and down a pair of parallel uprights, sloping, and mounted on a triangular base. Such a chair, as

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***Editorial Note.* The observatory was built entirely by my two cousins, R. A. Gulley and Brian Gulley. Neither is an astronomer in any sense of the word, and neither had previously built anything of the sort. On the other hand, it is fair to say that both are exceptionally skilful, and were able to make use of a very well-equipped amateur workshop; even so, the construction took an immense amount of time. The total cost of the materials was between £30 and £40, but if the construction had been tackled by a professional builder the labour cost would have been extremely high. The observatory has now been moved to Selsey, in Sussex.—P.M.

†*B.A.A. Journal,* Vol. 43, No. 7 (1933).

shown in Fig. 5. can easily be made out of 1½″ or 2″ square rough-sawn softwood, and is instantly adjustable to any height. In Sellers' model, the self-locking device is augmented by allowing the screws securing the two cross-battens to project slightly and catch in the uprights, but there are various alternatives, as, for instance, a series of notches in the uprights themselves, or, as Sellers suggested, rubber blocks fitted at the corners.

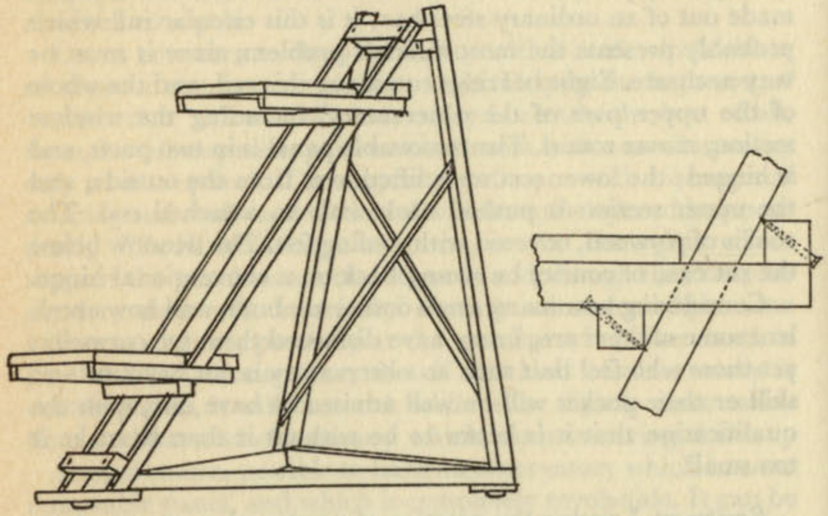

Fig. 5. *The Sellers observing chair should be designed according to individual needs, but in the Sellers model the ladder sides are* 5′ *long; the sides of the base of the triangle* 3′, *and the back* 2′ 3″. *He used* 40′ *of* 1½″ x 1½″ *timber, three dozen* 1½″ *and two dozen* 2½″ *wood screws. The detail illustrates the method of making the adjustable seat secure.*

There can be one drawback to this or any other similar arrangement. With some mountings, as for example with my own German mounting, it is impossible, because of the stand, to bring the seat near enough to the eyepiece when viewing at a high altitude. The only way that I know out of this difficulty is to have a pair of step-ladders which can be set on either side of the mounting, with a plank placed between the ladders. This has the disadvantage not only that it is cumbersome, but that the height of the seat can be adjusted only by moving up or down one complete step. There is no one perfect answer.

Although, strictly speaking, it is a matter of telescope design

and not of observatory equipment, it seems worth mentioning here that the difficulty does not occur in my case, as my telescope is equipped with a revolving end. I had the tube made in this way against the best professional advice, and have never regretted it. Of all the features which my telescope possesses, this is the one which I value most, apart from the excellent optics. In my opinion a well-made revolving end has almost everything to be said for it, except that it requires getting used to the fact that one constantly views celestial objects from different angles. Against this single disadvantage is the fact that with a twist of the wrist one can bring the eyepiece to exactly the spot where it is most convenient.

Other matters of observatory equipment are rather hard to write about, because the requirements of each observer are liable to be so different. One general idea which seems worth pursuing is that of the "observatory box". Most of us need an almost endless series of odds and ends when we are at the telescope. Often we want them in a hurry; and they are usually difficult to find. I have fitted up a large wooden box so that it will take, in different compartments, the separate eyepieces and a filar micrometer. I have, as well, a rack for filters and a compartment for pens, pencils, torches and papers.

Beyond such a general provision, there are one or two specific suggestions which may be useful. Most observers (or, at any rate, many of them) will make use of the knee-pad; but a valuable addition is the illuminated pencil or pen. Such devices may now be bought as a unit, which makes drawing at the telescope much easier.

For those who wear glasses, but prefer to observe without them, there is a great deal to be said for taking an old pair of spectacles and removing the lens from one eye. It takes a little while to get accustomed to using only a single eye for reading instruments or drawing; but once the habit has been acquired, a great deal of time and fumbling for spectacles can be obviated.

Despite my observing box, I still find that when I am at the eyepiece there seem to be an enormous number of gadgets to be parked; filters to be changed; pencils to be put down and picked up; eyepieces which have been discarded, or are awaiting use. As an alternative to losing them, or damaging them by rubbing together in one's pockets, it is possible, at any rate with lattice-tubed telescopes, to make a simple, light tray to clip on to the instrument in a convenient place. Tubed telescopes are not so suitable for this, but a little ingenuity will generally come to the rescue.

Space does not allow me to write at length about arrangements for recording time; but it is worth mentioning the problem of sidereal time. Of course, if one has money to spare, it is very nice to have a sidereal chronometer; but, with time-signals so frequently and so readily available, this is little more than a luxury to most amateurs. A simple note, before one goes to the telescope, of the relation between one's watch and the sidereal time is all that is necessary. To go a step further, an ordinary cheap clock can be adjusted to run 4 minutes a day fast; and a single setting at leisure any time during the day from a time-signal will provide the sidereal time to at least as high a degree of accuracy as is warranted by the setting circles on most amateur telescopes.

Conclusion. Of necessity there are many aspects of my subject which I have not covered. Each telescope requires its own forms of covering and accessories, and there can be few fields in which ingenuity has wider scope. Yet unbridled ingenuity can defeat itself. The prime object of a telescope is to observe the celestial objects, not to provide an opportunity for ingenious adaptations. To those of us who have studied astronomical history, the lesson is very clear that it is not always those with the most elaborate observatories or equipment who produce the best results. A glance at drawings of some of the early large telescopes can only leave one wondering at the marvellous skill which enabled the observers to see anything at all, let alone to produce the magnificent results which are on record.

Chapter Four

ASTRONOMICAL RECORDING

LESLIE F. BALL

IN SPITE OF photographic developments in recent years, there is no doubt that for lunar and planetary recordings of value the amateur observer with some aptitude for drawing, coupled with the use of a medium sized telescope, can still transcend the camera. The ability to produce a good drawing of the particular celestial object under study is a source of considerable satisfaction, and gives a feeling of completeness in one's endeavours which is not easily definable. The facility of transmitting what one sees to paper is, of course, the crux of the matter, and this to a large extent is really an exercise of the memory which can be improved, like most things, by constant practice.

In some ways it is a pity that the Moon is generally the first celestial object which the amateur attempts to draw, for, in truth, the complex appearance of the lunar surface is one of the most difficult to depict satisfactorily, and such first essays are generally disappointing. Rather the observer attempt to draw the planets where the technique is not quite so exacting. It is easy to give a list of materials which can be considered necessary, but from my experience of many years, part of the joy of illustration comes from experimenting with various mediums, and in this connection I am still learning. But that is not to say that satisfactory and accurate records cannot be made by very simple methods indeed. I shall, therefore, take the line that from relatively easy beginnings, good results can be obtained, and from them indicate more adventurous avenues of delineation, working up to the much desired photographic effect, and finally, in appropriate cases, colour work.

Technique. Before proceeding further, however, certain requirements must be considered, not the least of which is the personal comfort of the observer. For cold nights, sensible dress would be a thick overcoat with a scarf tied over the head and ears, or a duffle coat with hood is probably better still. Mittens to leave the fingers and thumb free for drawing, and fleecy lined boots or even gum boots should keep the extremities reasonably warm. Furthermore, a wooden boarding to provide insulation from the ground, is not to be despised. So much for one's personal comfort. Whilst some form of observatory is the ideal cover for both instrument and observer, a less expensive and lightly constructed windbreak either in portable or permanent form affords a considerable degree of protection. With a reflector of moderate aperture and tripod head or declination axis around three to four feet high, a low wall not exceeding four feet in height and constructed of oilbound hardboard on a light timber framing will serve the purpose admirably, and would not limit the accessible horizon very much, if at all. Some kind of canvas roof can be fitted later if desired.

Now comes the all important methods of transmitting what one sees through the telescope down on to paper. Provide yourself with a square of hardboard or plywood about eight inches across to which you can clip a piece of cartridge drawing paper with a bull-dog clip. A 2B pencil is probably the best for sketching; some prefer a carbon pencil, but this can be 'messy' when used under the usual restricted conditions of observing. An indiarubber affixed to the other end of the pencil is useful; otherwise, the rubber should be attached to the drawing board. The method of illuminating the paper will vary according to individual choice. I strongly recommend fitting a flashlight bulb to the top of the drawing board connected to a small battery secured to the underside of the board. The bulb and all other types of illumination used in this connection should be covered with orange or red translucent paper in order to cut down the glare and avoid affecting the sensitivity of the eye, so important when dealing with faint and elusive planetary shadings. Another method of illumination is to fix a flashlight bulb on the telescope itself and provide a cover to direct the light down on to the paper. Alternatively a torch pencil can be used, and it might be possible to incorporate an indiarubber as well.

For drawing lunar detail, a six-inch square of paper should be sufficient to cover the formation under review. It is essential that not too large an area is drawn, for then the scale of the significant detail will be too small to give worthwhile results. It is necessary to familiarize oneself with the varying aspects of lunar formations in relation to their position on the disk. This is relatively easy for centrally placed objects, but the increased effect of foreshortening as the limbs are approached must be considered carefully with regard to the correct shapes and shadows. Use a moderately-powered eyepiece of about 15 to the inch of aperture in order to provide a setting for the subject, and add the more delicate detail with as high a power as atmospheric conditions will allow. Note the correct orientation, the medial time of the observation, the 'seeing' conditions, and the range of magnifications used.

Similarly as regards the planets, a medium power should be used for recording the basic features, and the highest practical power for the finer detail. It should be borne in mind, particularly in the cases of Mars, and more especially Jupiter, that planetary rotation will carry features fairly quickly out of view on the preceding side, and obviously such detail should be recorded first. Furthermore, the rapid rotation of Jupiter limits the time available to make any particular drawing. Such time should not exceed 15 minutes. The phases of Mercury and Venus based on eye estimates should not be difficult to portray by working on a compass drawn circle. Saturn's variable outline is troublesome to draw accurately, and it is probably advisable to prepare a careful cut-out to cover each apparition, based upon information and outlines provided by the *B.A.A. Handbook*, or some similar source.

The following scales are recommended in drawing the various celestial objects.

The Sun.	Full disk: from four to six inches diameter.
	Sunspot groups: from four to six inches square.
The Moon.	Various rectangles according to type of formation, with no measurement greater than six inches.
Mercury.	One inch diameter.
Venus.	Two inches diameter.
Mars.	Two inches diameter.
Jupiter.	Two inches diameter (suitably flattened).
Saturn.	Three inches overall inclusive of the ring system.

The Sun. From these sketches and notes made at the telescope finished drawings are prepared. Full disk records of the Sun made by projection on the lines indicated in Chapter 5 need little finishing unless it is desired to black in the surrounding sky which can easily be done with either Indian ink or poster black. Accidental encroachment of the background brushwork can be avoided by drawing the Sun's disk with a pen and ink compass, using a broad nib to produce as thick a line as possible. Care should be taken to prevent the point of the compass from piercing the drawing paper. This can be avoided by inserting a small circle of fairly stout card under the compass point. Limb shading caused by solar atmospheric absorption can best be indicated with a 2B or 4B soft pencil, rubbing in carefully, either with a stump or the finger, and graduating out away from the limb. The use of a pointed rubber on this background will enable the faculæ to be realistically shown. As an alternative finish, pen and ink stippling can produce an effective picture, but this method is somewhat tedious. Because of the lack of colour in the superficial image of the Sun, few tinted pictures are made.

Large-scale active sunspot groups contain a mass of detail when viewed under good conditions and sufficient magnification, and present a challenge to the artist-observer which is not easily overcome. Bristol board should be used, or failing this a good quality faced board which is somewhat cheaper. Put in the umbræ either with Indian ink or a carbon pencil, and use a 2B pencil to indicate the intricacies of the penumbræ. Steady 'seeing' will resolve most of the penumbræ into long filaments trending towards the centres of the spots. The pointed rubber will need to be used extensively to pick out the highlights, and particularly the brilliant 'bridges' of bright material extending across certain umbræ. If Indian ink has been used for putting in the umbræ, it will be necessary to indicate these features with a finely pointed brush with poster or Chinese white. The addition of the solar granulations where recorded will give realism to the drawing. This again is an exercise for the pencil and rubber. Modification of the shapes of the granulations by the presence of the spot groups should not be overlooked.

The Moon. The easiest method of recording lunar detail is by pen and ink line drawn over a pencil base (see Plate 8). To all intents and purposes this is simply mapping the formation under review, and most observers will wish to obtain a more pictorial effect. As I have said earlier, this is one of the most difficult of drafting exercises, and requires considerable practice before a measure of success is achieved. An appreciation of lunar forms and shadows is an essential, and to this end an intelligent study of some of the excellent lunar photographs now available, coupled with a discerning eye at the telescope, will prove of great value. A good Bristol board will make the most of the dazzling highlights, and for the shadows of ramparts and peaks nothing produces the velvety blackness better than the carbon pencil. B grade pencils of varying softness should take care of the vast range of intermediate tints, and a stump and rubber need to be used widely to produce the unlimited variety of lunar forms.*

The Planets. Whilst the planets Mercury and Venus are generally depicted with a black sky background, in cases of twilight observation, which usually produces more satisfactory results, a more realistic effect can be achieved by putting in a sky of indigo blue of an intensity comparable with prevailing conditions. For this purpose lay down a wash of blue-black writing ink, and if a darker tint is required, allow the first coat to dry and proceed with others until the desired intensity is obtained. By using a thick grade of Bristol board any tendency of the drawing paper to buckle will be prevented. A careful interpretation of the shape of the terminator should be made at all times, particularly around that of dichotomy. The limb should be kept perfectly clean and sharp, and here again the sky background must not be allowed to encroach at any point on the drawing of the planet. The terminator and any elusive shadings that may be present should be put in delicately with a medium grade pencil and smoothed out with finger pressure.

Most Martian drawings are made around the time of opposition, and to meet this condition the drawing of a plain circle presents no difficulty (see Plate 9). Some slight shading will be evident at the terminator each side of opposition, and a gibbous phase is obvious at the quadratures. Allowances for these changes in aspect should be made. A 2B pencil and rubbing is all that is

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* See also Chapter 6.

needed to represent the Martian "seas". At all times the polar cap must be kept as clean and white as possible. There is considerable scope for colour work on Mars, provided that observations are obtained with a reflector.

I have found that coloured pencils are by far the best for this kind of work. They are available in a very large range of colour, and, as to some extent they blend with one another, such subtleties of tint present on the planet can be matched without undue difficulty.

Much of the previous instruction equally applies in drawing Jupiter and Saturn (see Plates 10 and 11), both in monochrome and colour. Previously prepared cut-outs are recommended in order to produce the correct shapes easily (see Fig. 14, page 107, and Figs. 19, pages 124 and 125). Under good "seeing" conditions, and at times of greatest Jovian activity, there is a large amount of fine detail visible in and around the cloud belts spanning the planet. Heavy atmospheric absorption causes all features to fade out rapidly as the limbs of both planets are approached, and the general effect to aim for is a central area of clarity with a hazy surround, the limb shadings being contiguous with the dimness of the polar hoods. Both planets can be represented attractively in colour, particularly Jupiter. Coloured pencils are again excellent for this purpose. Putting in the sky background on drawings of Saturn requires a steady hand with the paint brush unless, of course, the rings are presented edgewise to the Earth. If at such times the rings are visible, the straight line of light can be drawn with a sharply pointed white pencil. The presence of satellite phenomena can add to the beauty and interest of the picture.

These notes have been an attempt to point the way to a satisfactory pictorial recording of some of the more popular celestial objects. There are many other subjects such as solar and lunar eclipses, the auroræ, comets, nebulæ, double stars, meteor displays, star clusters and so on, each of which, to do full justice, requires a fairly advanced technique. The preparation of illustrations for publication is another special field, and often requires the use of expensive professional equipment.

Chapter Five

SOLAR OBSERVATION

W. M. Baxter

WHAT IS so interesting to the observer of the Sun is its ever-changing face. One never quite knows what one may see when turning a telescope on this impressive "star", with its sunspots coming and going, their varying shapes and sizes over the days, and the larger periodic changes corresponding with the cycle of solar activity. Observers with solar spectroscopes will have an added interest, but this chapter will chiefly be devoted to what can be observed on the Sun's surface by normal integrated light through an amateur's ordinary telescope, whether it be refractor or reflector.

In the Sun, we have a celestial object which provides our telescopes with abundant light but also with an excess of heat, so that we cannot—and must not—observe direct through a telescope unless it is a very small one, of say 1½-inch diameter or less, and then only through a tight-fitting dark filter. With larger instruments the concentrated heat at the eyepiece will splinter any glass filter, and irreparable damage to the eye will result.

Methods. There are only two ways in which the Sun's features should be studied with a telescope; one by means of a sun diagonal and the other by projecting the image. The diagonal is fitted in the telescope drawtube and reflects the image at right-angles, where it is magnified by the eyepiece in the usual way. The sun diagonal differs from the star diagonal by replacing the totally reflecting prism in the latter by a wedge-shaped piece of plain glass which directs a dim reflection from its upper surface into the eyepiece while allowing the concentrated heat to pass direct through, out of harm's way. Even with this accessory, the image is still too bright and a dark filter must be fitted on the eyepiece. It is preferable to have a few filters of different degrees of darkness to provide for the Sun's varying brightness with the seasons and time of day; they should be of a neutral tint.

The Sun, as seen through a diagonal fitted to an astronomical (inverting) telescope and looked at from directly behind the eyepiece, is reversed E. and W. compared with the naked-eye view, but there is a danger in standing in that position, as the heat coming straight through the diagonal is liable to burn one's clothes! It is usual to observe from the side; the image is then as the naked-eye view but inverted N. and S. For intermediate positions of the diagonal it must be remembered that the eyepiece image rotates twice as fast as the diagonal is rotated, i.e. if the diagonal is rotated from pointing upwards to pointing sideways, the solar image is rotated 180 degrees.

A check on orientation can always be made by watching which way the image of the Sun moves with the telescope stationary; it will drift to the W. due to the Earth's rotation. By tilting the telescope very slightly towards the N. point of the heavens it will readily be seen which part of the Sun's limb comes to the centre of the field, this being the N. point on the Sun, of course.

Undoubtedly the best way to observe the Sun is by projection, as no heat troubles are experienced. The image, magnified by an eyepiece, can be clearly projected on to a shaded white card or, better still, into a projection box fitted to the telescope and having a white card fixed at the far end, part of the side of the box being cut away to enable the image to be observed.

The first method is illustrated in Fig. 6 and shows a cardboard square fitted over the object glass end of the telescope to shade the projection card from the direct rays of the Sun. The dotted square is an alternative position, but the former has the advantage that it helps to balance the fittings at the eye end.

The eyepieces used should not contain cemented lenses, or they will be damaged by the heat. There are many uncemented types and the Huyghenian, as illustrated, is as good as any for projecting with an ordinary refracting telescope.

Whatever kind of support for the projection card is adopted, it should be attached to the telescope so that it can rotate round the telescope tube, thus enabling the card to be turned for orientating the projected image without displacing its position on the card.

By projecting into a dark box, a much better view is obtained and more detail is visible. A dark cloth can usefully be draped over one's head and box rather like an old-time photographer. Two types of box are illustrated in Fig. 7, (*a*) being a light wooden box and (*b*) a metal drum, and either can be counterbalanced by a small weight at the O.G. end of the telescope.

Amateurs who work with reflecting telescopes will be able to make similar arrangements for projecting the solar image, but those with the larger apertures should stop them down to about 6 inches, or even 4 inches in summer, or they will be faced with excessive heat troubles. The larger refractors should also be stopped down to 4 inches or less, for the same reason.

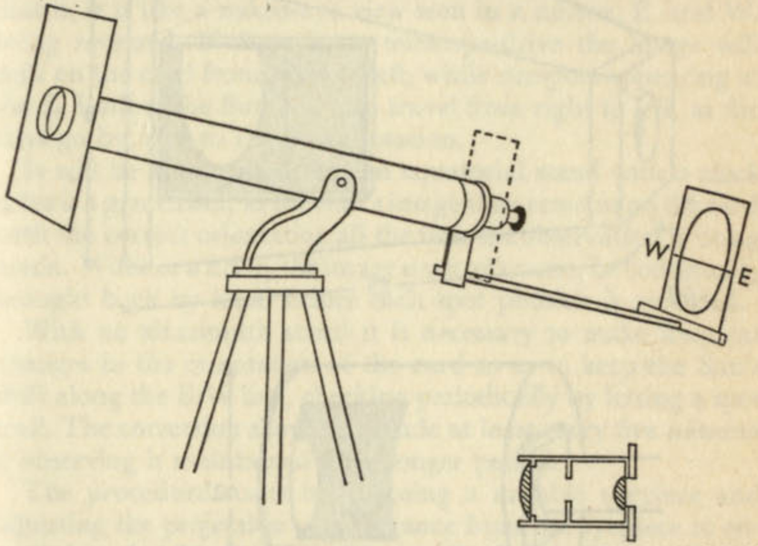


Fig. 6. *Projecting the Sun with a small telescope. The detail* (*right*) *illustrates an Huyghenian eyepiece.*

With a 6-inch solar image it is immediately apparent that the disk is not equally bright all over, but that it shades off darker toward the limb. This is known as the "limb darkening" and is due to the Sun being gaseous, so that in the centre of the disk we are looking further into the hotter, and therefore brighter, interior. Sunspots, if present and of any size, will readily be seen, as will the irregular bright areas of "faculæ".

The main task, and pleasure, for the amateur observer will be to plot the positions of all the visible sunspots as they vary from day to day over the whole sunspot cycle of about 11 years, and therefore the remainder of this chapter will be mainly devoted to this aspect of solar observation. Incidentally, with a high-power eyepiece the "granulation" over the whole solar surface will be well seen by projection.

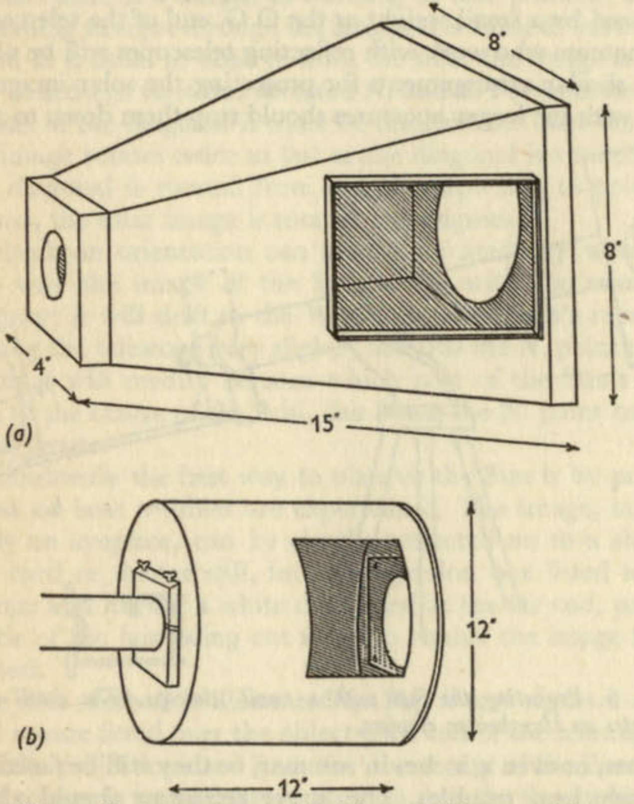


Fig. 7. Projection boxes—(a) Of wood; (b) a metal drum.

Recording Sunspots. Daily records of sunspot positions should be made whenever possible, and it is hoped that observers would wish to contribute to the co-operative activities of the Solar Section of the B.A.A. or of any local branch or Society.

A convenient size for the projected solar image is a 6-inch diameter disk. The projection card should therefore bear a 6-inch circle divided by fine and faint pencil lines into ½-inch

squares and diagonals, faint so as not to hide any small sunspots. A useful card can be made by mounting a piece of matt photographic paper (unexposed but fixed in hypo) on to a cardboard support. The paper is smooth, but does not give unwanted reflections from its matt surface. If the paper is fixed to its backing with photo corners, it can easily be replaced if it gets soiled. Dust particles *can* look like tiny sunspot pores.

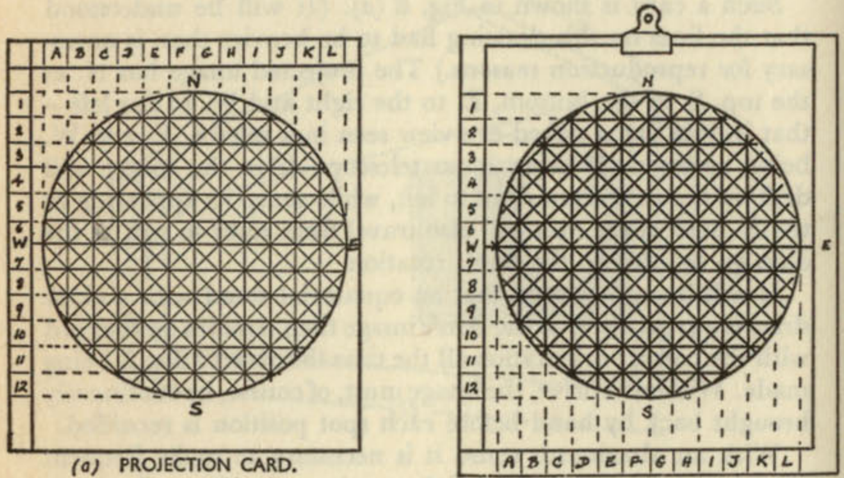
Such a card is shown in Fig. 8 (*a*). (It will be understood that the lines on this drawing had to be heavier than is necessary for reproduction reasons.) The projected image has N. at the top, S. at the bottom, E. to the right and W. to the left—that is, it is like a naked-eye view seen in a mirror, E. and W. being reversed. If there is no telescope-drive the image will drift on the card from right to left, while sunspots appearing at the E. limb of the Sun will also travel from right to left, as the days go by, due to the Sun's rotation.

It will be appreciated that an equatorial stand with a clock drive is a great asset, as the Sun's image then remains on the card with the correct orientation all the time the observation is being made. Without a drive, the image must, of course, be continually brought back by hand before each spot position is recorded.

With an altazimuth stand it is necessary to make frequent changes in the orientation of the card so as to keep the Sun's drift along the E/W line, checking periodically by letting a spot trail. The correction should be made at least every five minutes if observing is maintained for a longer period.

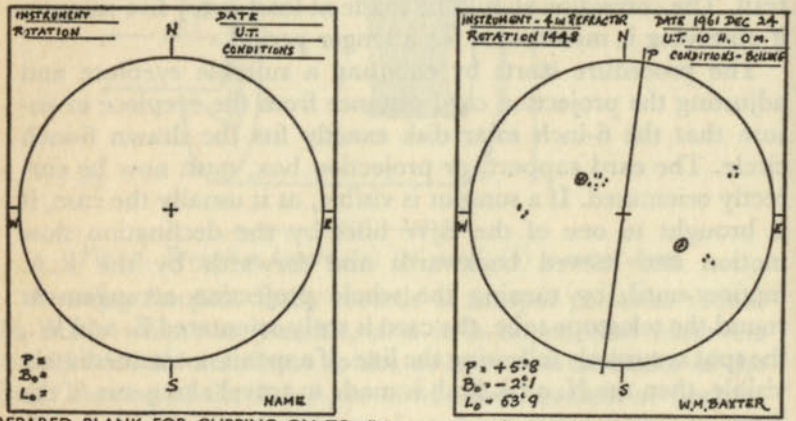
The procedure starts by choosing a suitable eyepiece and adjusting the projection card distance from the eyepiece to ensure that the 6-inch solar disk exactly fits the drawn 6-inch circle. The card support, or projection box, must now be correctly orientated. If a sunspot is visible, as is usually the case, it is brought to one of the E/W lines by the declination slow motion and moved backwards and forwards by the R.A. motion until, by turning the whole projection arrangement round the telescope tube, the card is truly orientated E. and W., the spot accurately following the line. If a spot is not immediately visible, then the N. or S. limb is made to travel along one of the lines.

A stout card, mounted on hardboard for handling and with a white surface, has a 6-inch circle and grid similar to that on the projection card, but with the lines heavily inked. Blank forms on thin typewriting copy paper (8″ × 6½″) are convenient for the recordings, and one is clipped over the hardboard card with the circles and compass points coinciding, prior to each observation. This paper blank is thin enough for the heavily inked lines underneath to be clearly visible, and blanks can be prepared at any convenient time and kept in stock.



(a) PROJECTION CARD.
(Faint pencil lines)

(b) THICK CARD WITH CLIP.
(Heavy ink lines)



(c) PREPARED BLANK FOR CLIPPING ON TO (b)
(Thin paper)

(d) COMPLETED DRAWING

Fig. 8. Spot recording chart.

The stout card and a blank form are shown in Fig. 8 (*b*) and (*c*) respectively, the blank already bearing the circle, the N., S., E., and W. points, the centre cross, the instrument used and the observer's name. Fig. 8 (*d*) shows the completed record. It will be appreciated that any spots that are visible as projected on the faint pencilled grid can have their positions exactly copied on to the thin paper, guided by the heavy lines underneath. A pencilled note of the time (U.T.) and of the seeing conditions is made at the time of the observation.

A higher power eyepiece is then substituted, and by slowly scanning the whole of the Sun's enlarged disk (projected now on plain photographic paper) one can frequently detect small pores that were originally missed but which, knowing where to look, can then be found on the 6-inch image and be recorded. Spotless days should, of course, be recorded as such.

Coming indoors the record is completed by filling in the remaining details as shown in Fig. 8 (*d*). The rotation number is obtained from the *B.A.A. Handbook*, as are the Sun's co-ordinates for the time of the observation, while the "U.T." and "Conditions" are self-evident.*

"Active Areas" are counted from the drawings and recorded, and if the total for any month is divided by the number of days when the observations were made the result is the "Mean Daily Frequency" for that month. This M.D.F. can be plotted against "months" and will provide a graph of solar activity over the years. Every spot, however small, is counted as a separate Active Area if it is at least 10 degrees of latitude or longitude from its nearest neighbour.

To define the position of a spot, or other centre of activity, on the Sun's disk by latitude and longitude, the use of "Stonyhurst Disks" is very convenient. These are made up of a series of eight transparent prints of the solar disk with the lines of latitude and longitude marked. The different prints are used on different dates varying with the tilt of the Sun's axis from + 7 to − 7 degrees (towards and away from us) and the Sun's image can be projected direct on to the selected print, enabling the latitude and longitude of any spots to be noted at once. Alternatively, the prints can be placed over the drawings or

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*An example to show how the solar co-ordinates for the time of observation are obtained is given in the Appendix at the end of this chapter.

E

vice versa and the co-ordinates read off. The true longitude is quickly calculated from the longitude of the central meridian at the time of observation as given in the *B.A.A. Handbook.*

The set of prints is rather expensive, and the same results can be obtained, with little extra trouble, by using a single "Porter's Disk" obtainable from the B.A.A.

At the commencement of a new solar cycle—from minimum activity—spots first appear in the higher latitudes, both N. and S., and as the cycle progresses the spots become more prolific and approach the lower latitudes, reaching about 15 degrees at solar maximum. As the number of spots becomes fewer, the spots continue to approach the Sun's equator until at minimum they are dying out as the high latitude spots of the next cycle are beginning to appear, so that there is a slight overlap. This is shown very graphically if sunspot *positions* are plotted against the years spread over several 11-year cycles, the resulting picture being known as the "Butterfly Diagram". The reason for this name will be obvious from the drawing in Fig. 9.

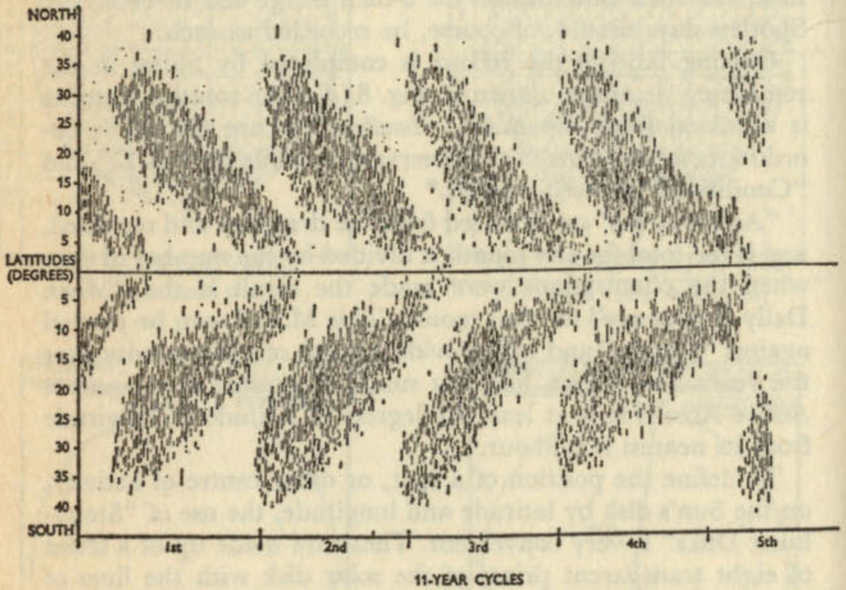

Fig. 9. *Representation of* "*Butterfly*" *Diagram.*

Adapting Observatories. Amateurs with the larger telescopes, and with equatorial stands and possibly clock drives, will usually have some form of observatory or shelter for their instruments. If the telescope can be enclosed except for one limited opening to the sky, it should be possible reasonably to dim the inside of the structure. This can conveniently be done with a double spring blind, one blind being fixed to the top of the observatory roof shutter opening and the other to its base. Then, if an open rectangular frame—as wide as the open shutter, with some overlap, and 8 inches or so high—is attached to the bottom of the upper blind and allowed to run up and down on curtain rails fixed to the sides of the shutter opening, the bottom blind can be hooked on to the bottom of the frame and the whole adjusted by means of cords so that the telescope when directed to the Sun points through the opening in the frame (the gap between the blinds). All that is then required to make a reasonably dark observatory is a cardboard rectangle large enough to cover the gap amply, and having a hole to fit over the telescope at the object glass end. Then one can do away with projection boxes and have a simple support for the projection card attached to the telescope and yet secure a bright image which will show all the solar disk features visible with the instrument. In fact one must not have the observatory too dark, or there will not be enough light to draw by.

Observing Prominences. Possessors of solar spectroscopes will know the pleasure of looking for, and studying, the solar prominences, but a brief word can be said to those first acquiring such an instrument. The small 3-prism combined star and sun spectroscopes are of little use for solar work, the dispersion being too small. For observing prominences, a spectroscope should easily split the twin sodium D lines of the solar spectrum and be applied to a telescope of 4-inches aperture or more if useful work is to be done. Since the slit has to be accurately kept tangential to the telescopic image of the Sun's limb, it is rather difficult to observe with a telescope on an altazimuth stand, and an equatorial is practically a necessity, while a clock-driven instrument is a great advantage.

The essential steps are—first to set the telescope with the primary image of the Sun fully on the spectroscope slit, with the latter nearly closed. The dark Fraunhofer lines will be seen, and the hydrogen Hα line (the C line of the solar spectrum) should be brought to the centre of the field of view and be focused as sharply as possible with the *spectroscope* eyepiece. Then the Sun's image should be brought centrally across the slit, but only half covering it, as a radius of the Sun projecting beyond the limb. The length of the spectrum will then appear half dark and half bright, and this line of demarcation should be focused by the *telescope* wheel. The Sun's image is then moved so that the slit is tangential to the Sun's limb; this is the delicate operation, as it has to be "spot on" and be kept there. If the slit is even slightly beyond the limb the spectrum is dark, but as the limb is brought to the slit a tapering tongue of light spreads along the spectrum and it is at the point of contact of this bright tongue with the C line that the line itself reverses from dark to bright. Keeping the slit in this critical position, it can be gently opened, and if a hydrogen prominence is there it will be seen as a pinkish, bright "flame".

One has to seek out the prominences and, by carefully "parading" the tangential slit round the Sun's limb, a search can be made.

Photography. This is not the place to go fully into the more specialized subject of solar photography*, but those wishing to experiment can first try by using an ordinary miniature camera held against a low-power eyepiece, fitted with a dark filter, mounted on a sun diagonal. The filter should be of a rather lighter shade than one used for visual observing through the diagonal, and the camera itself must be set to "infinity". By trying exposures of, say, 1/50 and 1/100 second, or whatever speeds are available, a series of pictures can be taken at a low cost, and experience gained.

The enthusiast will then procure, or make, a solar camera (no lens required) rather on the lines of the observing box illustrated in Fig. 7 (*a*), the back being a holder to take a ground glass focusing screen and plates, or films. There should not be any viewing opening in the side, of course. The shutter is the

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* Fuller information on solar photography as well as a more detailed account of observational procedure is given in the author's book, *The Sun and the Amateur Astronomer* (David and Charles, 1973).

problem and the best arrangement is undoubtedly a focal plane type. If a shutter is of the leaf type to operate near the telescope prime focus, it will be subjected to considerable heat, but a home-made spring-operated metal shutter has proved satisfactory. Another problem is to arrange for dark filters to be fitted where they are not shattered by the concentrated heat at the telescope eyepiece, but this trouble can be largely overcome by having a flap over the object glass, operated from the eye end, which is only opened during the brief moments of focusing on the ground glass screen and exposing the plates. The filters are preferably fitted in front of the field lens of the eyepiece.

Plate 12 is of a very remarkable and active spot group which was visible to the naked-eye. Note the changes in one day—the upper picture being taken on 1960 March 31 and the lower one on April 1. Plate 13 illustrates the work of H. N. D. Wright and the solar camera he uses.

APPENDIX

SOLAR CO-ORDINATES

To show how the co-ordinates P, B_0 and L_0, are obtained, Fig. 8 (*d*) is used as an example, the date of this chart being 1961 December 24.

The data in the annual *B.A.A. Handbooks* relating to the Sun are given for noon (U.T.) for every fourth day and the nearest date in the *Handbook* for 1961 (page 7) is December 23 with P = + 6°·3, B_0 = − 2°·0 and L_0 = 66°·0 (last three columns).

P: This is the position angle of the Sun's axis at noon and, being positive, indicates that the N. end of the axis is to the E. of the N. point of the disk.

At noon on 1961 December 23 the N. end of the axis was inclined towards the E. at an angle of 6°·3. Since the angle at noon on December 27 (i.e. 4 days later) is given as + 4°·4 we obtain for noon on December 24, by interpolation, an angle of + 5°·825. This, to the nearest decimal which is sufficiently accurate in view of the small daily change, gives + 5°·8 and the axis can be drawn in accordingly with the aid of a 6-inch protractor.

B_0: This is the latitude of the centre of the Sun's disk, indicating the tilt towards or away from the observer. If positive, the centre of the visible disk is above the Sun's equator, indicating that the N. end of the Sun's axis is tilted towards the Earth by the angle in the

Table. If negative, the axis is, of course, tilted away from the Earth.

On 1961 December 23 the angle was −2°·0 while on December 27 it was − 2°·5. Again interpolating, the angle on December 24 was − 2°·125, or to one decimal − 2°·1. This angle is not shown on the drawings, but the figure is inserted.

L_0: Here we have the longitude of the centre of the disk at the time of observation. This changes fairly rapidly and we have to take account of the actual time. As the Sun does not rotate as a solid body it was necessary for all recording purposes to fix an arbitrary (average) rate of rotation. This has been taken as 25·38 mean solar days and in the preceding page of the *Handbook* the rotation numbers throughout the year are given. December 24, 1961, fell within Rotation No. 1,448 and this is entered on the drawing.

Longitude 0° rotates with the Sun, and as the Sun rotates (as seen from the Earth) from E. to W. while the longitude on the surface is also counted from E. to W. it means that the longitude of the Sun's central meridian decreases day by day; in fact by 13°·2 per day.

For 1961 December 23 the longitude of the central meridian (L_0) at noon was 66°·0 and on noon on December 24 it must have been 66°·0 minus 13°·2 (1 day lapse) = 52°·8, but as the time of observation was 2 hours before noon we must *add* back the variation for this difference (given for various hours and minutes in the preceding page of the *Handbook*, above the rotation number) which is 1°·1 for 2 hours. 52°·8 + 1°·1 = 53°·9, which is entered on the drawing as the L_0 at the time of observation (U.T.). The resulting figures were therefore as shown in Fig. 8 (*d*).

Incidentally, 5 Active Areas were recorded for that day.

FURTHER READING

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Chapter Six

LUNAR OBSERVATION

PATRICK MOORE

UNDOUBTEDLY THE MOON is the most spectacular object in the entire sky from the point of view of the modestly-equipped amateur observer. Even a low magnification is enough to show a vast amount of detail; the mountains, craters, rills and valleys are there for inspection, and each feature has its own points of interest.

Not so very many years ago, the best maps of the Moon were of amateur construction, and the number of professional astronomers paying any attention to the lunar surface could have been counted on the fingers of one hand. Before the war, ideas of reaching the Moon by space-ship (either manned or unmanned) were officially dismissed as wild dreams, and professionals as a whole were profoundly uninterested in lunar research—apart, of course, from studies of the Moon's movements. Therefore, the field was wide open to amateurs, who made the most of their opportunities. For instance, an elaborate map was produced in 1875 by an English amateur, Neison, who also published a full account of the surface features. There were such men as T. G. Elger, Walter Goodacre and H. P. Wilkins—all, at various times, Directors of the Lunar Section of the British Astronomical Association—who used their telescopes to study the Moon intensively.

The main emphasis then was upon mapping. The method was to use photographs as a basis, and then fill in the fine detail at the eye-end of the telescope. Particular attention was paid to the libration regions—that is to say, those areas near the Moon's limb which are carried alternately in and out of view as the Moon seems to "rock" in the sky. Obviously, these areas are very foreshortened, and hard to study; it is difficult to tell a ridge from a rill. Moreover, it was always possible to happen upon some intriguing new feature. If I may cite a personal case: I well remember observing with a 15-inch reflector together with Wilkins, some time before the war, when we suddenly noted a curious object near the lunar limb which we thought might be a small sea or mare. We spent hours in charting it as well as we could, and sent in a report to the British Astronomical Association. So far as I know, this was the first sighting of the so-called Mare Orientale or "Eastern Sea"—now, from space-probe pictures and astronaut observation, known to be one of the most significant and important objects on the Moon.

This kind of discovery cannot be made now. In 1959 the first lunar probes were launched; in the 1960s came first the Rangers and Lunas, and then the Orbiters and Apollos. Earth-drawn maps were replaced by the superb, immensely detailed pictures obtained from close range. It is natural that these pictures should show objects much too delicate to be glimpsed from Earth; and the various features can be studied not only from nearby, but also from favourable vantage points. Foreshortening is no problem. We must agree, then, that mapping the Moon is now complete, and that charts drawn by telescopes on Earth are no longer of any scientific value.

This being so, it has been suggested that lunar research by amateurs has been superseded. Yet nothing is further from the truth. All that has happened is that the serious modern amateur must become more specialized, and recognize his limitations. There is still plenty of scope for him—as I hope to show during the course of this chapter.

I. THE BEGINNER

Scientific contributions can, in general, be made only by the practised observer; but everyone has to make a start, and I propose to quote from my own experience, though naturally others may well have different ways of tackling the problem.

The appearance of a lunar feature—be it crater, mountain or rill—depends very largely upon the angle at which the sunlight strikes it. When a crater is near the terminator, it will have much of its floor covered with shadow, and will appear very conspicuous. Then, as the Sun rises over it, the shadow will decrease, almost or quite disappearing near full moon; and the

crater will lose its prominence, unless it has some special characteristic (such as a very dark floor or very brilliant walls). The classic case is that of the vast plain Maginus, which becomes so obscure under high light that it is difficult to locate at all. Consequently, identifying the features under all conditions is more of a problem than might be thought.

My method was to obtain an outline map of the Moon, and practise with the 3-inch refractor which represented my astronomical equipment at the time. I made a list of all the named features, and then, over a period of a year or so, used my telescope to make drawings of each. I aimed for three drawings of every object, obtained under different illumination conditions. The drawings were of no scientific value (this, of course, was many years pre-Orbiter!) but they were priceless to me, because by the time I had completed the programme I was able to recognize the different features without any trouble at all. When I was able to use a more powerful telescope, I was ready to begin research—at least, I like to believe so.

There are several things to be borne in mind. First, never try to draw too large an area on too small a scale. To make a full drawing of, say, the Mare Serenitatis at one session is useless by any standards, because the craters will be so small that errors are bound to creep into the drawing—both in form and in position. A scale of 20 miles to the inch is about the minimum. This would make the 60-mile, dark-floored Plato three inches along its major axis.

Secondly, the drawing may be either line or half-tone. L. F. Ball, one of the most skilful of lunar artists, has given some instructions about half-tones elsewhere in this book (page 45). I am no artist, and I generally kept to line drawings, using Indian ink for the shadows. One useful hint is that when the drawing has been completed, it should be re-checked at the telescope if this is possible—though, of course, the Moon may have set or vanished behind cloud before a final inspection can be made.

I recommend beginning with a low magnification, for the main details, and then changing to a higher power for the fine detail. Never draw in any feature unless you are certain of its existence; and always add the time (GMT), date, magnification, seeing conditions (Antoniadi scale—from 1 to 5, 1 being superb and 5 being very poor), telescope and observer's name. If any of this information is omitted, the drawing will be of virtually no value at all. Also, never throw an observation away—and if you want to send off an observation to a colleague, send a copy rather than the original. I followed this procedure even in pre-war days, when the postal services were so much more efficient than they are now, and letters did not go astray so frequently.

A 3-inch refractor or a 6-inch reflector is ideal for this preliminary work, and smaller instruments are not to be despised. In former times, useful scientific work could be carried out with such telescopes. During one survey with a 3-inch refractor, again before the war, I discovered a large crater right on the Moon's limb at maximum libration; this object—now called Einstein—had not previously been recorded. I can claim no credit; it was simply that I was looking at the right place at the right time, and I did know what to expect and what was unfamiliar. Today, however, it is best to concede that even a 6-inch is generally too small an aperture for research, and so far as reflectors are concerned 8 inches is probably the minimum. (For a refractor, the limit is more like 5 inches. Here again there are many observers who will disagree with me.)

Formerly, all lunar sketches were made with south at the top, and telescopically the left-hand limb was regarded as west; thus Mare Crisium was in the western hemisphere of the Moon, Grimaldi in the east. A resolution by the International Astronomical Union has now altered this, reversing east and west, and official charts have north at the top. It is rather ironical that Mare Orientale, the Eastern Sea, is now regarded as being on the extreme western limb of the Moon as seen from Earth!

One further point is worth making. Though practically all the Moon has been photographed in detail from the various space-probes, there is still an area in the far south in which the coverage is not entirely satisfactory. Therefore, telescopic drawings of this region are still of value, and will remain so until further photographic probes are sent up—and as yet there is no official word of when this will be. However, the work is difficult, since it applies to the libration zones, and only the experienced observer can hope to contribute usefully.

II. CRATER DEPTHS

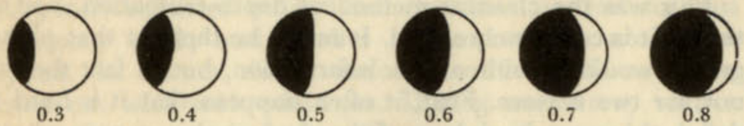
The depth of a walled formation is obtained from the length of the shadow cast by its rampart. The angle of the Sun's rays can be calculated accurately for any time; if the observation is carefully timed, and the amount of interior shadow is measured, the depth can be obtained.

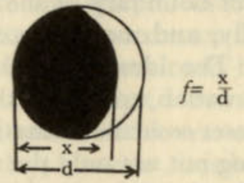
This was the classical method of depth-estimation, and in theory it is completely sound. It might be thought that photographs would provide all the information, but in fact they do not, for two reasons. First, it often happens that it is hard to define the exact boundary of the shadow shown on a photograph. Secondly, and more important, a single measurement is inadequate. The ideal is to obtain shadow measurements over a whole lunation, spreading them out at intervals between sunrise and sunset over the formation. This will provide all the data for working out not only the depth, but also the profile of the crater. Clearly, this would be difficult and laborious photographically.

Micrometrical measurements might be expected to provide the answers, but, rather surprisingly, it has been found that visual estimates are as good—perhaps better. The method to be described here applies only to small craters (below about 20 miles in diameter), and is accurate only for craters which are more or less regular in outline. It has been applied extensively by members of the Lunar Section of the British Astronomical Association, and has been nicknamed "Project Moonhole".

What is done is to make a mental division of the crater diameter into ten parts, reckoning along an east-west line. The observer locates the crater, and makes an estimate of the position of the boundary of the shadow. Thus if the shadow extends exactly half-way across the floor, the estimate would be recorded as 0.5.

Experience has shown that simple estimates of this kind are subject to considerable error. It is much better to compare the crater, as seen through the telescope, with a set of prepared disks, given in the diagram on p. 64. For reasons which will be fairly obvious by looking at these disks, there is a general tendency for the newcomer to underestimate the shadow; look for instance at the 0.5 disk—without careful analysis, it looks much more like 0.4, because we are reckoning from the *extreme* extent of the shadowed area. Obviously, it is essential to note the time of observation; it is sufficient to give it to the nearest minute. Under favourable conditions, it may be possible to estimate to better than a tenth: say 0.55, if you consider that the shadow is more than 0.5 but less than 0.6.





Observational Method

It is hopeless to attempt Moonhole work except when the seeing is good and the conditions steady. Otherwise, the crater will tend to jump around in the field of view, and accuracy will be reduced. Remember, we are dealing with small craters, and this means using as high a magnification as is consistent with steadiness and clarity. It also means that a reasonably large aperture is required. I would not be happy at making any attempts with a telescope of below 8-inch aperture (reflector) or 5-inch (refractor), though observers who are keener-eyed and more skilful may well be able to manage with smaller instruments.

The calculations needed are rather complicated, but this is not the task of the observer, whose rôle is to make the estimates and submit them for analysis. (In Britain, this is undertaken by the Lunar Section of the British Astronomical Association.) It is not yet certain how accurate the method will prove to be, but it does represent an interesting and potentially valuable investigation, since not even the Orbiter coverage can hope to provide photographs of all the small craters under a large number of different conditions of lighting; also, the position of the probe

itself is all-important, and the data are not always known sufficiently well.

The B.A.A. list of craters for this investigation includes 48 features, selected because of their positions on the Moon's face and because of their comparatively regular outlines. Observations made in the early hours of the morning (i.e. after full moon) are particularly valuable. With sufficient numbers of estimates, it is hoped to produce some good results with regard to the depths and profiles of the craters under study.

III. TRANSIENT LUNAR PHENOMENA (T.L.P.S)

Classically, the Moon has been regarded as a totally inert and changeless world, where nothing ever happens. This was the view expressed by the great German observers Beer and Mädler, in the 1830s, when they published their lunar map—much the best of its time, and not surpassed in accuracy for the next half-century. It is interesting to note that this led to a falling-off of enthusiasm for lunar work, and few observations were made between 1840 and 1866, because it was thought that there was nothing left to do!

It is, of course, correct to say that large-scale changes on the Moon ceased a long time ago. For many tens of millions of years there have been no marked structural alterations. There have been reports of variations; the most famous case is that of Linné, on the Mare Serenitatis, which was described as a deep crater before 1843 and as a small craterlet, surrounded by a white nimbus, since 1866. But the evidence is very slender, and it is now generally thought that no real change has occured. This is certainly my own view.

On the other hand, we do occasionally see phenomena which are on a much smaller scale, and take the form of local obscurations or reddish, short-lived patches. They are elusive—so much so that it is only since 1958 that they have been taken seriously by professional astronomers, though amateurs had been recording them much earlier. In a paper published around 1957 I called them T.L.P.s, an abbreviation for Transient Lunar Phenomena, and this term now seems to have come into general use.

T.L.P.s are of two main types. First, there are the localized obscurations, affecting the floors and sometimes the walls of certain crater structures: Plato is particularly subject to them. They are detected mainly by blurring of normally-visible but delicate objects, such as the craterlets on the floor of Plato or Schickard. Only the observer who is really familiar with the Moon can hope to be confident of tracking one down. It is essential to make sure that the obscuration is really confined to a small area, and that details all round are as hard and sharp as usual. These phenomena are very rare, and an observer may search for many years before seeing one; he may never be successful. Obviously, a relatively large telescope is needed, and the conditions of observation must be really good.

The second class includes the transient reddish glows which are seen for brief periods, from a few minutes to an hour or two. Amateur reports of these go back for decades, but until 1958 they were officially discounted. Then, on November 3 of that year, a red T.L.P. in the crater Alphonsus was seen by the Russian astronomer N. A. Kozyrev, using the powerful telescope at the Crimean Astrophysical Observatory; subsequently T.L.P.s in the Aristarchus area were recorded by J. C. Greenacre and his colleagues, at the Lowell Observatory at Flagstaff in Arizona. T.L.P.s became officially "respectable", and a catalogue of all reports was published by NASA.* I have since produced an extension†.

Really major T.L.P.s are visible in ordinary light; there was one interesting case in 1966, near the crater Gassendi, which was seen by four separate observers working quite independently. However, in general the intensity is so low that a device now called a Moon-Blink is used.

This consists essentially of a system of rotating filters, one blue and one red. The device is fitted to the telescope, and the eyepiece is screwed into it. By rotating a knob, the observer can use either the red filter, the blue filter, or no filter at all. He then "flicks" the knob to and fro, observing alternately in red and in blue. If there is a red coloration on the Moon, the red filter will suppress it while the blue filter will enhance it. The

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* *Chronological Catalog of Reported Lunar Events*. B. M. Middlehurst, J. M. Burley, Patrick Moore and B. L. Welther. NASA Technical Report TR R-277. Washington, July 1968.

† *Extension of the Chronological Catalogue of Reported Lunar Events*. Patrick Moore. Journal of the British Astronomical Association, Vol. 81, p. 365 ff, 1971.

flicking movement brings in the persistence of vision; and the red patch will show up as a "blink"—hence the name. The device is remarkably sensitive. (Anyone who doubts this need only test it by looking at the Great Red Spot on Jupiter, though this is of course much better-defined and much more strongly coloured than any lunar T.L.P.)

It is vital to remember that T.L.P.s are short-lived and by no means prominent or common, so that many hours of work will certainly be carried out with entirely negative results; thus I observed all through 1971 and 1972 without seeing anything definite. Yet these negative reports are invaluable. No T.L.P. observation is to be regarded as reliable unless it is confirmed by a second observer, entirely independently. It follows that the negative reports submitted make it possible to weed out "positive" reports which are erroneous.

I have little faith in any positive reports made with telescopes of small aperture, and I would never attempt a survey with any reflector below 8-inch; also, refractors are clearly less suitable for observing faint colour phenomena, unless they are optically very good. It is essential to use as high a power as is consistent with sharpness of definition.

Aristarchus, the brilliant crater which is always identifiable (even by earthshine), is the most T.L.P.-prone crater, but there are others: T.L.P.s have been reliably seen in or near Gassendi, Alphonsus, Grimaldi and Plato, to give only four examples. It has also been found that they are commonest near lunar perigee, and this agrees also with the frequency of the minor "moon tremors" recorded by seismometers left on the Moon by the Apollo astronauts. It is therefore wise to concentrate upon the known T.L.P. areas, but other regions should be observed as well, as otherwise any analysis will be unbalanced.

If a trace of colour or a local obscuration is suspected, the first thing is to check that it really *is* local. If other areas too show the same effect, it is obvious that terrestrial atmospheric effects or instrumental troubles are responsible; and the importance of this cannot be over-emphasized. When the Moon is low, or the atmosphere is not clear, there will be plenty of colour—but it will not indicate any activity on the lunar surface.

If the observer is reasonably confident that he really has detected a T.L.P., he should record all the relevant details at once. In Britain, the Lunar Section of the B.A.A. has a network of observers, so that other members can be contacted quickly (by telephone if possible); but when notifying a T.L.P. it is best to be vague, so as to avoid unconscious prejudice.

Let us sum up the situation. T.L.P. work is the province of the experienced observer, as only he can judge what is genuine and what is not; he must be equipped with an adequate telescope (for instance, a 3-inch refractor is useless for this kind of work) and the conditions must be good. A blink device is most useful, though it cannot be used with a small instrument; too much light is lost.

When starting out, undertake a general survey, first of known event-prone areas and then of others; it is a good idea to draw up a systematic personal list. If the results are negative (as they probably will be), fit the blink device, if available, and again survey. If there is any hint of a T.L.P., check all adjacent areas to make sure that atmospheric conditions or instrumental defects are not responsible. Also change eyepieces, and re-check. If there is still a positive response, note all the details, and contact a colleague if you possibly can.

One trouble about T.L.P. patrolling is that a faulty report is worse than useless: it is actively misleading, as it will distort the analysis. Tremendous care is needed at all times. Yet for any observer who is really serious, and is prepared to spend many hours at the telescope without seeing anything unusual, the programme is immensely rewarding.

Finally, it is worth mentioning the occasional reports of bright flashes seen on the Moon. I have never observed one myself, but there are a few instances which seem to be reliable. Their cause is uncertain—and indeed there is still a sharp difference of opinion as to the origin of any T.L.P.s, though many authorities favour the idea of gaseous emission from below the lunar crust.

IV. MISCELLANEOUS

Despite the probe results, there is still room for what may be called miscellaneous observations of the Moon. Thus the intensities of hue in some craters seem to vary, mainly according to the angle of solar illumination but possibly for other reasons as well. The rays coming from some of the craters will also repay study; the observer may compare the brightness of craters such as Aristarchus and Proclus, which may not be entirely constant; and it is also worth looking carefully at those areas of the Moon which are illuminated only by earthshine. One never knows what will be found. During the past decade we have learned more about the Moon than would have been thought possible before the age of space-probes; but we cannot claim that we have yet a really complete knowledge of the lunar world. And though the amateur's rôle is much more restricted than it used to be, he can still make himself really useful—provided that he is adequately equipped, and has sufficient enthusiasm and patience.

Of course, the exceptional amateur may equip himself with more complicated equipment, and extend his scope; but a discussion of these sophisticated techniques is beyond the range of the present book. Occultations and photographic work are discussed in separate chapters.

Finally, let us always remember that not all amateurs are anxious to carry out scientific research. And if you have no inclination to spend hours in searching for T.L.P.s, measuring crater shadows or timing occultations, you will still derive endless enjoyment from just looking at the mountains and craters of our companion world.

REFERENCES

Many lunar maps are now available. The old edition of Elger's (Geo. Philip & Son) is very good, though unfortunately the new edition has north at the top and is coloured—thereby reducing its value for the observer at the telescope. My own outline map, also 2ft. in diameter, retains south at the top, and can be obtained from the B.A.A. Lunar Section.

The B.A.A. has also published a 'Guide for Observers of the Moon', in which the subjects discussed in this chapter are dealt with in much more detail. It can be obtained from the Association.

Of the various photographic atlases, special mention should be made of *The Amateur Astronomer's Photographic Lunar Atlas*, by Henry Hatfield, published by Lutterworth Press. This includes an identification map, and is invaluable.

Theoretical books include *Lunar Geology*, by Gilbert Fielder (Lutterworth); *The Measure of the Moon*, by R. B. Baldwin (Chicago);

The Craters of the Moon, by P. J. Cattermole and myself (Lutterworth); and *The Earth and its Satellite*, edited by John Guest (Hart-Davis). Of course, there are very many others. The literature of the Moon has mushroomed during the past few years.

Chapter Seven

OBSERVATION OF OCCULTATIONS

Gordon E. Taylor

During its monthly course along the ecliptic the Moon will naturally pass in front of a number of stars. Such a phenomenon is referred to as an occultation, and in astronomy we can define an occultation as the passage of one body in front of another as seen from a third body. Thus an eclipse of the Sun could also, and more correctly, be described as an occultation.

For an observer on the surface of the Earth the phenomenon has two phases—disappearance and reappearance—as shown in the diagram (Fig. 10). At both these phases of a lunar occultation the geometrical condition is that the line joining the star and the observer is tangential to the limb of the Moon. Thus, if the positions of the observer and the star are known accurately, the position of the Moon's limb at the observed time may be deduced. The combination of observations from different

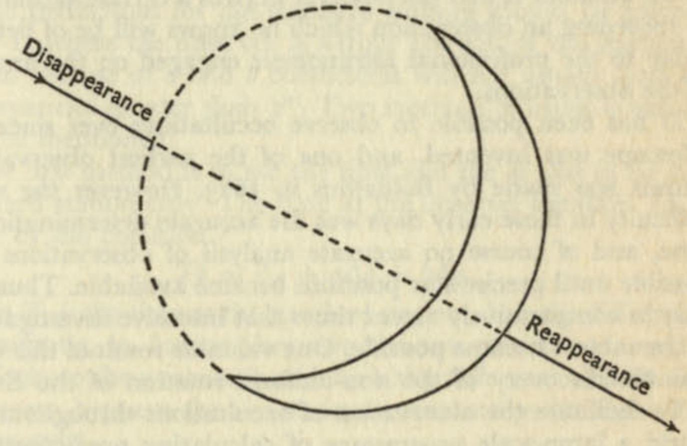

Fig. 10. Apparent path of an occulted star relative to the Moon.

stations enables an accurate position of the centre of the Moon to be derived.

Because the lunar atmosphere is either negligible or non-existent a star will disappear or reappear instantaneously—at any rate as far as the visual observer is concerned.

It is in the determination of the time of an occultation that the amateur observer can make a valuable contribution to the investigations of the motion of the Moon and the rotation of the Earth. This branch of astronomy is probably unique in one respect—observations of the amateur and the professional alike have equal weight when the analysis of the observations is made. The reason for this equality is that no large instruments or other expensive items of equipment are necessary. Many professional observatories have their instruments and staff fully occupied by other astronomical investigations which amateurs cannot undertake, and thus it is worth emphasizing the value and importance of amateur observations of occultations. A further point which should recommend this type of observation to the amateur is that the observer derives a certain satisfaction in recording an observation which he knows will be of definite value to the professional astronomers engaged on the analysis of the observations.

It has been possible to observe occultations ever since the telescope was invented, and one of the earliest observations known was made by Bullialdus in 1623. However the main difficulty in those early days was the accurate determination of time, and of course no accurate analysis of observations was possible until precise star positions became available. Thus it is only in comparatively recent times that intensive investigations of the subject became possible. One valuable result of this work was the discovery of the non-uniform rotation of the Earth.

To facilitate the observation of occultations throughout the world a large-scale programme of calculating predictions for about 90 stations is undertaken annually by H.M. Nautical Almanac Office.

Predictions. The process of prediction commences with a comparison of the positions of those stars of magnitude 7·5 or brighter listed in the *Catalog of 3539 Zodiacal Stars for the Equinox 1950·0* (hereafter referred to as the *Z.C.*), with the ephemeris of

the Moon. Calculations of all possible occultations are made and the circumstances of each individual occultation are predicted using a modern electronic computer.

Formerly a unique "occultation machine" was used for the first stages of the prediction. This machine simulated the relative positions of the Earth, Moon, star and Sun and correctly indicated the passage of the lunar "shadow" (regarding the star as the only source of light) across the Earth's surface. This method made it possible to determine which stations could observe the occultation under suitable conditions, and also to obtain approximate times and position angles for each station. Using this information more accurate calculations were then performed on an electronic computer.

The final times (to $0^{\mathrm{m}}{\cdot}1$) and position angles (to 1°) for standard stations are then printed in various publications,[*] together with certain quantities (a and b) which enable an observer who is not at a standard station to calculate the time at his particular station.

The predictions for the standard stations should be correct to $0^{\mathrm{m}}{\cdot}1$; where the observer is within 500 km of the standard station the use of a and b coefficients will not usually lead to discrepancies greater than 2^{m}. Two methods of using *a*s and *b*s may be mentioned.

The first method is to use the time and the *a*s and *b*s for the standard station only. The time at the observer's station Tp is given by the equation

$$Tp = T_1 + a\Delta\lambda + b\Delta\varphi$$

where T_1 is the time at the standard station, $\Delta\lambda$ is the difference of longitude, in degrees, between the two stations, measured positively to the westwards and $\Delta\varphi$ is the difference of latitude, in degrees, between the two stations, measured positively to the northwards.

The second method, although rather more complicated, is more accurate than the first method and is recommended to be used where the observer is more than about 200 km from a standard station. The method uses predictions for two standard stations and adjusted values of the a and b coefficients, which are then used with respect to the nearer standard station.

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[*] **E.g. The *Handbook* of the B.A.A. which contains predictions for Greenwich and Edinburgh, Sydney and Melbourne, and Dunedin and Wellington.**

Consider as an example the occultation of 33 Piscium (*Z.C.5*) on 1963 October 29. Predictions for the disappearance phase are given for two stations as follows:

Station	U.T.	a	b
	h m	m	m
Greenwich	22 34·9	− 2·0	− 1·4
Edinburgh	22 25·7	− 1·5	− 0·5

A predicted time is required for an observer at Manchester. The coordinates of the three stations concerned are as follows:

	Longitude	Latitude
	°	°
Greenwich	0·00	+ 51·48 (= φ_1)
Edinburgh	+ 3·18	+ 55·92 (= φ_2)
Manchester	+ 2·23	+ 53·48 (= φ)

The adjusted coefficients are obtained from the following equations

$$a = a_1 + \frac{(\varphi - \varphi_1)}{2(\varphi_2 - \varphi_1)} \cdot (a_2 - a_1)$$

$$b = b_1 + \frac{(\varphi - \varphi_1)}{2(\varphi_2 - \varphi_1)} \cdot (b_2 - b_1)$$

where φ_1, a_1, b_1, apply to the nearer standard station (here taken as Greenwich) and φ_2, a_2, b_2 to the more distant standard station and φ is the latitude of the observer. Thus

$$\frac{(\varphi - \varphi_1)}{2(\varphi_2 - \varphi_1)} = \frac{+2{\cdot}00}{2(+4{\cdot}44)} = +0{\cdot}23$$

It should be noted that this value of + 0.23 is a constant for this particular station. Now

$$\begin{aligned} \Delta\lambda &= +\ 2{\cdot}23 - \ 0{\cdot}00 = +2{\cdot}23 \\ \Delta\varphi &= +53{\cdot}48 - 51{\cdot}48 = +2{\cdot}00 \end{aligned}$$

Therefore

$$\begin{aligned} a &= -2{\cdot}0 + 0{\cdot}23\,[(-1{\cdot}5) - (-2{\cdot}0)] = -1^{\mathrm{m}}{\cdot}9 \\ b &= -1{\cdot}4 + 0{\cdot}23\,[(-0{\cdot}5) - (-1{\cdot}4)] = -1^{\mathrm{m}}{\cdot}2 \end{aligned}$$

and

$$Tp = 22^{\mathrm{h}}\,34^{\mathrm{m}}{\cdot}9 - 1^{\mathrm{m}}{\cdot}9\,(+2{\cdot}23) - 1^{\mathrm{m}}{\cdot}2\,(+2{\cdot}00) = 22^{\mathrm{h}}\,28^{\mathrm{m}}{\cdot}3$$

Before Full Moon predictions are given only for disappearances, and after Full Moon only for reappearances, except for the brighter stars when both phases may be given. This is because it is much easier to see the star near the unilluminated limb of the Moon than near the illuminated limb.

Predictions of grazing occultations are done separately. The track of a grazing occultation across the surface of the Earth can be predicted accurately and useful observations can be made within 1 or 2 kilometres of this line.

Observations. An important prerequisite of occultation observations is a knowledge of the observer's position. This position is required to an accuracy of one second of arc, equivalent to a distance of about 30 metres on the surface of the Earth. Thus an observer using a portable telescope sometimes in his front garden and sometimes at the end of his back garden might have to determine two sets of coordinates. The coordinates required are *geodetic* latitude and longitude, and altitude above sea level in metres. Large scale maps, capable of yielding the required accuracy, are normally available for examination at reference libraries and at surveyors departments of local councils. If it is not possible to obtain positions in latitude and longitude then the National Grid coordinates should be obtained. (H.M. Nautical Almanac Office will perform the reduction to latitude and longitude.) The altitude above sea level is required only to an accuracy of about 10 metres.

There are several methods of timing an occultation and three will be described here.

Many experienced observers prefer the eye-and-ear method whereby the observer listens to a signal giving seconds beats, counts from the minute beat and estimates the fraction of a second when the occultation occurs.

The usual method employed by observers without access to an audible seconds beat is to use a stop-watch. The watch is started at the moment of occultation and referred to a time-signal as soon as possible. The accuracy of the observation is improved if the observer first listens to a series of the seconds beats and determines the tenth or fifth of a second that the stop-watch is registering at each second. The stop-watch is then stopped on the next convenient second beat. It is quite likely that the observer will stop the watch a few tenths of a second late, but this will not matter, as he has already correctly determined the decimal of a second. Occasionally two or more occultations will occur close together in time (e.g. a double star or occultations of the Pleiades). In such cases a split-action stop-watch (with two hands) is obviously better than an ordinary stop-watch.

Few amateurs possess chronographs, but those who do will find the instrument very suitable for the recording of observations. The observer presses a key at the moment of occultation; this key actuates a pen which marks a paper tape which is also continuously recording a time-signal. An examination of the tape at leisure permits the determination of the time of the occultation.

In both the latter methods there will be a certain time lag between the moment of the actual occultation and the moment when the observer presses the stop-watch button or key, because of the suddenness of the event. This lag is referred to as the observer's personal equation. Strictly speaking, it will vary in amount from observer to observer, and will also depend on the state of the observer (alert or fatigued) and on the length of time which he has been waiting and watching for the occultation to occur. Interested observers should determine their own average personal equations—for example the author has found his personal equation to be about $0^{s}{\cdot}3$ for disappearances and $0^{s}{\cdot}5$ for reappearances. *However, no personal equation should be applied to the observation unless this fact (and the amount) is clearly stated.* There is no objection to an observer not indulging in this refinement.

In all methods it is necessary to use time-signals of some sort. If a short-wave radio set is available, then a station giving continuous seconds impulses is the most suitable—European observers would be best served by using DIZ on 4·525 Mc/s. If the observer does not possess a short-wave radio then he can use the "Speaking Clock" telephone service or ordinary time-signals from the B.B.C. The latter, however, is not a very useful source. There is at present a gap of 3½ hours between signals in the evening, and on some occasions the expected time-signal is suppressed to avoid interruption of a programme. A chronometer, rated with time-signals before and after the occultation, could also be used.

Predictions are given only for those occultations which can be observed with small telescopes.

If the observer has a choice of telescopes then he should note that aperture is not the only consideration. Focal ratio is also extremely important and personally I would prefer to use a 10 cm refractor working at f/15 rather than a 20 cm reflector working at f/5.

If the observer does possess a clock-driven equatorial telescope he may calculate the star's hour angle and then set this and the star's declination on the circles. This technique is only worth bothering about for reappearances or for large instruments with small fields of view. However, many amateurs will not have access to such elaborate equipment, so the ensuing paragraphs are written for their benefit.

The observer should note the predicted time and position angle and ensure that he has ample time in which to set up his instrument and, in the case of disappearances, to locate the star, or in the case of reappearances, to estimate the position angle.

When observing under poor conditions or when the star is relatively faint it may be difficult to locate the star, despite a knowledge of the position angle. Particularly with a slight mist or haze the glare of the Moon becomes overpowering, and in such cases it often pays to use an eyepiece of higher power so that the intensity of illumination is reduced and also less, if any, of the bright limb remains in the field of view. The observer should know the field diameter of each eyepiece used with the telescope and thus be able to arrange for the star to be in the centre of the field at the predicted time. If he does not do this he may have to move the telescope, at the critical moment, in order to counteract the Earth's rotation.

Reappearances are slightly more difficult to observe than disappearances, as the observer has to estimate where the star is to reappear. Partly for this reason, and also because predicted reappearances usually occur after midnight, observations of disappearances outnumber those of reappearances by about ten to one. Theoretically, equal numbers of each would be desirable, so observers are particularly requested to attempt more reappearances.

With an equatorially mounted Newtonian reflector and an astronomical eyepiece the position angle can be judged quite effectively. An observer in the northern hemisphere knows that if the line joining his eyes is made parallel to the optical axis of the telescope then East (position angle = 90°) is in the direction of his right eye (or left eye if he is in the southern hemisphere); position angle is measured from the N. point through E. (i.e. in an anti-clockwise direction). It must be emphasized that neither the direction of the Moon's N. pole nor the line joining the cusps is generally coincident with the direction of the N. point.

One method of determining the position angle relative to the line joining the cusps is to use the "Position Angle of the Bright Limb", tabulated in the almanacs. This enables one to draw a diagram showing the relationship between the two angles. Fig. 11 shows how this is done for the occultation of μ Ceti ($4^{\text{m}}{\cdot}4$) (*Z.C.* 405) on 1963 September 7, using the predicted position angles for Greenwich of 65° for the disappearance and 246° for the reappearance.

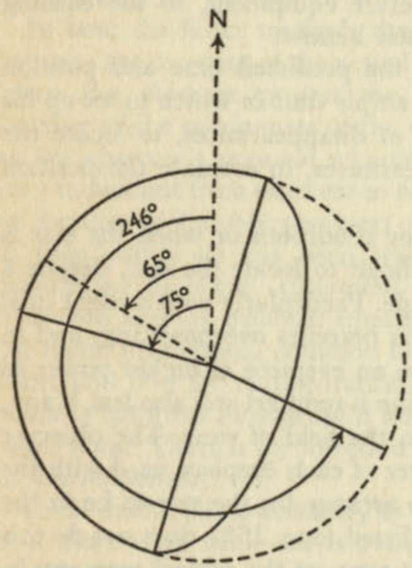


Fig. 11. *Showing the relationship between the position angle of the bright limb (here* 75°) *and the position angle of an occultation.*

Occasionally an observer may go to the telescope to observe a predicted disappearance phase of an occultation and find more than one star about to be occulted. It may be that the star is a close double so that the *Zodiacal Catalog* gives only a mean position e.g. γ Virginis (*Z.C.* 1821) is seen as a double by many observers; or it may be that one component of a double star is just fainter than the limit for predictions ($7^{\text{m}}{\cdot}5$); or it may be that the star is another star, an occultation of which is not predicted because it is not in the *Z.C.* Here again is an instance where the advantage of using a timing system whereby more than one time may be recorded is obvious.

In addition to occultations of stars, those of the planets Mercury, Venus, Mars, Jupiter, Saturn and Uranus and the minor planets Ceres, Pallas, Juno and Vesta are also predicted using the same limits. Note that Neptune is excluded because it is just fainter ($7^{\text{m}}{\cdot}7$) than the limit of $7^{\text{m}}{\cdot}5$.

Because of the comparatively large angular diameters of the planets, occultations of these bodies will not be instantaneous. Although obviously of great interest to the observer, particularly of an occultation of a crescent Venus, Jupiter and its satellites, or Saturn and its rings, the recorded observations cannot be used in the analysis of the Moon's motion.

When the observer has made his observation(s) he should record the details and send them, within six months, to H.M. Nautical Almanac Office, Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, Sussex.

An example of how such observations should be recorded is given below.

Station — Cowbeech
Geodetic Latitude — 50° 53′ 59″ N.
Geodetic Longitude — 0° 17′ 40″ E.
Altitude — 69 metres
Telescope — 20-cm reflector, ×125
Observer — Gordon E. Taylor
Remarks — Personal Equation of $-0^{\text{s}}{\cdot}3$ has been applied to both observations
Time — Stop-watch, radio time-signals

y	m	d	h	m	s	Lunation	*Z.C.*	Phase	Limb
1962	10	09	21	43	46·2 U.T.	492	3210	D	D
1962	10	09	23	13	09·2 U.T.	492	3217	D	D

The lunation number is usually given with a list of Moon's phases. The Phase is either D = disappearance, or R = reappearance. The Limb is either D = dark and B = bright. Special forms for recording observations are now issued to observers.

Observers should receive the results of a preliminary reduction of their observations within a month of the receipt of these observations.

It has been stated previously that an occultation occurs instantaneously. This statement requires modification if photoelectric recording equipment is used, as a light curve, occupying several hundredths of a second, may be detected. Employment of this technique has led to the determination of the angular diameter of the giant star Antares.

Reductions. When the observations for one year (usually numbering about 1,000–1,500) have been collected from all over the world they are punched on cards and an electronic computer is programmed to combine all these observations, one lunation at a time, to determine the difference between the Moon's actual and ephemeris positions. This eventually leads to an evaluation of ΔT, the difference between Ephemeris Time and Universal Time. This difference is currently (1969) about $+ 39^s$, and is caused by the non-uniform rotation of the Earth.

An examination of photographs of the limb of the Moon shows that the assumption of a smooth, circular outline is only approximately correct. Valleys and mountains give this outline quite an irregular appearance when viewed with a high magnification, and thus a star will disappear earlier if a mountain intervenes, or later if there is a relative depression of the lunar surface at that point. Such irregularities will clearly affect the results, and in order to eliminate such irregularities a programme of photographing the limb at varying states of libration has been undertaken at the U.S. Naval Observatory, Washington. Graphs compiled from these photographs enable each observation to be corrected for the effects of these irregularities, which sometimes amount to several seconds of arc. The size of this effect can be gauged by noting that the Moon's motion is about $0''.5$ in one second of time. One interesting feature of minor annoyance is that some extreme libratory regions which can cause occultations when unilluminated are never illuminated as seen from the Earth, and thus cannot be photographed from the Earth!

These "limb corrections", as they are called, will be applied to all occultations observed since 1943, and it is possible that some minor irregularities in the motion of the Moon may be detected in the subsequent analysis.

Observations of grazing occultations are also analysed separately and provide valuable information on the latitude of the Moon. They also provide a check on the accuracy of the limb corrections and have already brought to light a small discrepancy.

Planetary Occultations. Occultations of Radio Sources. The rapid motion and large angular diameter of the Moon give rise to numerous occultations during the year. Of course planets can also occult stars, but because of their relatively slow motion and small angular diameters such occurrences are comparatively rare.

Such occultations are useful for three reasons (i) an accurate position of the planet may obtained; (ii) the diameter of the planet may be derived—this would be especially valuable in the case of Pluto; (iii) grazing occultations, particularly of bright stars, should provide information about the planet's atmosphere, if any. Predictions of such events may be found in the *Handbook* of the B.A.A. Some valuable results have already been obtained from analysis of such observations, particularly regarding Venus in 1959, Neptune in 1968 and Pallas in 1961.

Although few amateur radio astronomers will have suitable equipment it can just be mentioned that occultations of radio sources may also be observed. Such occultations can be of great value in determining an accurate position for the radio source and also in investigating the structure of the source. It was the former line of research which played such a prominent part in the discovery of quasars.

Chapter Eight

OBSERVATION OF MERCURY AND VENUS

PATRICK MOORE

BOTH MERCURY AND VENUS are troublesome objects for observation, even though they are so close to us on the astronomical scale. The very fact of their being "inferior planets", nearer the Sun than we are, raises unique problems. When their distance from the Earth is least, the position is that of inferior conjunction, and the planet concerned is invisible (except, of course, during a transit). The apparent diameter is relatively large at the crescent stage, but shrinks with increasing phase, until by superior conjunction it is almost impossible to do any useful observing.

The difficulties are accentuated by the fact that when Mercury or Venus is easily visible with the naked eye, the altitude is bound to be inconveniently low—and trying to study a planet which is near the horizon is a fruitless occupation. Consequently, almost all the observational programme has to be carried out in broad daylight. With Venus, conditions are sometimes quite good at or soon after sunset, but this is never the case with Mercury.

The first problem facing the would-be observer is that of finding the planet. With Mercury, the only solution is to use a telescope on an equatorial mount and fitted with setting circles; moreover the circles have to be at least reasonably accurate. There is little point in trying to pick up Mercury in daylight with, say, an altazimuth 3-inch refractor. In addition, the angular distance from the Sun is not great, and it is dangerous to sweep around indiscriminately, as there is a real risk that the Sun will enter the telescopic field and damage the observer's eye.

Venus is so brilliant that it may often be seen before sunset or after sunrise, but is not easy to locate unless its position in the sky is already known, so that here too an equatorial telescope is generally needed. Setting circles are a great help, but a driving clock is not essential, and even if the circles are rough and ready they will allow Venus to be found without much difficulty. One method is to turn the telescope toward the Sun, or—more judiciously—very close to it; set the declination of Venus; and then move the telescope in R.A. by the amount of difference between the Sun's R.A. and that of the planet. A low-power, wide-field eyepiece, or an efficient finder, will then bring Venus into view.

When Venus has been located, it can usually be found again on subsequent days without much trouble by sweeping the area with a low power, making allowance for the planet's apparent motion and always taking great care not to bring the Sun into the field.

There is no reason to observe near noon, when, in fact, the atmospheric conditions are often poor. Excellent views are often obtained at twilight or dawn, with the Sun just about on the horizon, but Venus must of course be reasonably near elongation, so that the altitude will be tolerable.

MERCURY

It is, unfortunately, necessary to start off upon a somewhat discouraging note. Without an instrument of considerable size, it is impossible to see any surface details upon Mercury, and useful work is limited to measurements of phase.

Until the success of the Mariner 10 probe in 1974, the chart of Mercury drawn by E. M. Antoniadi in the 1930s remained the best. (It is reproduced in *The Planet Mercury*, the English translation of Antoniadi's little book, published by Keith Reid Ltd. in 1974.) Of course, the Mariner pictures alter the whole situation, and we now know that the surface of Mercury is very like that of the Moon, with many craters and mountains; but these details cannot be seen through any Earth-based telescope.

A 6-inch reflector is able to show the most conspicuous of the dark areas when conditions are really good but no more. Obviously, a larger aperture will reveal a greater amount of detail—but we must admit that all Earth-based drawings are now to be made "for interest only" in view of what Mariner 10 has shown us.

One field is, however, available, and has not received the attention which it has deserved; this concerns the planet's phase. In the case of Venus, theoretical and observed phase are often different; at evening elongations dichotomy occurs early, while at morning elongations it is late (Schröter's Effect). This discrepancy is generally attributed to the atmosphere of Venus. Mercury is virtually devoid of atmosphere, and it is therefore of real interest to see whether it, too, shows a Schröter Effect.

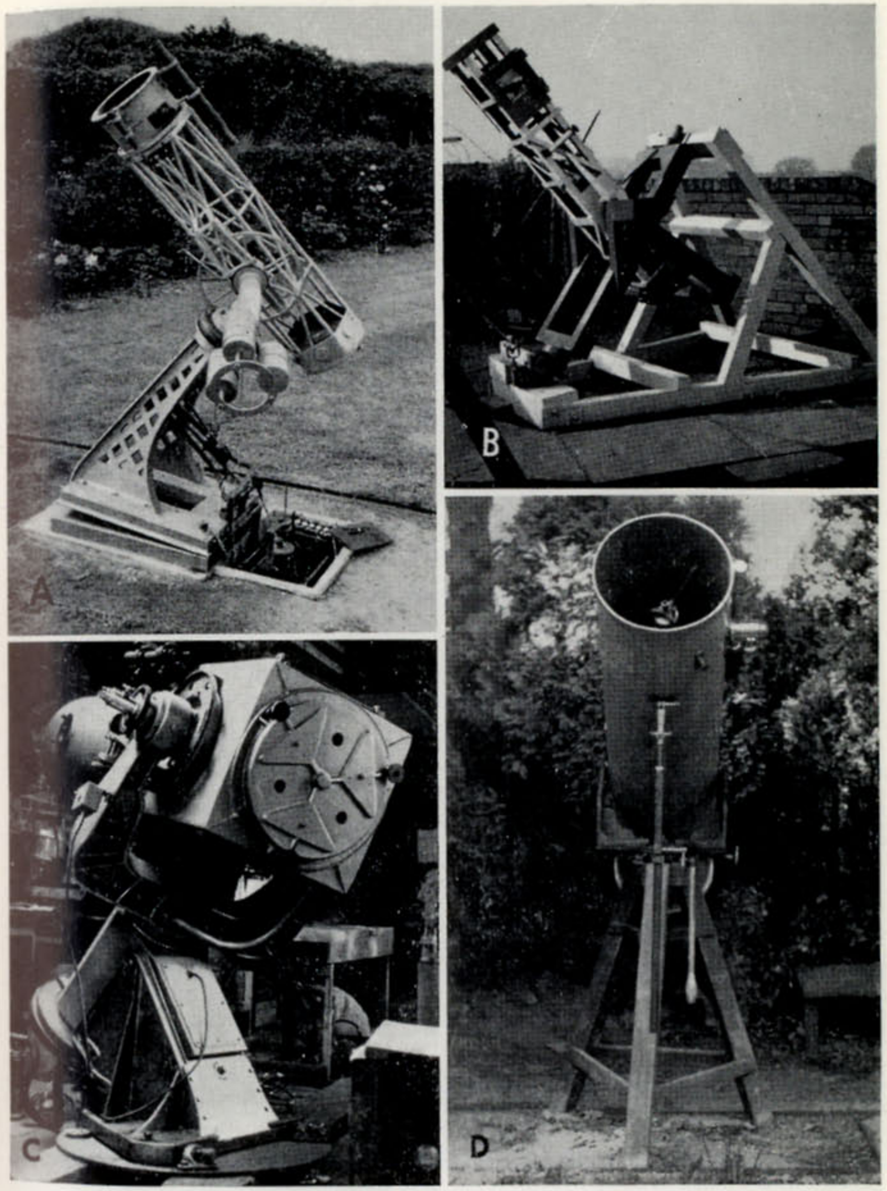
Visual estimates are of limited value, but a clock-driven 6-inch refractor or 12-inch reflector, for instance, will give an image which is large enough to be measured with a micrometer. Preliminary work, carried out largely by the Scottish amateur astronomer J. S. Glasby with his 13-inch reflector, indicates that there is no phase anomaly, but the question is still open, and further observations are needed.

Transits of Mercury are interesting to watch; at such times the planet is not visible with the naked eye, but projection of the solar disk with a small telescope, such as a 3-inch refractor, will show it clearly. The last transit occurred in 1973; the next will not occur until 1986. However, it must be admitted that little useful work can be done; exact timings of immersion and emersion are worth making, but the various strange appearances, reported occasionally during past transits, have never been confirmed and are probably due to observational errors.

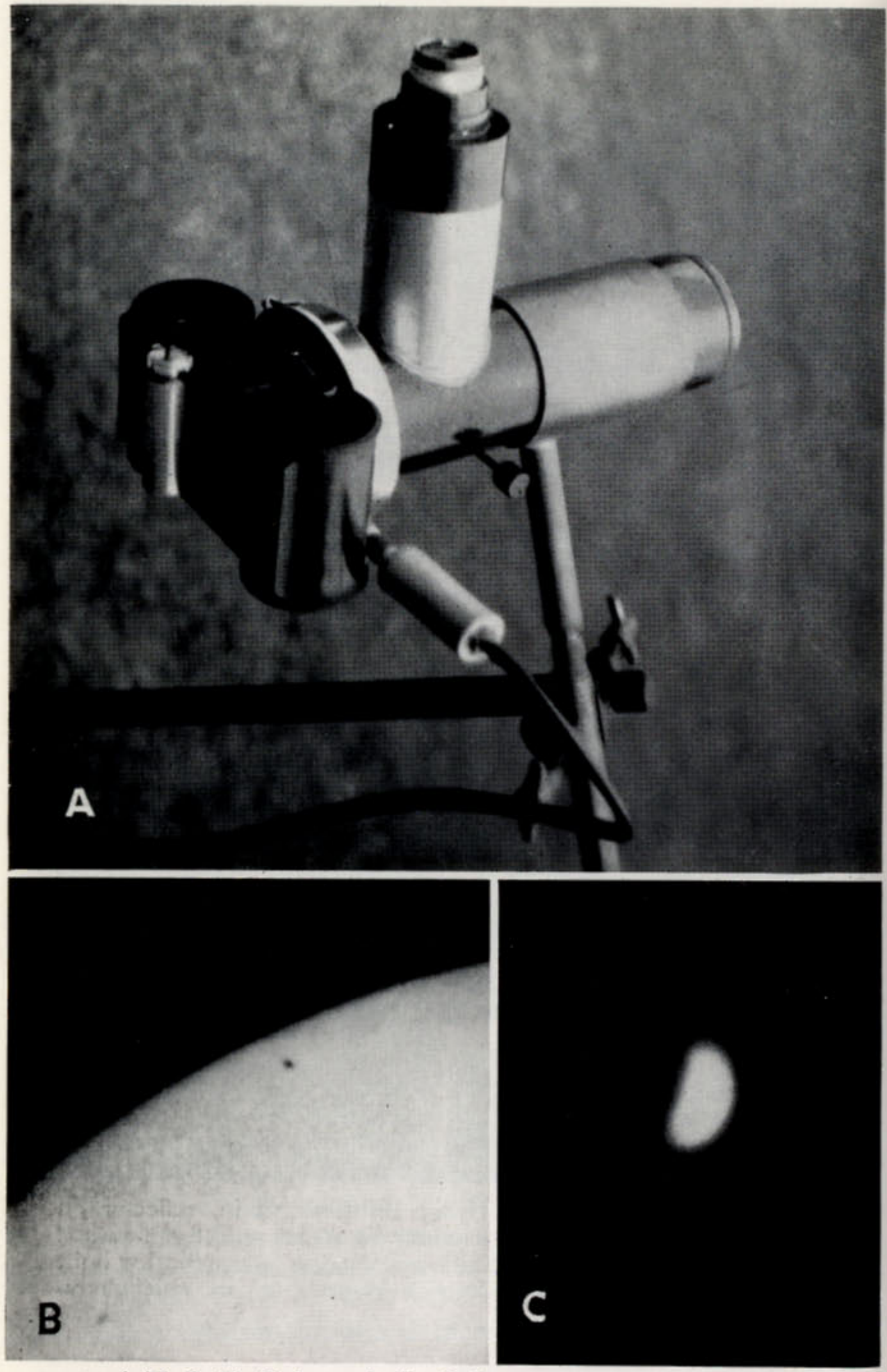
VENUS

Venus is a very different sort of planet, and will well repay close attention, even though we have learned so much about it from the Mariner 10 probe of 1974. In size and mass Venus is very like the Earth; but conditions there are totally alien to us.

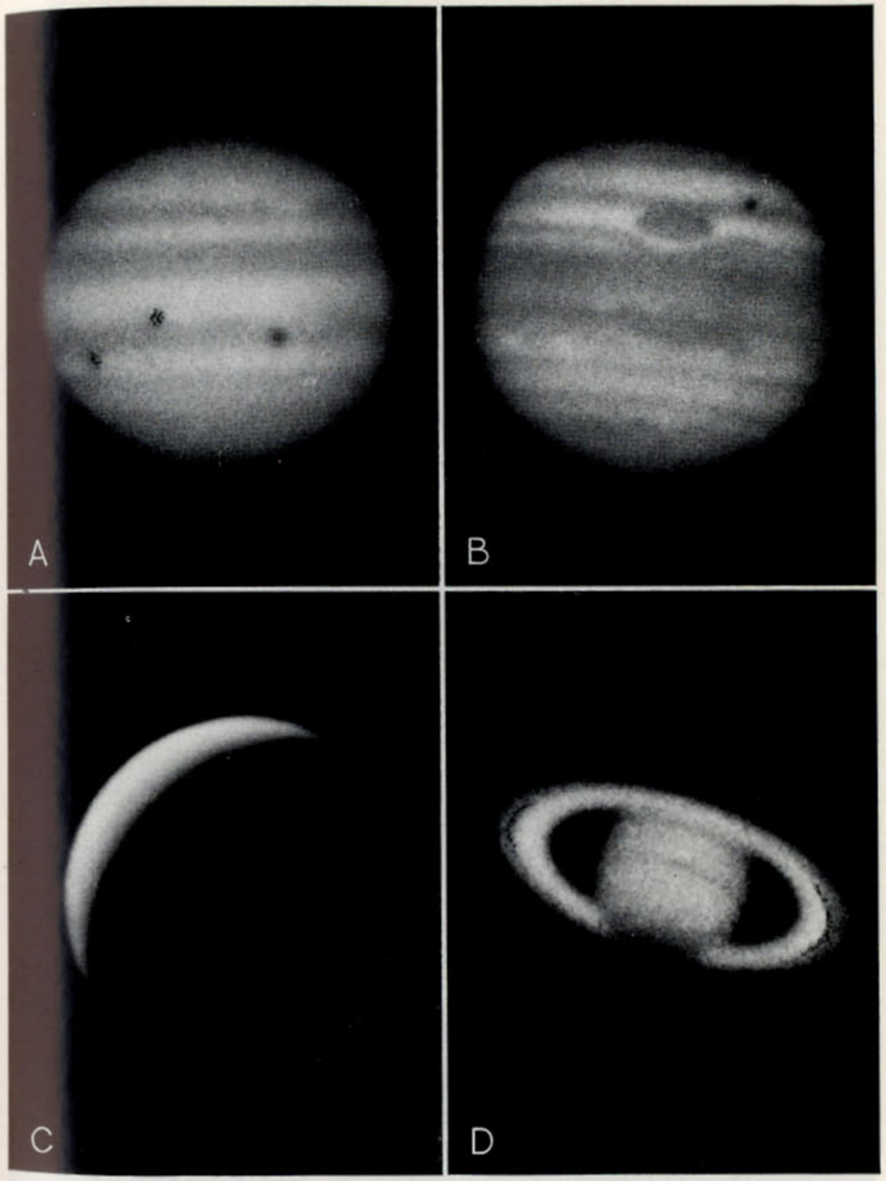
Unfortunately, Venus will not often bear high magnification, and—as always—a sharp view with a low power is to be preferred to a larger but blurred disk. It is not often that magnifications much in excess of 300 can be used. Generally speaking, certain lines of research may be followed up with very modest apertures (even a 3-inch refractor is not to be despised), and with a reflector of 8-inch or more there is great scope.



1. Telescope mounts. *A*, Henry Brinton's 12 in. reflector on German-type mount; *B*, A. Sanderson's 10 in. reflector mounted on a parallactic ladder; *C*, a 12 in. reflector on fork mounting built entirely by G. A. Hole; *D*, Patrick Moore's 12½ in. reflector on altazimuth mount.

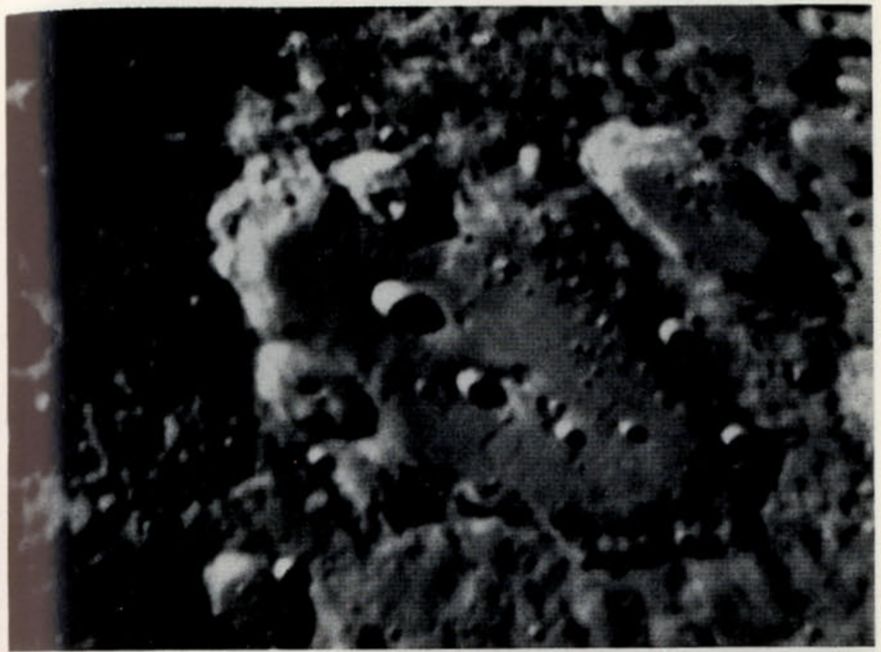


2. *A*, H. E. Dall's home-built, Reflex-type 35 mm astro-camera. *B*, transit of Mercury across Sun's disk, 1960 Nov. 7 (photo by W. A. Dovaston). *C*, Mercury, 19 h. 50 m 1963 Apl. 26 (photo by H. E. Dall).



3. Photographs taken by H. E. Dall using his $15\frac{1}{2}$ in. Cassegrain reflector. *A*, Jupiter, 1956 Apl. 21; the very rare event of three shadows in transit at one time. *B*, Jupiter, 1964 Nov. 1; broad equatorial belt with shadow of Satellite II to west of Red Spots and the satellite itself just emerging from east limb. *C*, Venus, 1961 March 15. *D*, Saturn, 1957.

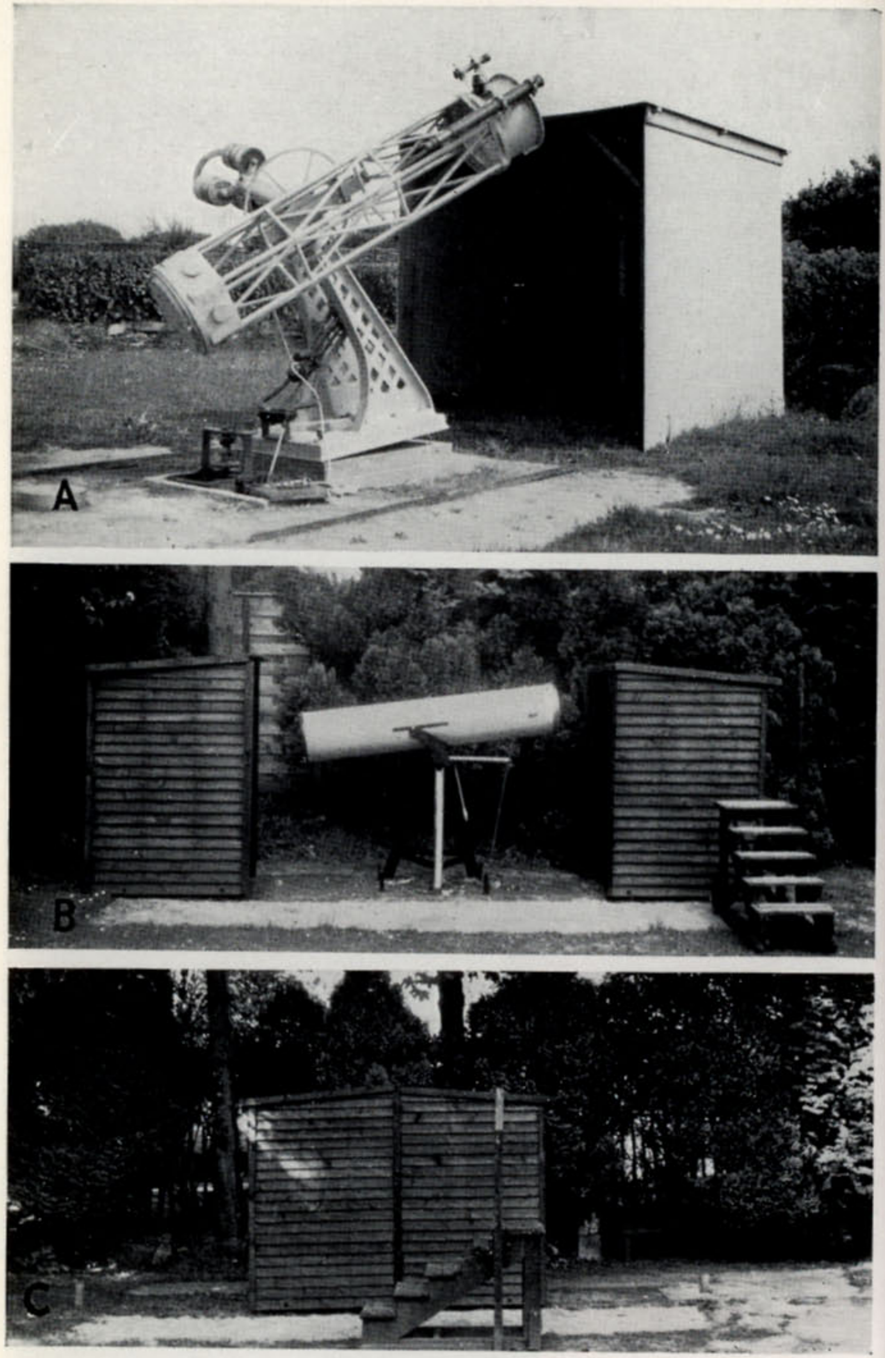
4. Janssen area of the Moon, 1961 Nov. 26, taken by W. J. Rippengale using a 10 in. Newtonian reflector.



5. Photographs of the Moon taken by H. E. Dall using his 15½ in. Cassegrain reflector.

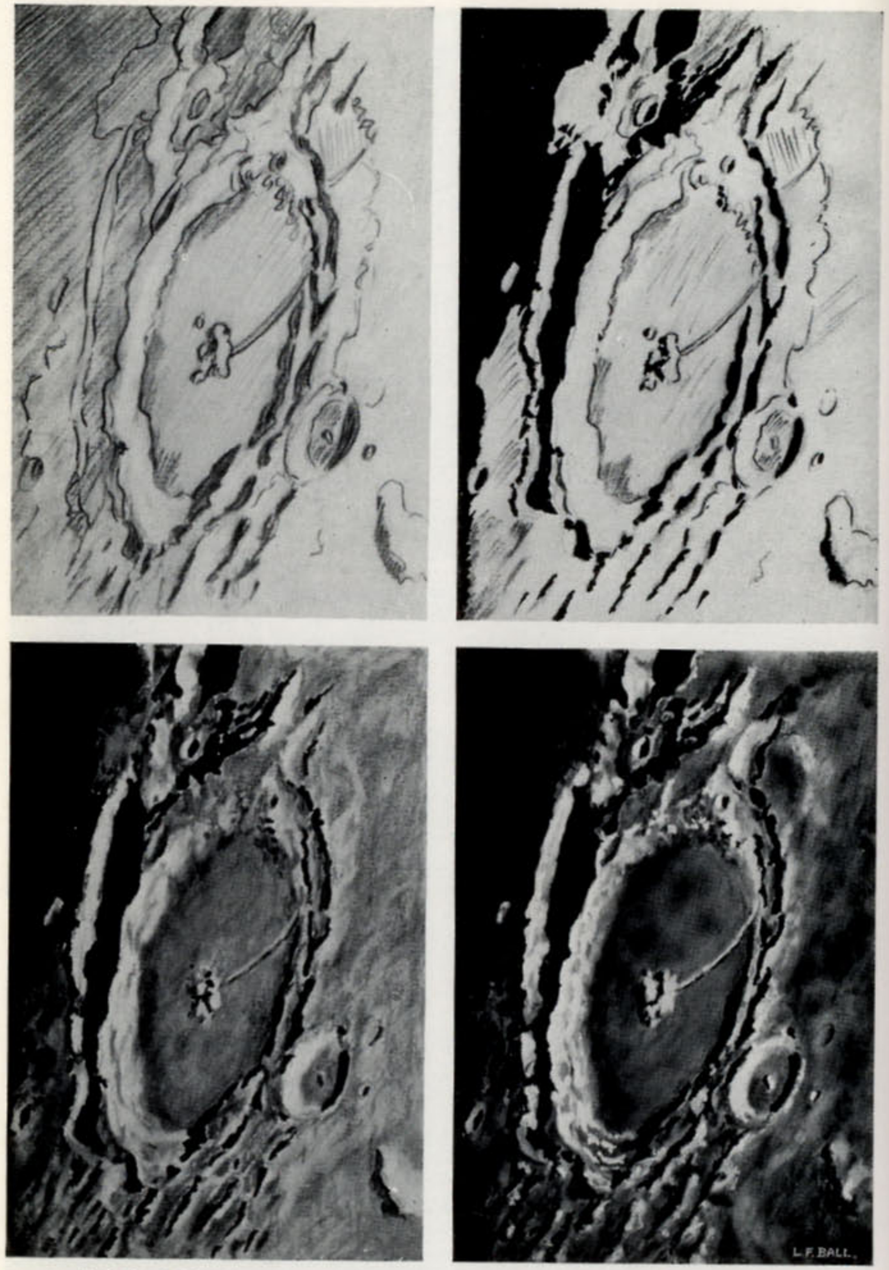
Above, Clavius, 1964 Sept. 28.

Right, Triesnecker and the associated cleft system (waning Moon, 1959 Sept. 24).

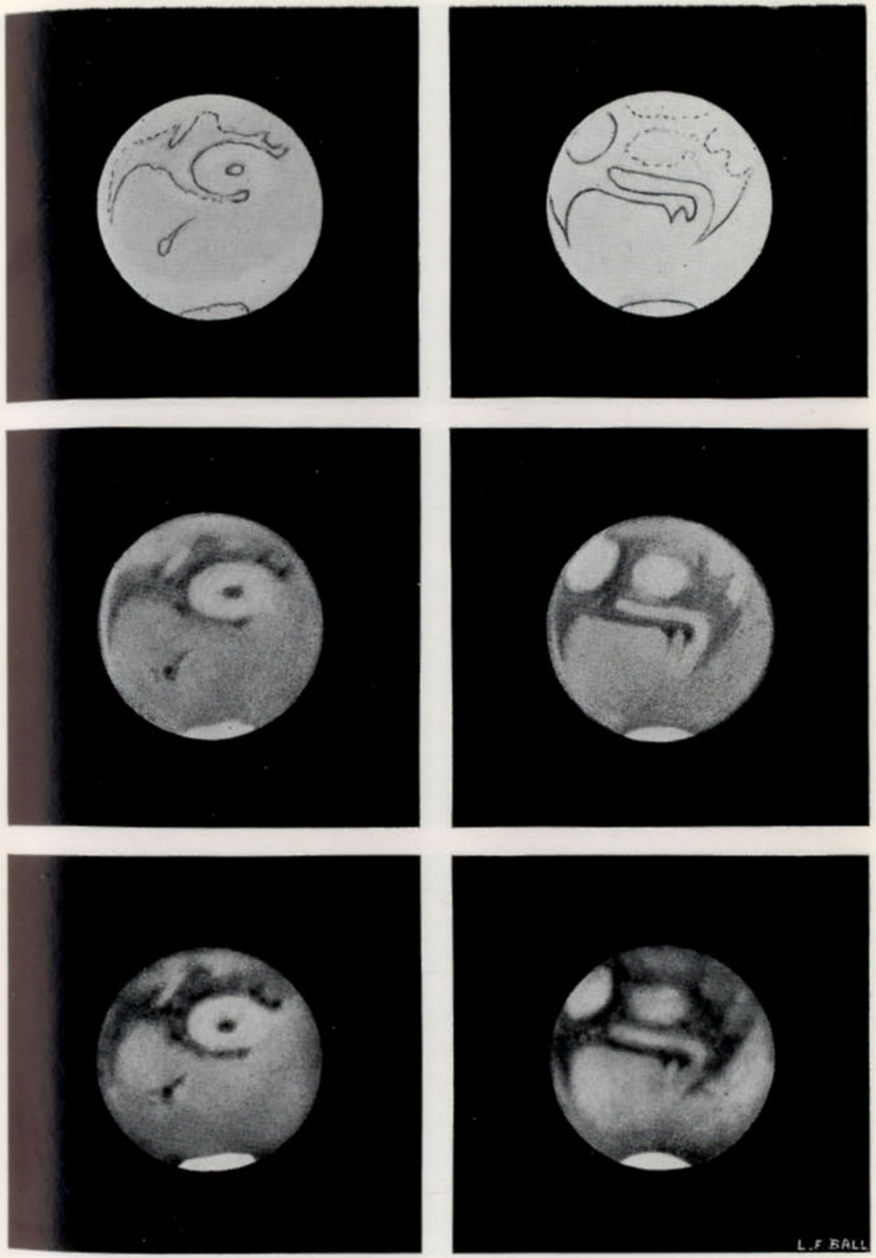


6. Run-off sheds. *A*, Henry Brinton's simple model with three fixed sides. *B* & *C*, Patrick Moore's double-ended shed, open and closed.

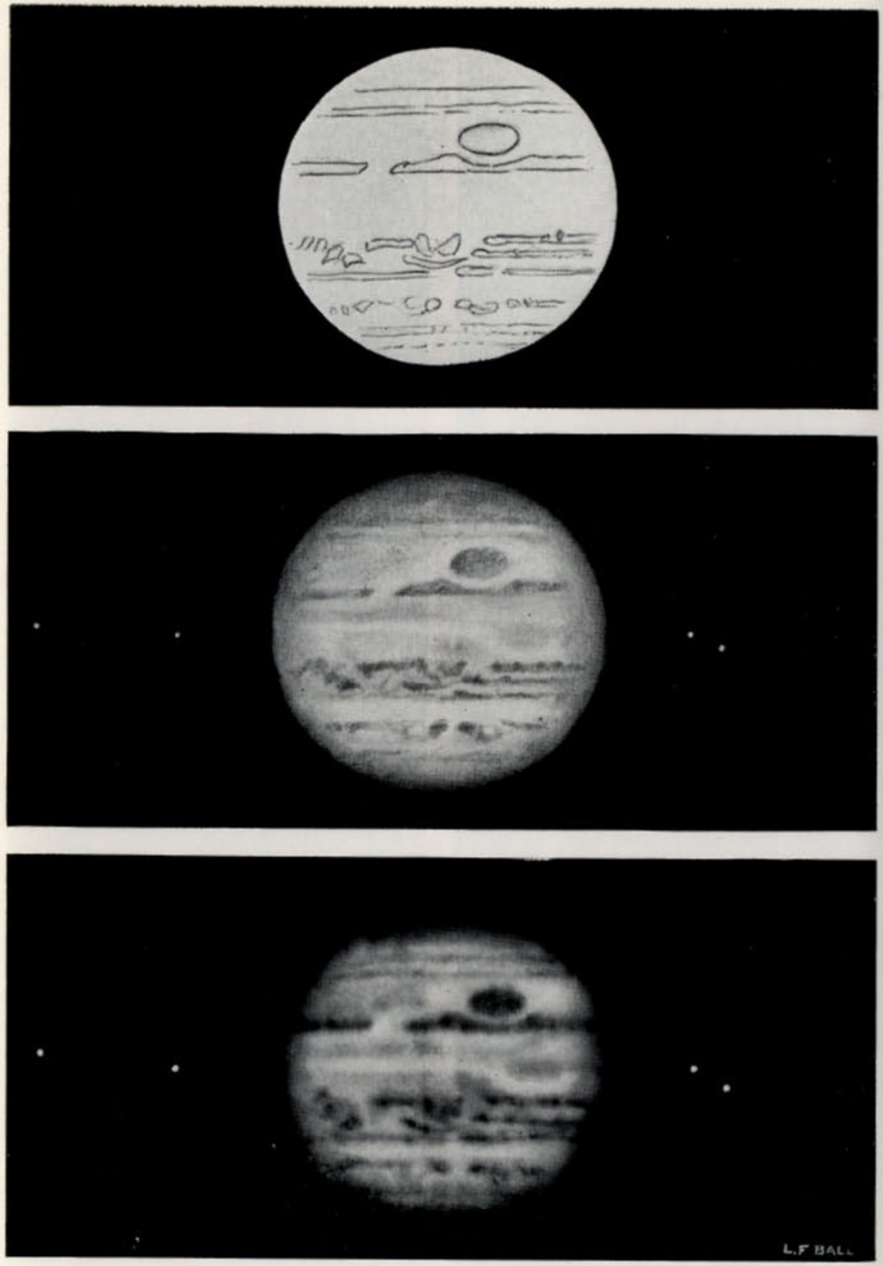
7. Observatories. *Above*, Patrick Moore's dome, the whole upper section of which revolves. *Below*, W. M. Baxter's solar observatory with a revolving roof.



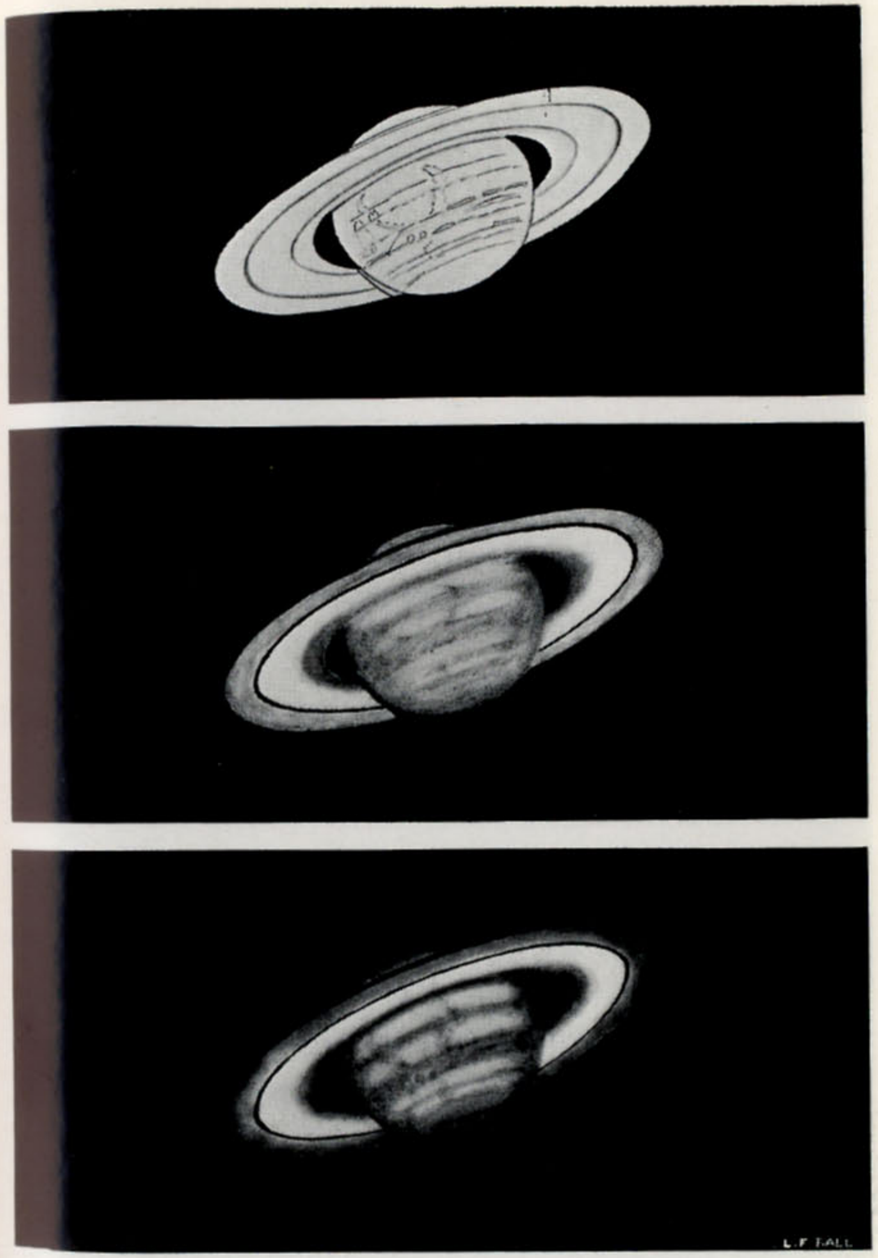
8. The Moon. Four stages in the drawing (by L. F. Ball) of the lunar walled plain of Petavius. Note the foreshortening effect on what is virtually a circular formation. Chinese White has been used to heighten contrast in the final result. The handling of the rampart, central mountain and the valley-rill should be carefully noted.



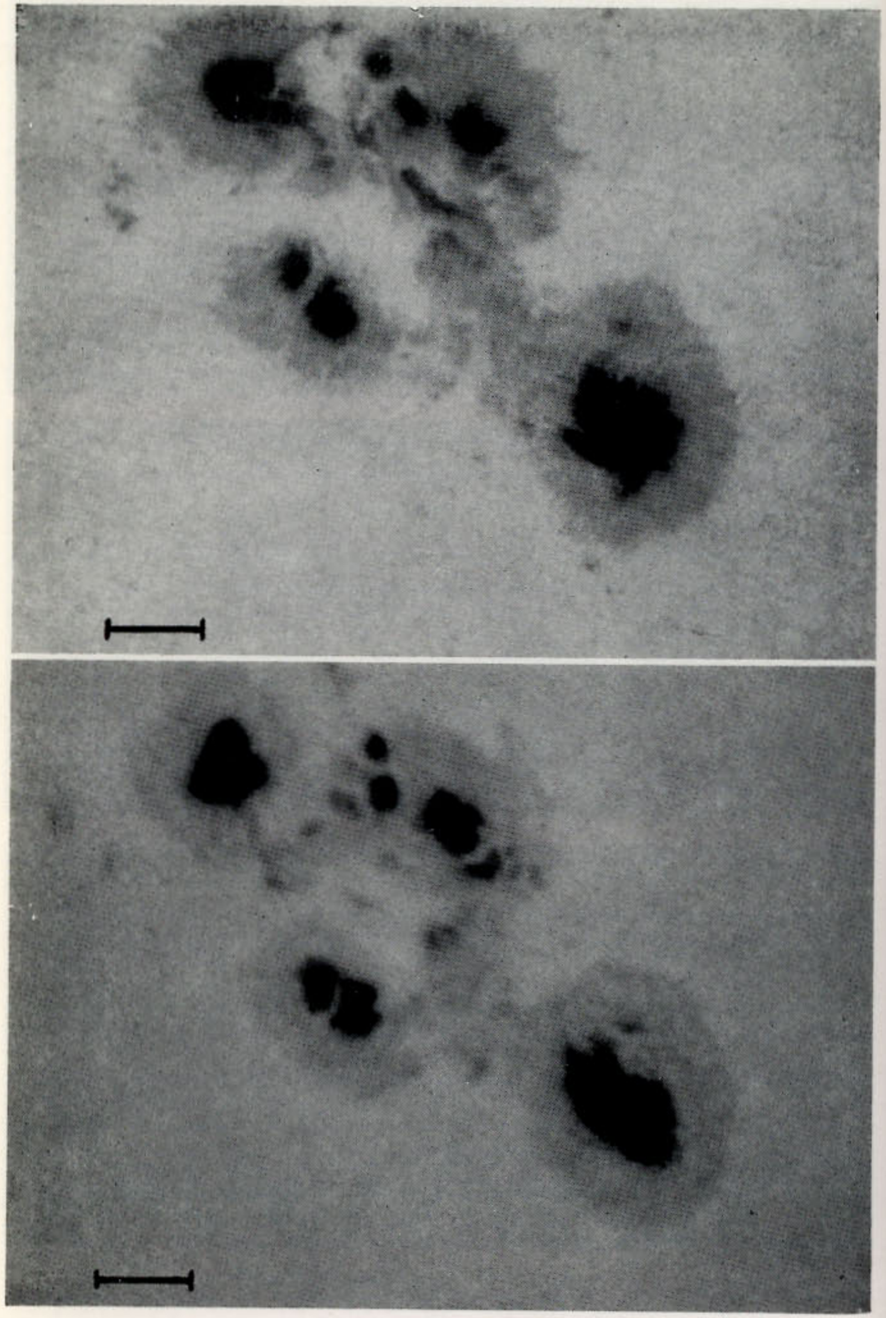
9. Mars. Progressive drawings of the planet by L. F. Ball. Two sets of three stages in drawing the planet, showing almost opposite hemispheres. Note the crispness of the north polar cap obtained without the use of white paint.



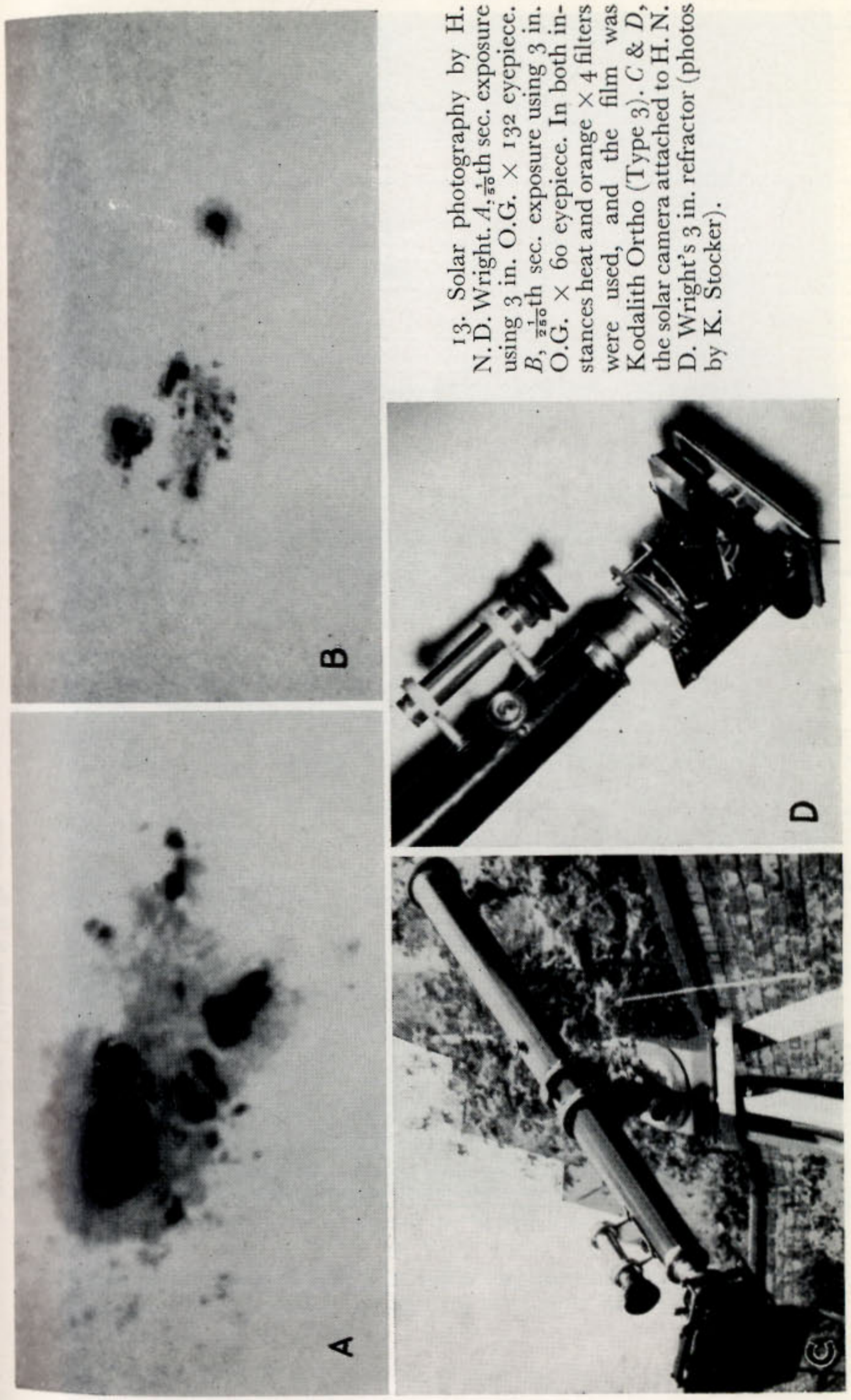
10. Jupiter. Progressive drawings of the planet by L. F. Ball. The polar compression has been incorporated in a previously prepared cut-out. Some experience is necessary to determine accurately the correct relative intensities of the various features.



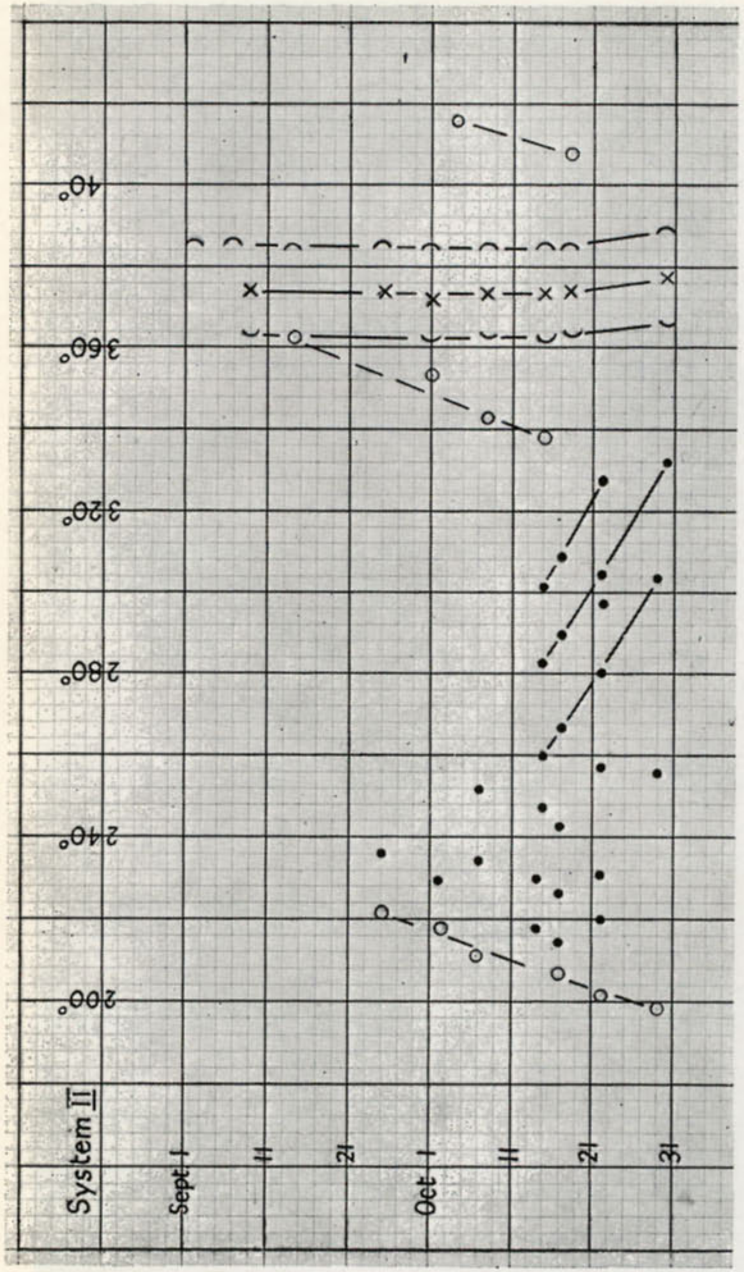
11. Saturn. Three stages in drawing the planet by L. F. Ball. Cut-outs were used to obtain the correct outline. Pencil and rubber have produced the planetary shadings.



12. Solar photography by W. M. Baxter. Two photographs, taken a day apart (1960, March 31 and, *below*, April 1), of a very remarkable and active sunspot group, visible to the naked eye. This group was associated with a major flare on April 1. The horizontal black lines represent a distance of 10,000 miles. The exposure was $\frac{1}{500}$th sec. using yellow plus neutral filters and 4″ O.G. × 120 eyepiece; the film was Ilford G30, chromatic backed plate.



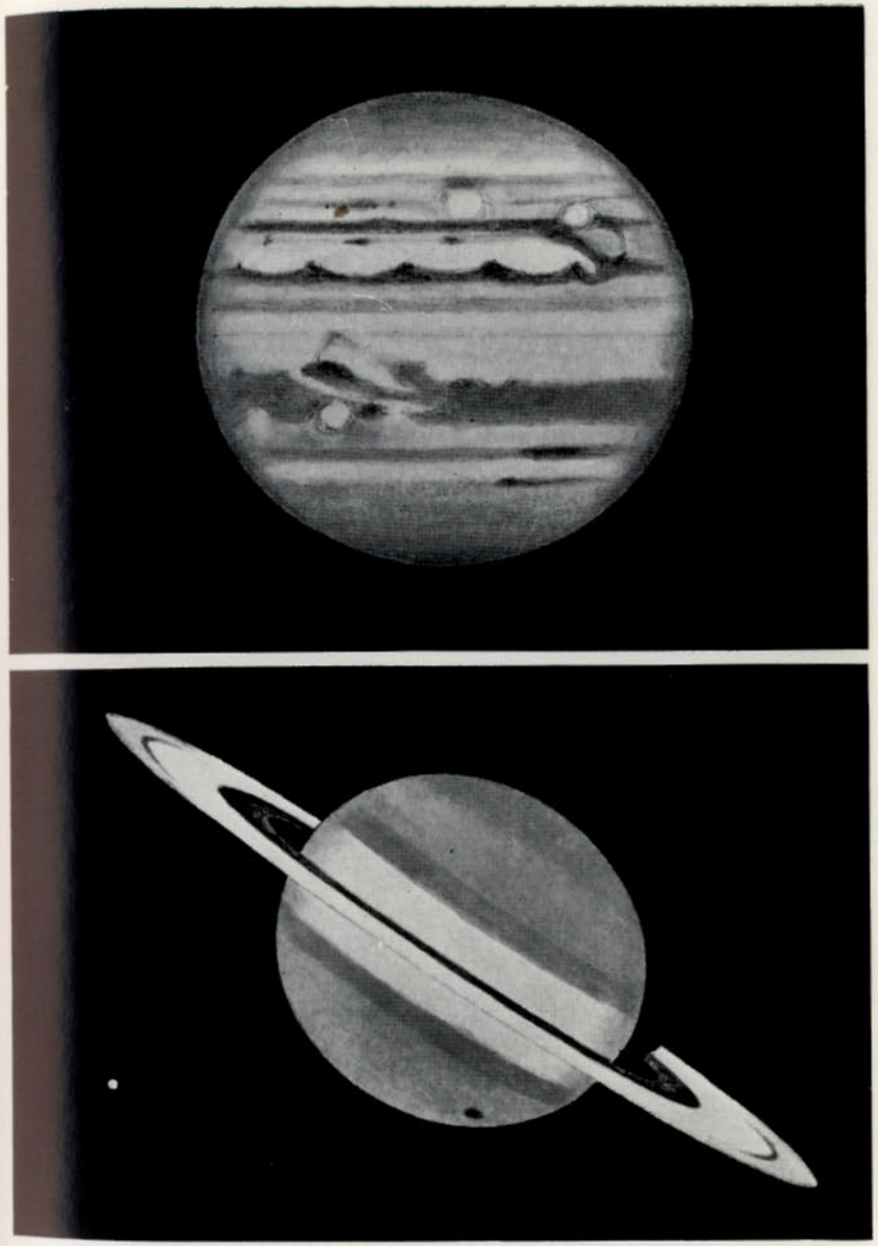
13. Solar photography by H. N. D. Wright. *A*, $\frac{1}{50}$th sec. exposure using 3 in. O.G. × 132 eyepiece. *B*, $\frac{1}{250}$th sec. exposure using 3 in. O.G. × 60 eyepiece. In both instances heat and orange × 4 filters were used, and the film was Kodalith Ortho (Type 3). *C* & *D*, the solar camera attached to H. N. D. Wright's 3 in. refractor (photos by K. Stocker).



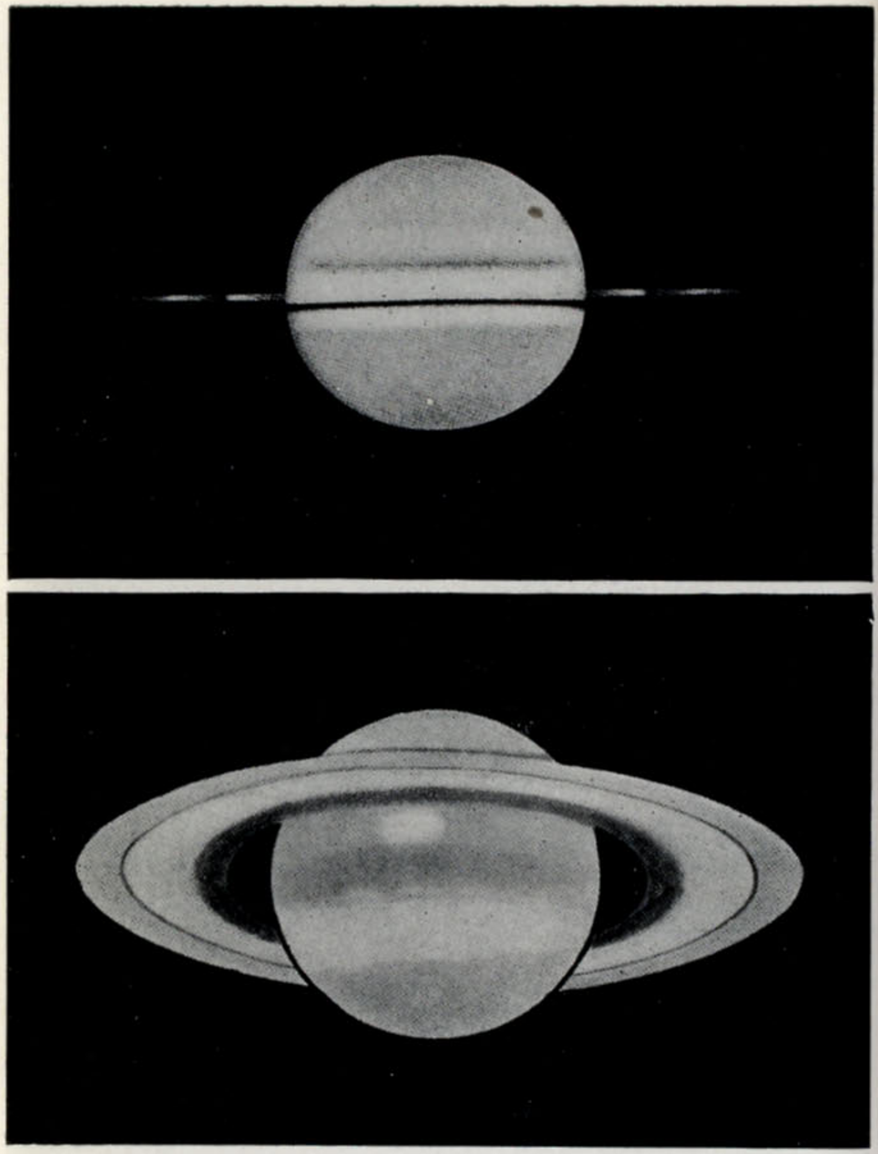
KEY

- o White South Temperate Spots
- • Dark spots on South component of Equatorial Belt
- (Preceding end of Red Spot
- X Centre of Red Spot
-) Following end of Red Spot

14. Recording Jupiter. Part of B. M. Peek's Longitude Charts for September and October 1962. The change in the rate of drift on the Red Spot during October is well shown; also the rapid retrograde motion of three S.E.Bs. spots.



15. *Above*, Jupiter, 1933 March 25. A drawing made with the aid of his 12½ in. reflector by B. M. Peek. *Below*, Saturn, 1950 May 6, drawn by G. Ruggieri with 5 in. refractor, showing Titan to the left of Saturn, Titan's shadow on Saturn, the Crêpe Ring etc.



16. Saturn. *Above*, W. H. Steavenson's drawing with Greenwich 28 in. refractor showing condensations on the ring's unillumined face, 1920 Nov. 16. (from *B.A.A.J.*, vol. 31, plate 4). *Below*, W. T. Hay's drawing with 6 in. refractor of the equatorial white spot, 1933 Aug. 3 (from *B.A.A.J.*, vol. 44, frontispiece).

It has become the fashion to adopt a drawing scale of 2 inches to the planet's full diameter. Many observers have varied the diameter of the disk according to the angular diameter of Venus at the time concerned, but though this may look spectacular it does not increase the value of the observations—and is, moreover, less convenient for analysis.

A newcomer to Venus study will generally find that at first he can see nothing at all apart from the characteristic phase, so that he may well suspect either his eyes or his telescope. Nothing could be further from the truth; even experienced observers frequently record a completely blank disk. However, practice will enable the observer to record any features which happen to be present, and it is important to remember that negative observations are just as valuable as positive ones, so that no drawing should be rejected because it shows nothing definite.

The Dusky Shadings. Under favourable conditions, vague darkish patches or streaks may often be seen on the disk. The weight of evidence indicates that they are real features, but they are of course atmospheric, since the actual surface is permanently concealed. Some observers claim to have recorded semi-permanent markings, but on the whole this seems unlikely.

There have been many attempts to use these shadings to determine Venus' rotation period, though it now seems that most of the published values were wildly in error. Radar and probe research has shown that the planet itself has a retrograde rotation period of 243 days, but that the upper clouds spin round in only 4 days, so that the atmospheric structure must be very unusual indeed. Observers will do well to concentrate upon any reasonably well-defined dark marking to see how it is moving across the planet's disk; remember, we do not yet know nearly as much as we would like to do about the wind systems in the upper cloud layer. The main trouble is that almost all the dark shadings are so ill-defined that their positions cannot be fixed accurately.

When a drawing of Venus is made, the shadings—if visible—should be put in as carefully as possible. However, it will often be found that in order to show them clearly on the sketch, they will have to be drawn in as darker and sharper than they really are. There is no harm in doing this, provided that a suitable note is written below the drawing.

Bright Areas. Apart from the cusp-caps, described below, mention must be made of certain local bright areas which appear now and then. These may be used in the same way as the dusky shadings, but they are comparatively rare. Most of the so-called "bright parts" of the disk seem to be due to contrast with the diffuse dusky patches.

The Cusp-Caps. The cusp-caps, now known (from Mariner 10 results) to mark the poles of Venus, are among the most interesting features of the planet, and have been recorded by all serious observers. Earlier suggestions that they might be due to contrast only have been finally discounted; not for the first time, the experienced amateur observers were proved to be right.

The caps are not always on view, and neither do they always lie exactly at the cusps. Sometimes a cap may appear to change into an elliptical bright patch, away from the cusp, and subsequently merge into a generally brightish area extending down the limb. Studies of the periodicity of the cusp-caps, in both position and appearance, will be of continuing value.

The caps are sometimes very well-marked indeed. It is useful to record whether either cap is visible, and, if so, what form it takes; note also the presence or absence of a dark "collar"—of the kind shown clearly in the Mariner 10 pictures. Remember, there is at present no space-probe orbiting Venus, and we need to maintain a careful watch on the planet so far as is possible with Earth-based telescopes.

The caps are at their most prominent during the crescent phase. They may also be seen during the half and gibbous phases, and even when Venus is almost full, but the small diameter of the apparent disk at such times means that telescopes of some size are needed—preferably accurately-driven refractors.

Intensity Estimates. Most planetary observers use intensity

scales for surface features; the generally-accepted Saturn scale, for instance, adopts 0 for pure white and 10 for black shadow. A scale may also be useful for Venus, but the vague nature of the markings means that a system such as that for Saturn is not suitable. After some experimenting, the British Astronomical Association observers have settled upon a scale as follows:

0 = white.
1 = general hue of the planet's disk.
2 = shadings, very nebulous and difficult to see.
3 = shadings dark enough to be seen with certainty.
4 = more definite shadings, somewhat rare.
5 = still darker shadings, seen only very occasionally.

The system has been found to be useful, though it has marked limitations, and it is not easy to correlate the results of different observers. The best method, probably, is to put the intensity figures upon sketches.

Schröter's Effect. The difference in date between theoretical and observed dichotomy was noted long ago by the German pioneer of planetary and lunar observation J. H. Schröter, and the term "Schröter's Effect", which I suggested in 1955, seems to have come into general use. It is not, however, confined to dichotomy, as was demonstrated originally by the Russian astronomer V. A. Bronshten. It seems that the phase is generally rather different from that indicated by calculation.

The actual date of dichotomy is not easy to determine, as the terminator is seldom perfectly regular; there are, for instance, apparent projections at the cusps. The dichotomy date should be taken as the time when the main curve of the terminator is completely straight, neglecting the cusp projections. It will be found that this is generally the case for several consecutive days, so that a mean value must be taken.

Visual estimations of phase at other times are not wholly reliable, but useful results may be obtained. The best method is to draw the planet as it is seen, and measure the phase afterwards from the drawing. Of course, micrometrical measures are much more reliable, and can be undertaken by any observer who has, say, a 12-inch reflector equipped with a clock drive. There is much work to be done here, since at present there is not enough material for a wholly satisfactory analysis, and it is important to find out whether the anomaly is consistent or not.

The Ashen Light. The faint luminosity of the night side of Venus was also noted by Schröter, and has since been seen on numerous occasions. It is, however, very elusive, and cannot be expected when the phase exceeds around 30 per cent. It is particularly hard to observe inasmuch as Venus has to be studied against a fairly dark background, which means that the altitude will be unsatisfactory.

Contrast is not easy to eliminate, and the only possible method is to block out the bright crescent by means of an occulting bar or some such device; a special curved bar, to "fit" the crescent, is the best solution. If the Ashen Light is still seen when the bright part of the planet is hidden, it may be regarded as real.

Spectroscopic work by N. Kozirev in the U.S.S.R. and G. Newkirk in the U.S.A. has supported the theory that the Light is due to effects analogous to terrestrial auroræ, but there is no proof, and some astronomers still dismiss the whole phenomenon as being due to contrast. It would be valuable to try to ascertain whether the Light is at its most prominent during times of peak solar activity, as with our auroræ, but once again the available material is insufficient for thorough analysis. Here, too, negative observations are as useful as positive ones.

Quite different is the famous illusion of the night side of Venus being seen, against a brightish sky, as darker than the background; this seems certainly to be a contrast effect.

Filter Observations. Considerable attention has been paid during recent years to observations of Venus made with colour filters. There is sharp disagreement as to the value of such work. Some observers claim that filters reveal features which are normally invisible; others hold that a red or topaz filter will bring out the usual features more clearly; yet others maintain that filters are quite useless in this connection, and serve only to reduce both illumination and quality of definition. The controversy continues, and further observations are therefore desirable.

Summary. From what has been said, it is evident that there is much of interest to be seen on Venus, despite the difficulty of observations. Results from probes indicate that the planet is extremely hot and hostile, but this does not make it any the less interesting, and the amateur will find that a careful study of it is well worth while.

Table I

PHENOMENA OF VENUS, 1964 to 2000. Computed by M. B. B. Heath, F.R.A.S

Year	*Greatest Elong., E.*	*Inferior Conjunction*	*Greatest Elong., W.*	*Superior Conjunction*
1964	Apr. 10	June 19	Aug. 29	—
1965	Nov. 15	—	—	Apr. 12
1966	—	Jan. 26	Apr. 6	Nov. 9
1967	June 20	Aug. 29	Nov. 9	—
1968	—	—	—	June 20
1969	Jan. 26	Apr. 8	June 17	—
1970	Sept. 1	Nov. 10	—	Jan. 24
1971	—	—	Jan. 20	Aug. 27
1972	Apr. 8	June 17	Aug. 27	—
1973	Nov. 13	—	—	Apr. 9
1974	—	Jan. 23	Apr. 4	Nov. 6
1975	June 18	Aug. 27	Nov. 7	—
1976	—	—	—	June 18
1977	Jan. 24	Apr. 6	June 15	—
1978	Aug. 29	Nov. 7	—	Jan. 22
1979	—	—	Jan. 18	Aug. 25
1980	Apr. 5	June 15	Aug. 24	—
1981	Nov. 11	—	—	Apr. 7
1982	—	Jan. 21	Apr. 1	Nov. 4
1983	June 16	Aug. 25	Nov. 4	—
1984	—	—	—	June 15
1985	Jan. 22	Apr. 3	June 13	—
1986	Aug. 27	Nov. 5	—	Jan. 19
1987	—	—	Jan. 15	Aug. 23
1988	Apr. 3	June 13	Aug. 22	—
1989	Nov. 8	—	—	Apr. 5
1990	—	Jan. 19	Mar. 30	Nov. 1
1991	June 13	Aug. 22	Nov. 2	—
1992	—	—	—	June 13
1993	Jan. 19	Apr. 1	June 10	—
1994	Aug. 25	Nov. 2	—	Jan. 17
1995	—	—	Jan. 13	Aug. 20
1996	Apr. 1	June 10	Aug. 19	—
1997	Nov. 6	—	—	Apr. 2
1998	—	Jan. 16	Mar. 27	Oct. 30
1999	June 11	Aug. 20	Oct. 30	—
2000	—	—	—	June 11

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Chapter Nine

OBSERVATION OF MARS

M. B. B. HEATH

MARS IS NOT easy to observe. A small planet, having a diameter only a little more than half that of the Earth, it is comparatively near us only for a short time about every 2 years 2 months on the average, though this interval is subject to considerable variation. Favourable conditions for observation occur around about the time of each opposition, but since the orbit of Mars has a very appreciable eccentricity it necessarily follows that the planet is much nearer the Earth at some oppositions than it is at others. At every opposition occurring when Mars is near perihelion the apparent diameter of the disk may become as much as 25 sec. of arc, or the apparent size of a halfpenny as seen from a distance of about 229 yards, but at those oppositions which occur when the planet is near aphelion this is reduced to some 14 sec. of arc, which is less than a third of the apparent equatorial diameter of Jupiter or the diameter of Saturn's outer ring at average oppositions.

For advanced work, therefore, an aperture of less than 8 or 8½ inches is not recommended, and that can with advantage be increased to obtain greater light grasp and separating power. Most amateurs use reflectors on account of their cheapness, portability and ease of management, whereas refractors are costly and require a well-appointed observatory to house them; they are, however, less troubled by air currents in the tube, have a greater light grasp, aperture for aperture, and very rarely need any adjustment. As regards eyepieces, the writer generally preferred the orthoscopic type, but solid eyepieces of the Tolles form are very useful when observing neighbouring areas having much difference in brightness and in the detection of slight tonal contrasts nearing the threshold of vision, on account of their freedom from scattered light.

In consequence of the Earth's greater orbital velocity it approaches Mars before every opposition and recedes from it afterwards, so the apparent disk becomes smaller and fainter. Owing to the combination of these adverse circumstances there is a tendency among many amateurs to cease observing quite soon after opposition, but there is really no necessity for this. Good views may often be had throughout the time when the apparent diameter is not less than 7 sec. of arc, when a magnification of × 266 will give a telescopic image equal in size to that of the average Full Moon as seen with the naked eye. With the planet high in the sky and in steady seeing conditions this magnification may be somewhat exceeded. H. McEwen often used to observe Mars when it appeared even smaller than this, comparing its image with that of Mercury. Of course it must not be expected in these circumstances that any small detail can be observed; nevertheless, it is possible to see well some interesting phenomena such as the rapid melting of the polar caps and the ensuing darkening of all the markings in the corresponding hemispheres, the broadness of Syrtis Major and the darkening of Acidalium Mare at certain seasons of the Martian year.

As an example of what may be seen in suitable conditions on such a small disk, the writer quotes from his Observation Book:

> 1935, January 6, $5^{h}\ 10^{m}$ to $6^{h}\ 5^{m}$ U.T. 9¼-inch reflector, magnification ×230 and ×308 solid (Tolles type) eyepieces, the latter giving the better view. Air moderately steady and definition passably good, transparency good in breaks in cloud. The planet is decidedly gibbous on its preceding side, about 9/10 illuminated. North Polar Cap is about 25° across, quite bright white with a fairly sharp edge bordered by a dusky band which is definitely darker on the preceding side where Utopia and Casius are the darkest markings on the disk. Umbra is well shaded and to a slightly lesser degree, Dioscuria, Cydonia, Cecropia and Ortygia. The northern end of Syrtis Major is fairly dark, but Hellas is not distinctly seen, all the southern parts of the planet being invisible under a dull white pall. Considerable detail in the markings north of the Syrtis but impossible to hold or to draw them—a few faint streaks suspected on several occasions. Slight shading along the terminator.

This observation was made three months before opposition on a disk only 7·2 sec. of arc diameter.

The Gibbous Disk. Prolonged observation of Mars necessarily includes observations of the gibbous disk. At maximum gibbosities the planet shows a phase like our Moon some 2¾ to 3½ days before or after Full, a portion of its dark side being turned towards us. At gibbosities occurring before opposition the darkened part is seen on the left of the disk in our northern hemisphere when using an astronomical telescope giving an inverted image. The terminator marks the boundary between Martian day and night, and all places seen near it are speeding towards their sunset. In these circumstances the central meridian does not mark the hour of high noon at places upon it, but sometimes as much as three hours after it.

After opposition the dark portion of the planet is seen to the right of the disk, and all places coming into our view around the terminator are emerging from the darkness and coldness of the Martian night into the brilliance of Martian day. Some areas may be seen here to rise more or less brilliantly white, among which may be included Aeria, Arcadia, Argyre, Ausonia, Chryse, Eden, Electris, Elysium, Eridania, Hellas, Isidis Regio, Libya, Memnonia, Neith Regio, Noachis, Ophir, Phaethontis, Pyrrhae Regio, Tempe, Tharsis, Thaumasia and Thymiamata. Some of these have been observed more or less bright on the sunset terminator also.

Twilight Observations. Provided the planet has a moderate altitude, very good views of it may be had in quite strong twilight. This diminishes the glare which tends to swamp the markings when seen on a dark sky. A well-adjusted equatorial mounting is a great help in locating the planet—indeed, it is practically a necessity. A slight mist or haze, if atmospheric turbulence is not obtrusive, also has the effect of eliminating glare and improving the image of the planet even on a dark sky.

Seasonal Variations. Great changes, largely depending on the waxing and waning of the polar caps, sweep across the surface of the planet. At the end of winter the cloud cover of the South Polar Cap is very extensive, spreading over some 60° of latitude, and is first seen a little before the pole itself comes on to the visible disk at the vernal equinox. In the spring the cap becomes smaller and glistening white, melting slowly at first but at an ever-increasing rate. A dark spot, Hellespontica Depressio, appears in the cap and from it a dark rift, Rima Australis, appears dividing the main cap into sections of different brightness. The smaller section of the snows so divided lies in the direction of Syrtis Major and covers the region of Novissima Thyle, which may first be seen as a sparkling white spot in the cap, later assuming the appearance of a promontory to it and eventually detaching itself as a bright white area. This gradually narrows as Rima Australis broadens into a wide channel, and finally is reduced to a few bright dots prior to its final disappearance before the Summer Solstice. About a fortnight after the appearance of Rima Australis another rift, Rima Angusta, is seen cutting across the cap from about the longitude of Syrtis Major to that of Solis Lacus. The cap continues to decrease and may become so small as to vanish completely, but that is not generally the case. It must be remembered that the cap is not situated exactly at the pole of the planet, but is some 7° of Martian latitude to the north of it in the direction of 30° of Martian longitude approximately. Consequently the tiny white kernel will sometimes be seen very near the southern limb of the planet, but will be invisible about 12 hours later because its daily rotation has carried it round to the invisible side of the disk. Towards the end of the southern summer, when the cap has become very small, brightish diffuse spots will appear in the south polar regions, but of a rather dull whiteness; and these quickly increase in size so as soon to cover all the polar region and even a part of the temperate zone before the cap enters upon its long polar night.

During the spring when the cap is diminishing most rapidly, it is bordered by a dark band with a markedly irregular outline, notches in its boundary appearing towards Argyre, Ulysses Fretum and a little west of Novissima Thyle. At the same time the darkness of all the markings increases rapidly from the pole towards the equator, and great dark tracks form, issuing from the notches in the polar band. One of the most remarkable of these is Hellespontus, adjoining the following border of Hellas. During the summer the dark band edging the polar snows gradually ceases to be visible. These phenomena are repeated, though not quite so prominently, in the melting of the North Polar Cap, which is a little smaller than the southern one,

having a diameter of about 50° of latitude at most. A little after the summer solstice of the northern hemisphere a bright area, Olympia, detaches itself from the North Polar Cap.

Fortuitous Changes. In addition to the regular seasonal changes, there are sometimes alterations in the features which cannot be foreseen, but which are occasionally so extensive as to alter materially their size, shape or intensity. Among the areas observed to be so affected are Solis Lacus and Laestrygonum Sinus, the former once taking some 4 years to regain its former appearance and the latter about 9 years. Many others have been observed to be subject to these variations. Moreover bright, sometimes even star-like, spots may suddenly appear in the ochreous regions of the planet where perhaps they have not been seen for years. Well-known instances of bright spots occasionally seen are Nix Atlantica, closely preceding Syrtis Major, and Nix Tanaica in Tempe, near Acidalium Mare. Others have been recorded in Aethiopia, the Amazonis-Arcadia region, Ausonia, in the north of Hesperia, Icaria, etc.

Veiling by Clouds. At irregular and unspecified intervals the surface markings are more or less veiled by clouds in the Martian atmosphere. They are of two kinds, the yellowish and the whitish. The former are visible in red light but not visible in blue; the latter are visible in blue light but invisible in red, and are also very prominent on photographs. Large and bright clouds of this type, masking considerable areas of the planet, were observed visually during the opposition of 1952 and numerous examples of them were seen in 1958.

The yellow clouds also occasionally cover great areas of the planet, so that even the experienced Martian observer, who in normal circumstances can easily recognize what particular hemisphere is turned towards him, may find it difficult to identify any familiar landmark. These conditions may even persist for months at a time, and may sometimes even cover the South Polar Cap, as happened in 1956, 1971 and 1973.

Method of Observation. It is assumed that the observer has had plenty of previous experience so that his eye and mind have been trained to perceive the planet's delicate detail. If he has not had that training it is never too late to begin by observing and drawing it on every possible occasion; notwithstanding that his first attempts may show very little. An excellent adjunct to training in the perception of faint nuances of shade, so very necessary in all planetary work, is to draw the Moon as seen with the naked eye. This must be done some time after sunrise and before sunset as the glare of our satellite on a dark sky effectively blots out the finer detail. Obviously this cannot be done with a winter Full Moon. A *very* lightly tinted sun-cap, or better still a neutral tinted Venus glass, should then be used to reduce glare.

It is a mistake to begin any observation by straining after delicate detail—the larger and darker of the Martian markings and the pole caps should be concentrated upon at first, and only when these have been accurately recorded should the finer detail be looked for.

Next to experience comes systematic observation. Sporadic and hurried spells of short duration must be avoided, and every effort made to observe as often as possible. It is in the frequent observation, particularly of the larger markings, that the value of the amateur's work lies. Mostly and usually he has the whole field to himself, for the upkeep of the large observatories is very costly and their great telescopes are generally employed, with few exceptions, on photographic and spectroscopic work.

If atmospheric turbulence is unduly obtrusive at the beginning of an observation or becomes so in the course of it, the telescope should be left in the open air, or in the dome with the door and shutter fully open, before the quality of the seeing is again inspected. Sometimes it will have considerably improved, but, if not, a further interval should be given and not while any chance of improvement remains should observation be abandoned.

The Use of Filters. Indiscriminate use of filters by inexperienced observers with insufficient apertures on disks already enfeebled by distance or magnification has brought undeserved discredit on their use in *any* circumstances. Certainly they should never be employed if they reduce the brightness of the image so much that details on it are brought down to near the threshold of vision, nor should the magnification be reduced to brighten up

the image in order to retain their use. It must always be remembered that *any* filter must of necessity dim the image, and the narrower the band of light passed by it the fainter must that image inevitably become.

In those years when the oppositions of Mars occur near perihelion it shines with a brilliance equal to or even slightly surpassing Jupiter at its brightest, but it is very low in the south for observers in the northern mid-latitudes. In these circumstances, a filter passing a moderately broad band in the reddish orange not only helps to diminish the glare from the brighter parts of the planet but also, by its selective action, increases the relative visual intensity of the dark markings.

Blue filters have precisely the opposite effect, suppressing the dark markings but enhancing the visibility of the white clouds and veils which sometimes shroud the surface of the planet.

Recording Observations. A separate book should be kept for all observations of Mars, and preferably its pages should be unruled. On the left-hand page enter the date, time in U.T., aperture and type of telescope, magnification and type of eyepieces, atmospheric steadiness or "seeing", transparency and kind of filter (if any). The right-hand page is reserved for drawings, the outlines of which have been drawn just previously. The more prominent markings near the central meridian are first sketched in, noting the time, next those on the preceding edge of the planet and lastly those on its following edge. Only after the main markings have thus been drawn should search be made for fine detail. Particular attention must be paid to the intensity of the markings. Begin by drawing the darkest first, or you may find that you cannot make the very darkest dark enough. Anything that is "suspected" should be carefully noted, but is best left out of the drawing. The drawings are usually made for a circle of 2 inches diameter, but a scale of 3 mm. to the second of arc has been advocated, and it certainly avoids crowding detail at perihelic oppositions by observers in the southern hemisphere and a comparative blankness of the gibbous disk.* The *B.A.A. Handbook* gives data whereby the position angle of the axis of rotation and the phase can be correctly drawn on the outlines. If the observer wishes to

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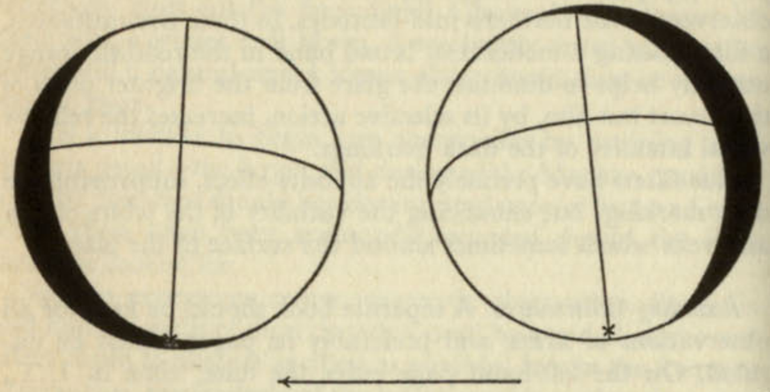
*See also plate 9.

indicate the planet's equator and earthward pole also (and these are a great help in placing the markings correctly, especially when the tilt of the pole towards us is large) he should refer to the writer's paper on "The Axial Pose of Mars", *B.A.A. Journal* Vol. 67, No. 7. If the construction is done lightly in pencil it can easily be erased once it has served its purpose.



1962 October 23
Diameter 7″·1

1963 May 13
Diameter 7″·0

Fig. 12. *Disk outlines of Mars for two different dates, showing phase, axis of rotation (Central Meridian), Martian equator and pole turned earthwards (marked ×), for an observer in our northern hemisphere, using an astronomical telescope giving an inverted image. The planet passes through the telescopic field in the direction indicated by the arrow.*

Probably there is hardly a regular observer of Mars who has not been tempted to make a coloured drawing of it. Such drawings, especially if blacked around, are very pretty, and give a good idea of the planet's appearance, but they have comparatively little scientific value owing to the absence of any fixed standard whereby the estimates of different observers can be compared; also there are great variations of sensitivity to colour between different observers. A good drawing in black and white in which the intensities of all the features are faithfully recorded is more valuable, while its nuances of shade form a picture which is just as artistic.

Coming Apparitions. These notes give some idea of what may be seen. The dates given are a general average—much will

depend on whether the Martian season is forward or backward. The observational periods cover the times when the planet has a diameter of 7 sec. of arc, though occasionally this limit is slightly exceeded or reduced.

Opposition 1965 March 9. Observe December 1964 to July 1965. North pole turned earthwards. Cap melts rapidly at first. Detachment of Olympia in early April. Acidalium Mare very dark. Syrtis Major very wide from mid-March. Northern whitenesses frequent. Southern whitenesses unusual.

Opposition 1967 April 15. Observe January to September. North pole turned earthward. Cap becomes difficult to see soon after opposition. Detachment of Olympia towards end of February. Southern Cap reappears end of July. Syrtis Major very wide. Acidalium Mare very dark. Northern whitenesses frequent.

Opposition 1969 May 31. Observe February to November. South Polar Cap appears in June, very large. Towards end of September it melts very rapidly and indentations in its dark band may be looked for. Syrtis Major very wide until well past opposition, becoming very narrow in October. Acidalium Mare very dark. North whitenesses frequent.

Opposition 1971 August 10. Observe March 1971 to January 1972. South polar cap reappears towards the end of April, very large, melts rapidly a little before opposition. Watch for rifts in cap and irregularities in its dark band. Detachment of Novissima Thyle about mid-August. Syrtis Major very wide at first, narrows towards opposition. North whitenesses frequent.

Opposition 1973 October 25. Observe May 1973 to February 1974. South polar cap very large at first, melts rapidly about mid-June. Detachment of Novissima Thyle early July, when Syrtis Major becomes very narrow. Acidalium Mare very dark at first. North whitenesses frequent.

Opposition 1975 December 15. Observe August 1975 to March 1976. South pole enters dark hemisphere soon after opposition. North polar cap appears mid-October, very large. Syrtis Major narrow at first but slowly broadens. Northern whitenesses frequent from September.

Opposition 1978 January 22. Observe October 1977 to April 1978. North polar cap clearly seen early November, large, visible for remainder of observational period. Syrtis Major slowly broadens. Acidalium Mare very dark. South whitenesses very unusual. North whitenesses frequent.

Opposition 1980 February 25. Observe December 1979 to June

1980. North polar cap large at first, melting quickly at opposition. Detachment of Olympia late April. Syrtis Major very wide after opposition. Acidalium Mare very dark throughout. South whitenesses at the limb are uncommon. North whitenesses frequent.

Old and New Nomenclature. The first map of the planet was made in 1840 by Beer and Mädler using only a 3¾-inch refractor and the main features, named after prominent astronomers, were well represented considering the smallness of the aperture employed. Green in 1877 constructed one showing considerably more detail but retaining the previous nomenclature. Schiaparelli in 1877, finding a great complexity of detail in exceptional seeing conditions, made a new map with a completely new nomenclature based largely on names of lands bordering the Mediterranean and in the Middle East, and on classical mythology. With additions, mostly by Lowell and Antoniadi, these names eventually became so numerous that a drastic revision of the nomenclature became necessary. Thus Lowell in his book *Mars* (1896), listed 288 named formations and by the time Antoniadi produced his monograph *La Planète Mars* in 1930 their number had risen to over 580, with every prospect that future investigations would still further increase it. Accordingly Committee No. 16 of the International Astronomical Union appointed a sub-committee to improve the procedure of the identification and designation of the markings. The larger features are of a more or less permanent character, subject only to some seasonal and fortuitous variations, but it was the smaller details, often of an ephemeral character, which were the chief cause of the great increase in the number of names. The sub-committee, having thoroughly examined the whole question, decided to retain names for only 128 features, distributed as evenly as possible over the disk. A few modifications were made in the former classical nomenclature of which the most important were (*a*) the region centred upon longitude 75°, latitude − 20° is now called Sinai, (*b*) the region in longitude 100°, latitude −20°, near Phoenicis Lacus is designated Syria, the neighbouring regions in longitude 255°, latitude −40°, and longitude 263°, latitude −25°, previously named Ausonia Australis and Ausonia Borealis, are to be called Ausonia and Trinacria respectively. All small features are to be distin-

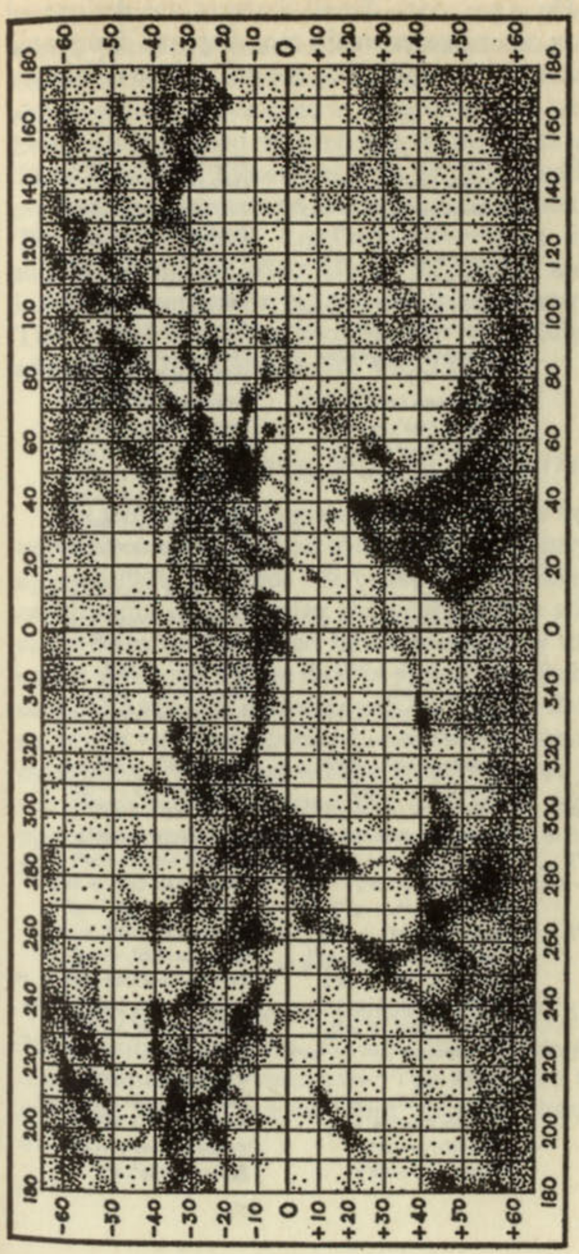


Fig. 13. Nomenclature of Mars, as standardized by the International Astronomical Union. The co-ordinates of the named features are given on the opposite page.

84°,0 = Beginning of northern spring.
174°,0 = Beginning of northern summer.
264°,0 = Beginning of northern autumn.
354°,0 = Beginning of northern winter.
227,7.10^6km = 1,5237 U.A. = Mean distance from the Sun.
0,0933 = Excentricity of the orbit.
334°35' = Longitude of perihelion.
1°51' = Inclination of the orbit.

48°36',5 = Longitude of ascending node.
686 j 23 h 30 m 41 s = Martian year.
α = 316°,8 δ = + 53°,0 = Celestial coordinates of the axis of rotation.
24°,8 = Inclination of the axis of rotation.
24 h 37 m 22 s 6 = Martian day.
0,530 = 6760 km = Equatorial diameter.
60 km = 1° Planetocentric at the surface.

Referring to Fig. 13 p. 101—Small features are designated by their planetary co-ordinates; main markings are designated by names according to the following record and co-ordinates.

Acidalium M. (30°, + 45°)
Aeolis (215°, — 5°)
Aeria (310°, + 10°)
Aetheria (230°, + 40°)
Aethiopis (230°, + 10°)
Amazonis (140°, 0°)
Amenthes (250°, + 5°)
Aonius S. (105°, — 45°)
Arabia (330°, + 20°)
Araxes (115°, — 25°)
Arcadia (100°, + 45°)
Argyre (25°, — 45°)
Arnon (335°, + 48°)
Aurorae S. (50°, — 15°)
Ausonia (250°, — 40°)
Australe M. (40°, — 60°)
Baltia (50°, + 60°)
Boreum M. (90°, + 50°)
Boreosyrtis (290°, + 55°)
Candor (75°, + 3°)
Casius (260°, + 40°)
Cebrenia (210°, + 50°)
Cecropia (320°, + 60°)
Ceraunius (95°, + 20°)
Cerberus (205°, + 15°)
Chalce (0°, — 50°)
Chersonesus (260°, — 50°)
Chronium M. (210°, — 58°)
Chryse (30°, + 10°)
Chrysokeras (110°, — 50°)
Cimmerium M. (220°, — 20°)
Claritas (110°, — 35°)
Copais Palus (280, + 55°)
Coprates (65°, — 15°)
Cyclopia (230°, — 5°)
Cydonia (0°, + 40°)
Deltoton S. (305°, — 4°)
Deucalionis R. (340°, — 15°)
Deuteronilus (0°, + 35°)
Diacria (180°, + 50°)
Dioscuria (320°, + 50°)
Edom (345°, 0°)
Electris (190°, — 45°)
Elysium (210°, + 25°)
Eridania (220°, — 45°)
Erythraeum M. (40°, — 25°)
Eunostos (220°, + 22°)
Euphrates (335°, + 20°)
Gehon (0°, + 15°)
Hadriacum M. (270°, — 40°)
Hellas (290°, — 40°)
Hellespontica Depressio 340° — 6°)
Hellespontus (325°, — 50°)
Hesperia (240°, — 20°)
Hiddekel (345°, + 15°)
Hyperboreus L. (60°, + 75°)
Iapigia (295°, — 20°)
Icaria (130°, — 40°)
Isidis R. (275°, + 20°)
Ismenius L. (330°, + 40°)
Jamuna (40°, + 10°)
Juventae Fons (63°, — 5°)
Laestrigon (200°, 0°)
Lemuria (200°, + 70°)
Libya (270°, 0°)
Lunae Palus (65°, + 15°)
Margaritifer S. (25°, — 10°)
Memnonia (150°, — 20°)
Meroe (285°, + 35°)
Meridianii S. (0°, — 5°)
Moab (350°, + 20°)
Moeris L. (270°, + 8°)
Nectar (72°, — 28°)
Neith R. (270°, + 35°)
Nepenthes (260°, + 20°)
Nereidum Fr. (55°, — 45°)
Niliacus L. (30°, + 30°)
Nilokeras (55°, + 30°)
Nilosyrtis (290°, + 42°)
Nix Olympica (130°, + 20°)
Noachis (330°, — 45°)
Ogygis R. (65°, — 45°)
Olympia (200°, + 80°)
Ophir (65°, — 10°)
Ortygia (0°, + 60°)
Oxia Palus (18°, + 8°)
Oxus (10°, + 20°)
Panchaia (200°, + 60°)
Pandorae Fretum (340°, —25°
Phaethontis (155°, — 50°)
Phison (320°, + 20°)
Phlegra (190°, + 30°)
Phoenicis L. (110°, — 12°)
Phrixi R. (70°, — 40°)
Promethei S. (280°, — 65°
Propontis (185°, + 45°)
Protei R. (50°, — 23°)
Protonilus (315°, + 42°)
Pyrrhae R. (38°, — 15°)
Sabaeus S. (340°, — 8°)
Scandia (150°, + 60°)
Serpentis M. (230°, — 30°)
Sinai (70°, — 20°)
Sirenum M. (155°, — 30°)
Sithonius L. (245°, + 45°
Solis L. (90°, — 28°)
Styx (200°, + 30°)
Syria (100°, — 20°)
Syrtis Major (290, + 10)
Tanaïs (70°, + 50°)
Tempe (70°, + 40°)
Thaumasia (85°, — 35°)
Thoth (255°, + 30°)
Thyle I (180°, — 70°)
Thyle II (230°, — 70°)
Thymiamata (10°, + 10°)
Tithonius L. (85°, — 5°)
Tractus Albus (80°, + 30°)
Trinacria (268°, — 25°)
Trivium Charontis (198, + 20)
Tyrrhenum M. (255°, — 20°)
Uchronia (260°, + 70°)
Umbra (290°, + 50°)
Utopia (250°, + 50°)
Vulcani Pelagus (15, — 35)
Xanthe (50°, + 10°)
Yaonis R. (320°, — 40°)
Zephyria (195°, 0°)

guished by their planetary co-ordinates to the nearest degree, which permits a practically unlimited future expansion. The co-ordinates are expressed by figures enclosed in parentheses showing the planetocentric longitude and latitude, the latter being distinguished by prefixing + for north and − for south. Thus Hesperus, sometimes seen as an intensely dark marking separating Hesperia and Eridania, is designated as (223° −38°). The sub-committee suggested that these recommendations should be put into effect as soon as possible and should be used in the next opposition in 1958 and in all subsequent oppositions. The report of the sub-committee was duly approved and adopted by the Council (see Fig. 13).

DATA FOR FUTURE OPPOSITIONS

The following table gives data which will be found useful for oppositions up to the end of the present century. Shortened and approximate methods were used in making the necessary calculations and this may occasionally give rise to small differences from data derived by more rigorous means. The particulars given are for the date of opposition. Before and after that date the apparent diameter will be less and the planet not quite so bright as that specified, but the changes are slow near opposition. Also Mars will be found more or less to the east of the given position among the stars when seen a little before opposition and somewhat to the west of it a little after opposition.

MARINER RESULTS

In 1971–2, spectacular photographs were obtained from the Mars probe Mariner 9. We now know that Mars is a world of craters and giant volcanoes. Yet there are no active probes orbiting Mars at present, and amateur observation is still of value.

Table 2

(*a*) Date	(*b*) Nearest Earth	(*c*) Apparent diameter	(*d*) Magnification	(*e*) Pole towards Earth	(*f*) Stellar magnitude	(*g*) Constellation
		″			m	
1965 March 9	March 12	14·0	×133	North	—1·1	Leo, between Beta and Chi.
67 April 15	April 21	15·6	119	North	—1·4	Virgo, near Spica.
69 May 31	June 9	19·5	96	North	—2·1	Scorpio, near Antares.
1971 August 10	August 12	24·9	75	South	—2·7	Capricornus, between Zeta and Theta.
73 October 25	October 17	21·4	87	South	—2·1	Between Pisces and Aries.
75 December 15	December 8	16·5	113	South	—1·4	Taurus, between Beta and Zeta.
78 January 22	January 19	14·3	130	North	—1·1	Between Gemini and Cancer.
1980 February 25	February 26	13·8	135	North	—1·0	Leo, a little east of Regulus.
82 March 31	April 5	14·7	127	North	—1·2	Virgo, near Gamma.
84 May 11	May 19	17·5	107	North	—1·8	Libra, between Alpha and Gamma.
86 July 10	July 16	23·1	81	South	—2·6	Sagittarius, near Zeta and Sigma.
88 September 28	September 22	23·7	79	South	—2·4	Near middle of Pisces.
1990 November 27	November 20	17·9	104	South	—1·7	Taurus, near Pleiades.
93 January 7	January 3	14·9	125	North	—1·2	Gemini, a little west of Pollux.
95 February 12	February 11	13·8	135	North	—1·0	Leo, a little west of Regulus.
97 March 17	March 20	14·2	131	North	—1·1	Virgo, near Beta.
99 April 24	May 1	16·2	115	North	—1·5	Virgo, near Kappa.

Column (*a*) gives the date of opposition, (*b*) the approximate date when Mars is nearest the Earth, (*c*) the apparent diameter of the planet—the value given is occasionally uncertain to a unit in the decimal place, (*d*) the magnification necessary to yield a telescopic image equal in size to a mean Full Moon as seen with the naked eye, (*e*) the Martian pole turned towards the Earth, (*f*) the stellar magnitude of the planet and (*g*) the position of Mars among the stars.

Chapter Ten

OBSERVATION OF JUPITER

B. M. PEEK

OF ALL THE planets, Jupiter is surely the most rewarding to observers who possess telescopes of moderate size. Mars is a fascinating object on the rather rare occasions when it is really well placed, but Jupiter comes to opposition every thirteen months, when it can be studied throughout the hours of darkness; moreover, it is available during considerable portions of the night for several months on either side of these times. Only when opposition occurs during high summer are observers in temperate latitudes at a disadvantage, the planet being then well placed for those living in the opposite hemisphere.

Again, Jupiter exhibits a large disk, not much less than a minute of arc in diameter when it is nearest; so it requires a magnifying power of only about 40 to make it comparable to that of the Moon as viewed with the unaided eye. This disk seldom fails to display a considerable amount of interesting detail.

It is true that this detail represents only the structure and behaviour of the planet's cloudy atmosphere, which must always obscure whatever solid surface may lie beneath it; but the formation and movements of the clouds present remarkable and beautiful characteristics and are clearly subject to controlling influences which, although they can be enumerated and described, have not as yet been satisfactorily explained.

By "telescopes of moderate size" is meant those whose apertures lie in the range from 6 to 12 inches. The two most famous visual observers of Jupiter, the Rev. T. E. R. Phillips and A. Stanley Williams, did most of their work with an 8-inch refractor and a 6½-inch reflector, respectively.

It would be unfair and probably erroneous to state that useful systematic work could not be carried out with a 3-inch refractor; but the amateur who proposes to make a special study of Jupiter would be well advised to equip himself with an instrument of at least 6 inches aperture. Anything over 12 inches is a luxury—and a very pleasant one too, if cost and accommodation are of no consideration.

Jupiter rotates on its axis in a few minutes under ten hours, with the result that in a 2½-hour spell of observation a quarter of the planet's surface will have crossed the centre of the disk. During such a session it is the duty of the observer to make a record of the various features, as they go by, and there are two main methods of doing this which may, if desired, be conducted simultaneously. The first is to make drawings of the planet, the second to time the spots and markings as they reach the central meridian. A third would, of course, be to photograph the disk; but to make a success of this would require larger and more elaborate equipment than most amateurs have at their disposal; so we shall confine ourselves to a discussion of the two former. Of these the second is immeasurably the more important; but before we describe the procedure of recording meridian transits we shall consider the making of drawings.

Drawing the Planet. A well executed drawing can be of considerable value; but its accuracy will depend upon the steadiness of the image at the time it is made and the ability of the observer to portray faithfully the detail that is presented to him. Two experienced observers may differ appreciably in their interpretation of the markings displayed, while an inexperienced one may produce a picture that is far from being an accurate record and may be misleading rather than of value.*

The publication of too many inaccurate drawings has been responsible for a great deal of the mistrust that many astronomers have felt in the past of visual observations. It is only human for the beginner to feel that he is a heaven-sent draughtsman, and it is probably good advice that he should draw to his heart's content at first, until he has worked this impression out of his system, though he should not necessarily be encouraged to publish his efforts. This is in no way intended to discourage the really capable draughtsman; but even he will come to realize that the production of, say, half a dozen really good disk drawings each Jupiter season (apparition), as an adjunct to his main work, are sufficient to represent the general

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*See Chapter 4 and Plate 10.

appearance of the planet during the period covered. Probably the most valuable pictures are those of small, interesting regions and those which confine themselves to a long, narrow band of latitude and illustrate in sequence the various features as they go by. The latter are usually referred to as "strip-sketches".

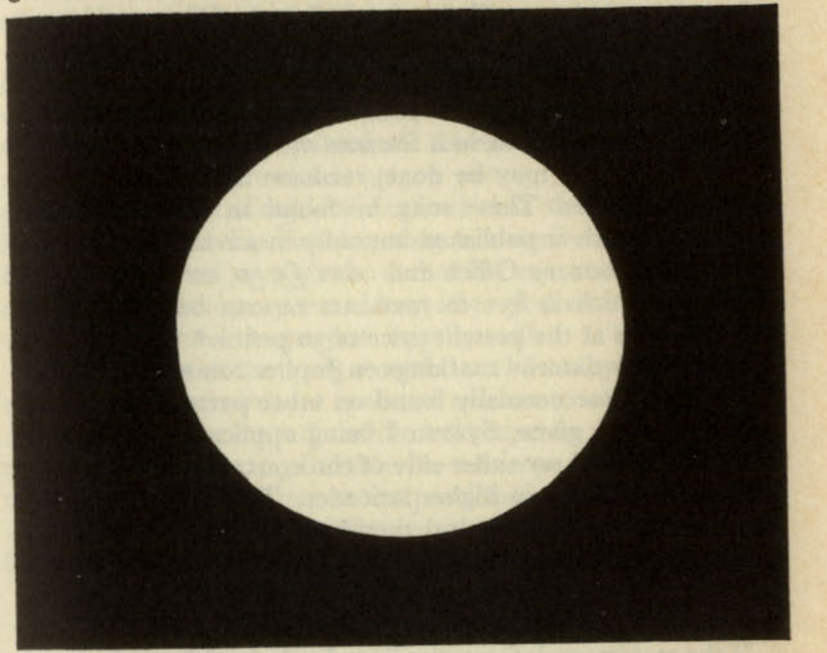

Fig. 14. *A specimen diagram of Jupiter from which tracings can be taken or a line-block made so that a printer can run off a stock of blanks.*

Timing the Planet. It is the individual motions of Jupiter's surface markings that are of paramount interest, and these take place almost entirely in longitude, comparatively few objects have been seen to drift in latitude to any significant degree. We come, then, to the more important business of timing the spots and markings as each arrives in due course upon the central meridian of the visible disk. It is from the accumulation and pooling of such records that our very considerable insight into the behaviour of Jupiter's upper atmosphere has been acquired.

The only necessary equipment, in addition to the telescope, is a watch that can be relied upon to give the time to the nearest minute, extreme accuracy being superfluous. Jupiter rotates so rapidly that, if the observer leaves his post when an object is near the central meridian and returns after only a couple of minutes, the apparent displacement will be quite obvious and, with sufficient practice, accuracy to within two or three minutes should be readily attained, though different observers may show small systematic differences in their estimates of the exact position of the central meridian.

At the end of the night's work, or as soon as is convenient, the longitudes of the various features must be worked out and, in order that this may be done, recourse must be had to the published Tables. These may be found in *The Astronomical Ephemeris*, which is published annually in advance in England by H.M. Stationery Office and costs £3·50, or in the *B.A.A. Handbook*, which is free to members or can be obtained by non-members at the present price of 50 pence.*

Since the equatorial markings on Jupiter rotate considerably faster than those normally found on other parts of the planet, two Tables are given, System I being applicable to markings within about 10° on either side of the equator and System II, in general, to those in higher latitudes. The A.E. Tables give the longitudes of the central meridians of the two systems at midnight, those of the B.A.A. at the hour that is considered to be most convenient for the observer. Subsidiary Tables give the differences to be applied for various intervals of time.

If the maximum information is to be derived from the longitudes, it is almost essential for the observer to be a member of some fraternity, such as the British Astronomical Association or a similar body in other countries, where his results can be combined with those of other observers and used by the Director of the Jupiter Section to determine the rates of drift of the spots that have been recorded. Nevertheless, the observer will miss a great deal that is of interest if he does not make longitude charts (see Plate 14) for himself on which to plot his own positions. Increasing longitude should run from left to right on the charts and time should progress down the page, convenient scales being 40° of longitude and 20 days to the inch, using paper divided in inches and tenths. A study of his charts will then give him a sort of bird's-eye view of the manner in which the spots are drifting. In the southern hemisphere (of the Earth), however, it might be more realistic if longitude were made to increase from right to left. Separate charts should be kept for the different belts and zones; but some economy may be effected by using inks of different colours on the same chart.

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*It is convenient to use these together with the Tables given in B. M. Peek's invaluable book, *The Planet Jupiter*.—Editor.

The standard way of expressing the rates of drift is to give the change of longitude in thirty days. There are Tables for converting longitude changes into rotation periods, in which form the results are usually published. The rotation period of the zero meridian of System I is $9^{h}\ 50^{m}\ 30^{s}.003$, that of System II $9^{h}\ 55^{m}\ 40^{s}.632$. It should be realized that these two periods have no physical significance; they are derived from figures that were adopted towards the end of last century as providing convenient reference systems. Any other periods close to these would have served the purpose equally well.

The latitudes of the spots recorded are described with reference to the various belts or zones, on or close to which the spots appear. The exact latitudes of the belts must be determined by means of a micrometer, fitted to the telescope; since, however, the majority of amateurs are not provided with such a luxury, we shall not take up space by describing the procedure here. Fig. 15 illustrates the nomenclature that has been universally

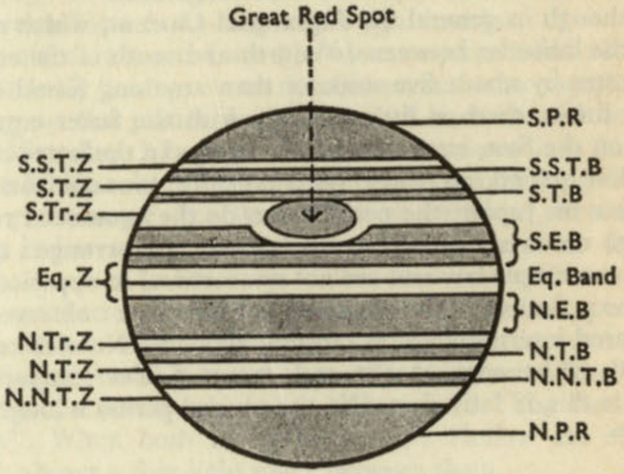

Fig. 15. *The nomenclature of Jupiter.*

adopted. It will be noted that all the dusky strips are referred to as "Belts", with the single exception of the thin "Equatorial Band", while the bright strips are called "Zones". Abbreviations, such as N.E.B., S.S.T.B., S.Trop.Z. are convenient but care must be taken to avoid ambiguity. For instance, S.E.Bn. may be used to denote either the south edge of the S.E.B. or its south component and it must be made perfectly clear which is intended.

A. Stanley Williams was one of the pioneers of the simple method, just described, of determining the longitudes of the surface features. In 1896 he published his classical paper, "On the Drift of the Surface Material of Jupiter in Different Latitudes", in which he distinguished nine different surface currents. In each of these the spots were drifting at a rate that had been characteristic of that latitude for several years and has remained so ever since. We can now recognize some twenty similar drifts among the planet's surface features, each one characteristic of the particular latitude.

Some latitudes, however, exhibit alternative rotation periods, as in the case of the southern branch of the Great Equatorial Current; the normal drift has an average period of $9^h\ 50^m\ 26^s$, while since 1917 a period of over $9^h\ 51^m$ has frequently been observed. On two or three occasions the two rates have operated simultaneously in different longitudes.

Although in general the Equatorial Current, which dominates the latitudes between 10° north and south of the equator, is shorter by about five minutes than anything found outside these limits, there is little analogy with the faster equatorial drift on the Sun, as revealed by sunspots. In the latter case the rotation period increases systematically towards the poles, whereas on Jupiter the periods outside the equatorial regions, though obviously related to the latitude, are arranged according to no simple law and are not symmetrical in opposite hemispheres. Actually the swiftest current ever observed has appeared intermittently in latitude about 24°N. with rotation periods of between $9^h\ 48^m$ and $9^h\ 49^m{\cdot}3$. Yet comparatively close to this, in latitude 30°N., the normal period is longer than $9^h\ 56^m$.

Surface Features. The majority of Jovian markings tend to

assume a few characteristic forms, e.g. white spots of various sizes and brilliance and dark spots or streaks, the streaks being usually elongated along parallels of latitude. White streaks are also sometimes seen in the middle of the dusky belts; but under the best observing conditions these are frequently resolved into chains of small bright spots. Dark projections from the edges of the belts are common, numerous examples of which are nearly always to be found at the south edge of the N.E.B. The northern half of the Equatorial Zone is sometimes filled with a series of rather large, light ovals, which may appear to be enclosed by grey arches, whose feet are the N.E.Bs. projections. This effect may, however, be partly one of contrast at the edges of the light ovals.

Such features as have just been described undergo changes of varying rapidity. They may last for weeks or months but it is only rarely that they can be identified from one year to the next. The most notable exception is that most famous of all Jovian features, the Great Red Spot.

The outline of the Red Spot is an oval some 25,000 miles long and 8,000 miles wide. These are enormous dimensions, even on a planet whose equatorial and polar diameters are 89,000 and 83,000 miles respectively. The centre of this oval lies a little to the north of the middle of the S. Tropical Zone—see Fig. 15—and the whole of its area may be dark or dusky, or it may resemble a dusky ring with a light interior.

This object attracted world-wide attention from 1878 to 1880, not only because it was the darkest and most conspicuous marking on the planet, but because of its brick red colour. Since 1882, when it began to fade, it has at times been faint or even invisible, only to return at intervals to something like its former prominence. For the last few years up to the time of writing it has surely been nearly as conspicuous as it was in 1879.

The northern edge of the Red Spot encroaches upon the latitude that in other longitudes is occupied by the south edge of the S. Equatorial Belt and appears to scoop out of the belt a semi-elliptical cavity which has been named "The Red Spot Hollow". When both the Spot and the Hollow are visible, there is always a thin light space between them.

Fortunately, at times when the Spot has faded to invisibility, the Hollow has almost always been evident and this has enabled the formation to be traced with certainty back to 1831, when the Hollow was definitely shown on one of Schwabe's drawings. It seems highly probable, moreover, that a similar, dark, S. Tropical Oval, that was recorded intermittently from 1664 to 1713, was a manifestation of the same object.

Two other long enduring features will be mentioned here. The first dated from 1901, when a grey wisp appeared joining the S. Temperate Belt to the S.E.B. This became rapidly drawn out in longitude, the extent of which in its early stages varied between 30° and 100°. The dusky part of the S. Tropical Zone, which was named "The South Tropical Disturbance", lay, of course, in the same latitude as the Red Spot. Since the initial rotation period of the Disturbance was about 20 seconds shorter than that of the Spot, it seemed inevitable that the former, if it survived, should overtake and pass the latter. Altogether nine such conjunctions were observed, though the eighth was abnormal in that the Red Spot drew clear ahead again of the Disturbance before the passage had been completed.

The S. Tropical Disturbance was last seen in 1939. During the latter part of its history its rotation period gradually lengthened, so that conjunctions with the Red Spot occurred less frequently. Its length also became greatly extended, reaching a maximum of 230° in 1935.

Three times during its lifetime the Disturbance faded to invisibility in company with the S. component of the S.E.B. and the R.S.Hollow. With the revival of the S.E.B., however, the Disturbance was restored to its familiar aspect, when the longitudes of its ends showed that it had suffered no unexpected acceleration during its temporary obliteration.

Since the feature was last recorded in 1939 there have been three occasions when it seemed that some sort of rejuvenation had occurred. In 1941, 1946 and 1955 dusky streaks, whose appearance resembled rather closely that of the Disturbance in its early years, developed in the S. Tropical Zone. In each case the rotation period was again about 20 seconds shorter than that of the Red Spot; but none of them survived for as long as two years, and it was not possible to relate their longitudes with any certainty to that of the old Disturbance.

In 1939 there were three sections of the S. Temperate Belt that either exhibited a south component or were considerably widened towards the south. During the ensuing years these sections became gradually extended in longitude with the result that the gaps between them grew shorter until, during recent years, the gaps have become the prominent features, each appearing to be caused by the presence of a bright oval spot in the S. Temperate Zone. The phenomenon may therefore be considered to have persisted continuously for twenty-three years. The white spots are still prominent objects.

The upper picture of Plate 15 shows a characteristic view of a very remarkable phenomenon associated with the South Tropical Disturbance, of which the preceding end is the oblique, dark streak on the right hand part of the S. Tropical Zone. The dark projections at the S. edge of the S.E.B. were all moving rapidly to the right; but when they reached the Disturbance they were somehow or other deflected across the zone and returned equally rapidly in the opposite direction in the form of dark spots or streaks close to the N. edge of the S.T.B. The illustration depicts three such objects that had previously travelled along the S.E.Bs. This phenomenon was first seen in 1920 and was much in evidence from 1932 to 1934. It has not been seen since.

The Nature of the Planet. The last few paragraphs have described the appearance and behaviour of some of Jupiter's surface features. What is their true nature and what the general constitution of the planet?

It is now generally conceded that the elements hydrogen and helium provide at least 95% of the masses of Jupiter and Saturn, hydrogen being by far the more abundant. The heavier elements should be present but in comparatively small proportions.

There is some experimental evidence that the mean molecular mass of Jupiter's atmosphere does not exceed 5, but this is not inconsistent with the presence, as revealed by the spectroscope, of appreciable amounts of methane (16) and ammonia (17). The measured temperature of the visible surface is about 130°K, in good agreement with theory; as in the case of the Earth, the temperature must increase with depth. Such considerations have led to the current opinion that Jupiter's clouds are formed of droplets or crystals of ammonia, which fills the rôle played by water in our own atmosphere. The observer should never forget that such clouds, viewed from above, appear white and that the darker markings, which look so objective, may signify little more than absence of condensation.

Of the nature of the solid surface we can know little, except that its depth below the top of the cloud layer cannot be greater than about 2% of the planet's radius. Deeper than that, the atmosphere itself would solidify under its own enormous pressure and even at 1% of the radius would, if still fluid, have properties resembling more closely those of a liquid than a gas. In any case there can be little difference in chemical composition between the fluid and the solid strata of the planet; it is known, however, that at a critical depth not exceeding 15% of the radius the hydrogen must have become suddenly compressed to a modification that has more than twice its previous density and is endowed with metallic properties.

The Great Red Spot. A problem that is at least as old as the century continues to baffle students of Jupiter. It concerns the nature of the Red Spot.

The first and most obvious suggestion was that its appearance was the effect of smoke and ashes, poured into the atmosphere by some form of volcano on the solid surface below; but the location of the Spot has not remained constant with respect to any uniformly rotating system of longitudes. Indeed, whatever uniform reference system is chosen, it is found to have drifted through at least 1080° since 1831, which is three complete circuits of the planet, and it has, moreover, experienced a number of accelerations and decelerations, which are difficult to associate with a solid core. On the other hand, if the Spot is a purely atmospheric phenomenon, how can it have preserved in all essentials its size and form for at least 130 years and quite probably for nearly 400?

To meet these objections it has been proposed that the permanent feature is an enormous elliptical solid mass of low density, floating at an appropriate level in the lower part of the highly compressed fluid atmosphere and affecting the state of the "sky" above it. If the level of this body were to fluctuate

through only a few kilometres, the need to conserve its angular momentum about the axis of rotation could account for all its observed excursions in longitude. The difficulties encountered by this theory cannot be entered into here, but they are considerable.

The modern tendency is again to anchor the Red Spot to the solid surface and to seek an explanation of the formidable changes in angular momentum that it must be capable of sustaining. Those who postulate an interchange between the core and the atmosphere must realize the probable shallowness of the latter and the fact that there is no known correlation, either positive or negative, between the vagaries of the Red Spot and those of other visible features.

We are unfortunately almost completely ignorant of the properties of matter under extremely high pressures. Laboratory data are available for a number of substances up to pressures of 100,000 atmospheres, but these are insignificant compared with those that must obtain in the deep interior of Jupiter, where the temperature is also presumably high. It is well known that for every gas there is a critical temperature, above which no pressure, however high, can liquify it. The kind of thing we should like to know is whether there are critical temperatures of not more than a few thousand degrees, above which the solid state is also impossible. If that were so, the innermost core of Jupiter might well be fluid like the Earth's. Electric currents in this fluid could account for the planet's magnetic field, which is to be inferred from the radio observations. Also, exchange of angular momentum of the right magnitude between such a core and an outer solid shell, bearing the seat of the Red Spot, is perhaps less unlikely than between the shell and the atmosphere.

Radio "signals" are received from Jupiter on a number of frequencies from 27 megacycles per second (Mc/s) downwards but nothing has been detected above 40 Mc/s. Of particular interest are those in the range 14 to 27 Mc/s. From observations obtained in 1951, C. A. Shain deduced a source that had a rotation period of $9^h\ 55^m\ 13^s$, which he provisionally identified with one of the white S. Temperate ovals mentioned above. A large number of observations, made during the seven years since 1955, point, however, to a radio period of $9^h\ 55^m\ 29^s$, which appears to have remained sensibly constant and with which Shain's observations can be reconciled. Although this result has been obtained by statistical analysis, the probable error that the figures indicate is so surprisingly small, that it is claimed that the sources of the radiation, which are three in number, are features of a uniformly rotating solid surface.

Or do they represent the period of a fluid core? If the latter, will the radio period vary in the opposite direction to that of the Red Spot, which of late has been fairly constant near $9^h\ 55^m\ 43^s$, when the next considerable change in the motion of the Spot takes place?

Theories, like the ones we have been discussing, are fascinating and may be exceedingly fertile. In the end, however, the conclusions that are drawn from them must always stand up to the crucial test of observation. There is, therefore, an urgent need for more observations and then again more. In spite of the rapid strides that have recently been made in the photography of planetary detail, there will be scope for a long time to come for systematic visual observation. The study of Jupiter's surface, requiring as it does only quite modest optical equipment, still offers unlimited opportunities to the enthusiastic amateur astronomer.

Results from Pioneer 10. In December 1973 Pioneer 10 bypassed Jupiter at a distance of about 80,000 miles, and sent back a tremendous amount of information. This is not the place to discuss the new results; but bear in mind that Jupiter is an ever-changing world, so that observations of it continue to be of great value.

Chapter Eleven

OBSERVATION OF SATURN

A. F. O'D. Alexander

Saturn, though the most beautiful planet, is not the easiest to observe or to draw. Both procedures are complicated by the presence of the rings, their varying apparent tilt, their shadow across the globe, and the globe's shadow across them; and rings and shadows produce various optical illusions against which the observer has to be on guard. Moreover, it is only in years when the rings appear more or less edgewise (e.g. 1966, 1980), and for a few years before and after, that the ring opening is narrow enough to let both hemispheres of the globe be observed; in other years the rings, more widely open, cover all or most of one or other hemisphere. The apparently calm and changeless look of Saturn is a delusion, tending to discourage frequent and careful scrutiny, and there can be no doubt that in the past many of the rather infrequent spot outbreaks, and other (slighter but significant) changes—in the intensity, position, width and visibility of belts and zones—have been missed even when Saturn has been well placed for observation, owing to neglect to observe often enough.

Estimates of Relative Intensity. To ensure a constant watch on the planet being kept, the B.A.A. Saturn Section in 1946 introduced a system of frequent routine observations (say, twice a week during apparitions), observers being asked to estimate the relative intensity of rings, belts, zones (and their various parts) and shadows, on a scale from 0 (brightest) to 10 (darkest), using halves and quarters if desired (e.g. 2¾, 3½). Two standards were taken as fixed: 1 for the brightness of the outer part of ring B (B^1) in the ansæ by Cassini's division, anything brighter being assessed ¾, ½, ¼ or even 0 if very exceptionally bright; 10 for the blackness of a very dark sky or deep black shadow. The nomenclature and normal positions of the chief belts and zones of the globe are shown on Fig. 16. The outer bright ring is called A, the middle bright one B, the faint inner one C; the outer, middle and inner parts of each can be distinguished by using the suffixes 1, 2, 3 respectively. The quickest and easiest way to record intensities is to write down the numbers (of the scale 0 to 10) on outline sketches of the globe and rings, and it is a good plan to make one series of estimates taking the features in order from brightest to darkest and another series in reverse order, taking means where the two results differ. Personal equation, rating all features too dark or too light, can be allowed for by the Director, provided it is consistent; unsteady air usually reduces the intensity of all dark markings. A good example of the usefulness of these estimates was shown in 1956 by the recorded variations from month to month of the brightness and tint of the E.Z.

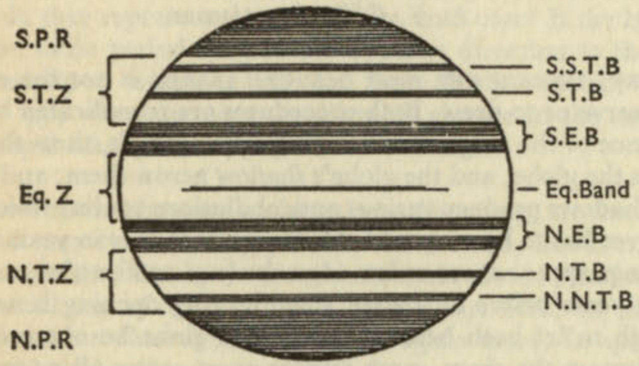

Fig. 16. *Nomenclature of Saturn's belts and zones. The rings have been omitted to show the whole disk. T—temperate; P.R.—polar region.*

Drawings. Good drawings of the complete planet are usually to be preferred to partial ones, and often show better what was seen than long descriptions. They should show all the observer is quite sure of, but no more. Partial drawings on a larger scale can be made also when there is fine detail or an unusual feature to be shown. The correct placing and shaping of the shadows reveal the quality of the observation. The globe's shadow falls on the rings on the p. side before opposition, on the f. side after, usually becoming invisible for a few days at opposition. The shadow of the rings may fall across the globe inside the inner edge of ring B (and be involved with ring C) or outside the outer edge of A, or occasionally be entirely hidden by the rings. It is important to draw the globe the correct elliptical shape and the rings at the correct tilt, and the following particulars should enable observers to do this. They are extracted from the fine paper* 'Drawing the Planet Saturn' written by M. B. B. Heath, former Director of the Section, values being here rounded off to the nearest 0·01 inch. He said that accurate outlines could be drawn quickly and without much difficulty by making a series of stencils from postcards. The stencils, if carefully used, would produce hundreds of outlines. The scale recommended is 4 inches for the major axis of the outer edge of ring A; then the following dimensions will also remain unchanged whatever the tilt of the ring-plane to that of the Earth's orbit:

	ins.
Inner ellipse of outer ring (A)	3·52
Outer ellipse of inner ring (B)	3·44
Inner ellipse of inner ring (B)	2·66
Inner ellipse of dusky ring (C)	2·19
Major axis (equatorial diam.) of globe	1·78

The minor axis (polar diameter) of globe will vary a little according to the value of B, the saturnicentric latitude of the Earth referred to the ring-plane (particulars of which are given in *The Astronomical Ephemeris*):

B	*minor axis of globe*	B	*minor axis of globe*
0°	1·59 inch	21°	1·62 inch
7°	1·60 „	28°	1·63 „
14°	1·61 „		

The following table gives the minor axes of the rings in inches for all values of B for every degree from 1° to 28°:

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* *B.A.A. Journal*, Vol. 63, No. 8, p. 342.

B	Outer edge ring A	Inner edge ring A	Inner edge ring B	*B*	Outer edge ring A	Inner edge ring A	Inner edge ring B
1°	0·07 in.	0·06 in.	0·05 in.	15°	1·04 in.	0·91 in.	0·69 in.
2	0·14	0·12	0·09	16	1·10	0·97	0·73
3	0·21	0·18	0·14	17	1·17	1·03	0·78
4	0·28	0·25	0·19	18	1·24	1·09	0·82
5	0·35	0·31	0·23	19	1·30	1·15	0·87
6	0·42	0·37	0·28	20	1·37	1·20	0·91
7	0·49	0·43	0·32	21	1·43	1·26	0·95
8	0·56	0·49	0·37	22	1·50	1·32	1·00
9	0·63	0·55	0·42	23	1·56	1·38	1·04
10	0·70	0·61	0·46	24	1·63	1·43	1·08
11	0·76	0·67	0·51	25	1·69	1·49	1·12
12	0·83	0·73	0·55	26	1·75	1·54	1·17
13	0·90	0·79	0·60	27	1·82	1·60	1·21
14	0·97	0·85	0·64	28	1·88	1·65	1·25

Heath suggested that a good way to construct the ellipses was to mark out a series of points by the use of a paper trammel and then join the points by freehand drawing; this is more satisfactory than the pins and thread method when *B* is small. To make the trammel the straight edge of a narrow strip of paper is marked off so that AC is equal to the semi-major axis of the required ellipse and AB equal to its semi-minor axis—see Fig. 17.

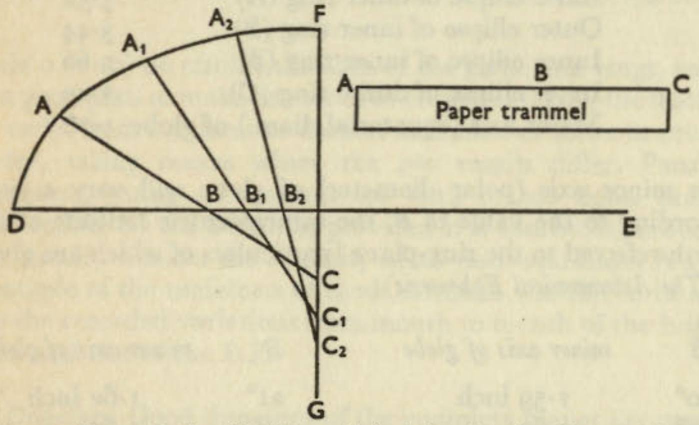

Fig. 17. Demonstrating Heath's method of drawing the ellipses of Saturn.

Two straight lines, DE equal to the major axis and FG equal to the minor axis, are drawn bisecting each other at right angles. The trammel is then moved into various positions such as ABC, $A_1B_1C_1$, $A_2B_2C_2$, as shown in the figure, so that B falls on the major axis and C on the minor axis. The points A, A_1, A_2 are

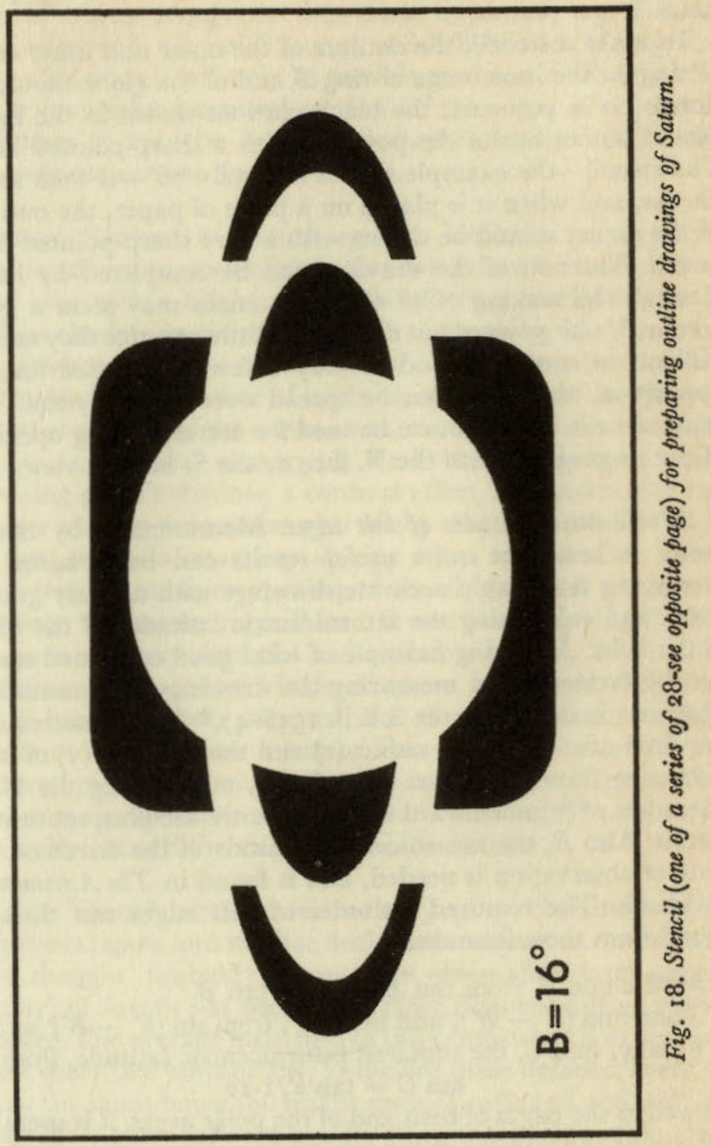

Fig. 18. Stencil (one of a series of 28—see opposite page) for preparing outline drawings of Saturn.

then on the perimeter of the ellipse. As many points as desired can be thus marked for the perimeter in each of the four quadrants.

To make a stencil, the outlines of the outer and inner edges of ring A, the inner edge of ring B and of the globe should be drawn on a postcard; the black portions shown in the figure should be cut out of the postcard with a sharp-pointed knife. The stencil—the example shown is for $B = 16°$—is then ready for use, and when it is placed on a piece of paper, the outlines of the planet should be drawn with a very sharp-pointed hard pencil. The rest of the drawing can be completed by hand. Though the making of 28 of these stencils may seem a great labour, Heath pointed out that with a little practice they are not difficult to construct, and as only a few are needed for one apparition, the work can be spread over several years. The same stencils can of course be used for corresponding openings of the rings either with the N. face or the S. face on view.

Saturnicentric latitudes of belt edges. Measurement by micrometer is best, but quite useful results can be obtained by measuring reasonably accurate drawings with a finely graded scale, and calculating the saturnicentric latitudes of the edges of the belts. A striking example of what good combined results can be arrived at by measuring the drawings of a number of observers is shown for the S.E.B. 1946–47.* The measurements required are: the polar radius (r) and the distance (y) of each belt edge from the centre of the disk, taken along the C.M. Measures of (y) northward from the centre are plus, southward minus. Also B, the saturnicentric latitude of the Earth on the date of observation is needed, and is found in *The Astronomical Ephemeris*. The required latitudes of belt edges can then be found from these formulæ:

Find angle B' from $\tan B' = 1{\cdot}12 \tan B$
Then find $(b' - B')$, and hence b', from $\sin (b' - B') = y/r$
Finally, find C, the required saturnicentric latitude, from:

$$\tan C = \tan b'/1{\cdot}12$$

As well as the edges of belts and of the polar areas, it is useful to determine the latitude of the central line of the E.Z. and of the inner edge of the Crêpe Ring across the globe. Some belts, e.g.

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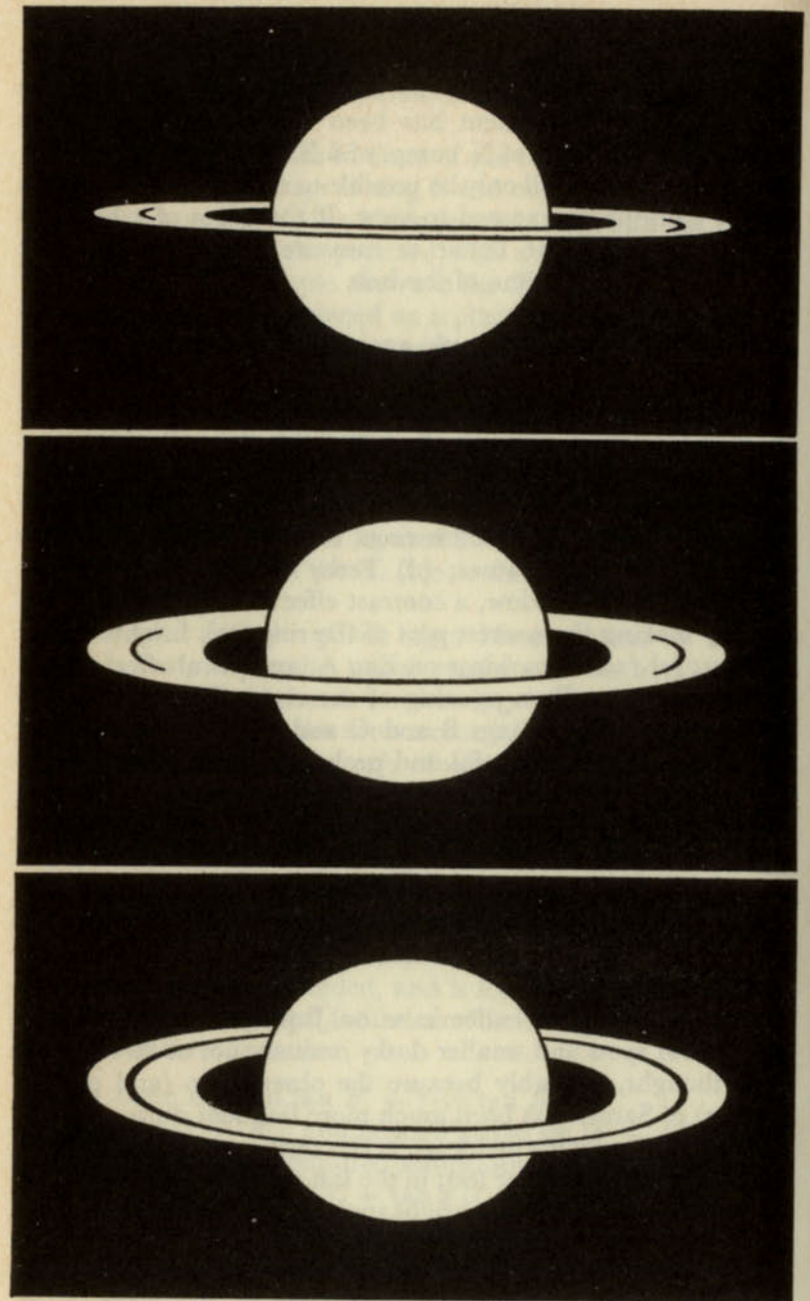
* *The Planet Saturn*, p. 404.

S.E.B., are often seen as two components separated by a narrow light intermediate zone; it is here important to specify which edge of which component has been measured, e.g. S.E.B.$_N$ south edge = S. edge of N. comp. of S.E.B. When the rings are fairly wide open it will only be possible to measure belt latitudes on the hemisphere exposed to view. If the edges of a belt are very hazy it may be better to measure the latitude of the approximate central line of the belt.

Optical illusions to guard against include: (a) 'square-shouldered' appearance of globe due to contrast between a dark polar area with a bright zone or bright ring contiguous to it; (b) false shadow on rings on one side of the globe when the real thin shadow is on the other side—this has been observed *and photographed* near the time of opposition; (c) 'peaked' or queerly shaped shadow of globe across rings, explained as due to atmospheric and optical causes; (d) Terby's white spot on rings adjoining globe's shadow, a contrast effect, the darkness of the shadow making the nearest part of the ring look brighter than the rest; (e) radial markings on ring A, an optical effect sometimes seen at medium opening of the rings. Dark concentric markings separating rings B and C and dividing ring C into two parts are very doubtful and probably optical. The reality of various dusky concentric markings on both faces of rings A and B has been hotly disputed, but their existence as surface ripples or light minima seems to have been vindicated by the observations of Lyot and Dollfus, though these markings are by no means always visible and not fixed in position. The only true gap right through the rings is Cassini's division.

Spots. Though not endemic as on Jupiter, Saturnian large bright oval spots and smaller dusky ones are not as rare as was once thought, probably because the observation (and photography) of Saturn has been much more frequent during recent decades. The average incidence in this century has been an outbreak every five years or less; in the last three decades, every 3½ years, the latest being the bright spots of 1960 and 1962. When dusky spots occur they are usually on or at the edges of the chief belts, bright ones mostly in the E.Z., though that of 1960 was in a high latitude zone (N.N.T.Z.). When one bright spot



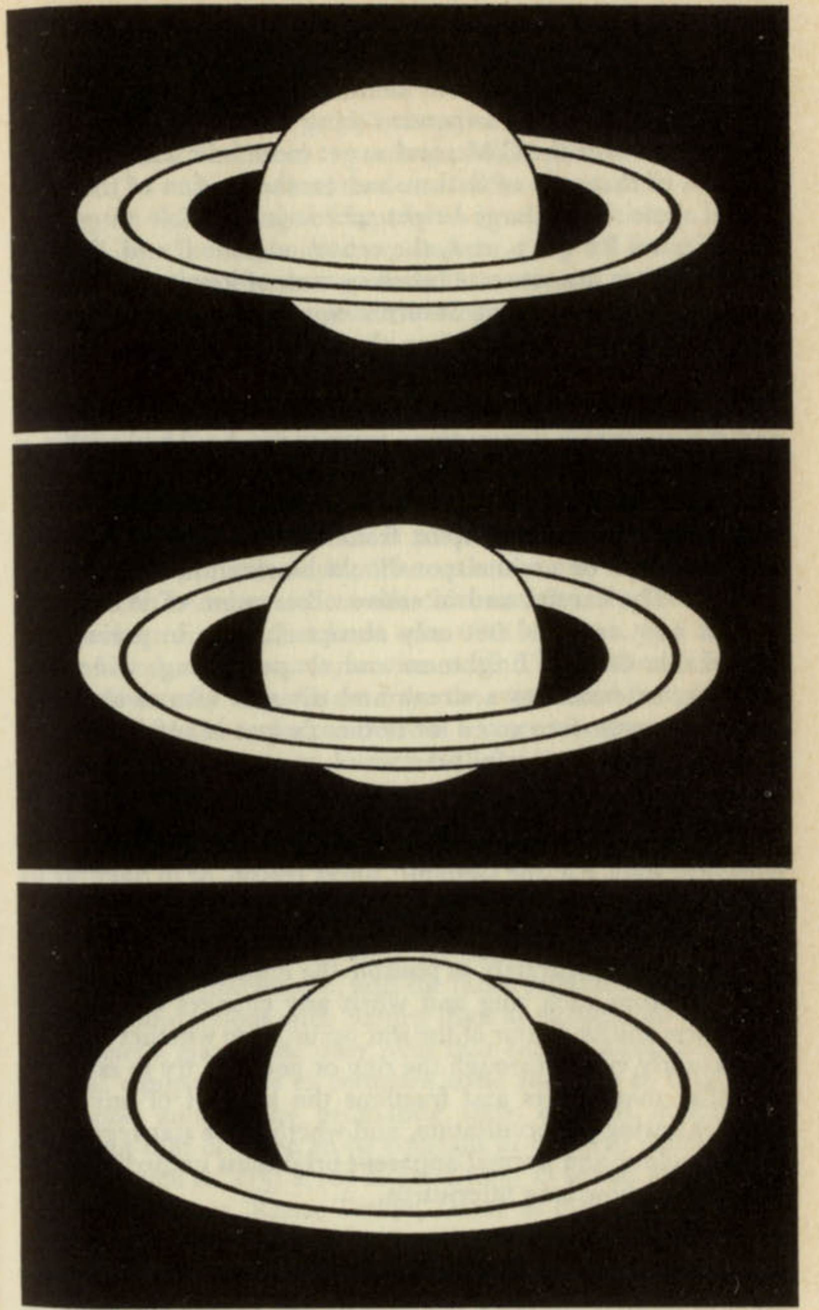


Fig. 19. Saturn 'blanks' drawn by David Hardy, for various ring aspects. These may be traced and used as outlines.

occurs, others may appear in different parts of the same zone, and this can lead to mistaken identifications and errors in rotation periods. The most important thing is to try to time transits of any spots over the C.M., and so get more information on the rotation of that part of Saturn and on the motion of the individual spots. For a large bright spot it is desirable to get the transit times for the p. end, the centre and the f. end. Saturn, unlike Jupiter, has no established systems of longitude, but it is useful to remember that Saturn's equatorial region rotates 7 times in $71^{h}\ 38^{m}$ (22^{m} less than three complete days), while in higher latitudes 7 rotations take about $74^{h}\ 26^{m}$. Hence in either case further transits can be expected every third night, and if two, or still better, three transits can be timed within a week or so, an approximate rotation period for the spot can be calculated on the basis of 7 rotations in every $71{\cdot}6^{h}$ (or for higher latitudes $74{\cdot}4^{h}$). Apart from timing it, the brightness, size and shape of a white spot should be carefully watched for changes. The careful and intensive observation of Will Hay's spot in 1933 revealed not only abrupt changes in period but remarkable ones in brightness and shape (fading, widening, tapering, extension to a streak and division into two); some similar changes were noted for Botham's spot of 1960. Detailed drawings would be useful here.

Occultation of Stars by Rings. This phenomenon is rather rare and is most likely when Saturn is in a part of the Zodiac rich in telescopic stars, e.g. the Gemini-Cancer region, or in Sagittarius (when the planet is badly placed for N. Hemisphere observers, but well placed for those of the S. Hemisphere). The observer should time as accurately as possible the immersion behind and emersion from each ring and when any changes of apparent brightness and/or colour of the star occur, note whether the star is constantly visible through the ring or not, and try to estimate in stellar magnitudes and fractions the amount of any light changes during the occultation, and whether the star regains its normal colour and normal apparent brightness immediately on emersion or how long afterwards.

Eclipses of Iapetus by the Rings. At intervals of 14 or 16 years, two years before the rings become edgewise, the orbit of the satellite Iapetus becomes edge-on to the Earth, and Iapetus

appears to move in a straight line across Saturn, so that transits, eclipses and occultations of the satellite can occur, e.g. about 1978, though, as in 1948, the phenomena may sometimes happen when Saturn is near conjunction and unobservable. Barnard (12-inch aperture) made a famous observation in 1889, tracing the light-change of Iapetus as it crossed behind ring C, eclipsed by the ring's shadow, and in 1919 W.F.A. Ellison (10-inch aperture) made a partial observation of that satellite's passage behind and emersion from ring A.

Satellite Visibility and Variability. Janus is too near Saturn to be seen except with large instruments when the ring-system is edge-on. Mimas is so near Saturn and so much involved in its glare that very good conditions and an aperture of at least 10 inches are needed to see it. Enceladus is also too near to be seen easily, but is sometimes detectable with a 6-inch aperture telescope. The other inner satellites and Iapetus can be seen with smaller instruments. Hyperion, faint but far from Saturn, has been seen with a 6-inch, and is most easily found when in conjunction with Titan. Phœbe is very faint and usually very distant from the others and from Saturn, so is doubly hard to find and needs a large telescope.

Iapetus has long been known to be about two magnitudes brighter at western than at eastern elongation. All the five inner satellites are believed to be variable by about half a magnitude or less, and Titan is suspected of slight variability. Trying to assess their variation by ordinary visual methods, as for variable stars, is beset with difficulties. Saturn is always moving with respect to the stars, so there is no handy field of comparison stars of known magnitude; and the inner satellites look dimmer around conjunctions with Saturn than at elongations owing to the planet's glare. The only plan that can be attempted with normal equipment is to compare these satellites in brightness with one another by estimating steps of 1/10 magnitude, assuming that of Titan to be constant at 8·3. For example, an estimate such as T(5) I(10) R(10) Tys(5) D would give magnitudes for Iapetus, Rhea, Tethys, Dione as 8·8, 9·8, 10·8, 11·3 respectively. Any report of such observations should have notes of seeing conditions and as to which (if any) satellites were at or near W.E. or E.E. *The Astronomical Ephemeris* and the *B.A.A.*

Handbook each year give satellite ephemeris (position angles, elongations, etc.).

Transits of Titan and Shadow. Only during 5 years in every 15 will the apparent tilts of the rings and of the orbits of most of the satellites be small enough for phenomena (eclipses, occultations, and transits of satellites and their shadows) to be observable, and for such periods (e.g. in 1978–82) the *B.A.A. Handbook* will publish ephemerides. In other years the satellites will appear to cross N. or S. of Saturn. Transits of the fainter satellites and their shadows are very difficult to detect, though a number are said to have been observed with 6-inch apertures in the 1890s. It is certainly worth while to look out for transits of Titan and/or shadow, timing immersion, C.M. passage and emersion, noting what belt or zone of Saturn is crossed, and, if both Titan and its shadow should be in transit together, comparing their apparent size and darkness. Titan, when crossing a light zone, would look dusky by contrast.

Edgewise Rings. The remarkable phenomena caused by the passages of the Earth and Sun through Saturn's ring-plane were last seen in 1966. At times the rings became very difficult to see, but at Armagh Observatory, using the 10-inch refractor, Moore and Moseley were able to follow them at all times when observing conditions were good. Unfortunately the next edgewise presentation will not occur until 1980. So far as the satellites are concerned, in the past some remarkable observations have been made with apertures of 9 inches and under, e.g. those of Innes of the 'ghost ring' (unillumined face) in 1907, the testing of small apertures on the almost edgewise ring in 1920–21, and the striking observation of Coleman and Knight in 1936 and of Congreve-Pridgeon in 1937.

NOTES: (1) *Opposition Places of Saturn 1964–2000*. The following list has been worked out by M. B. B. Heath.

Date of Opposition	*Place of Saturn in Sky*	*Ring aspect*
1964 Aug. 24	Aquarius, near θ	North face of rings on view
1965 Sept. 6	Aquarius, near λ	
1966 Sept. 19	Pisces, near λ	Rings edgewise to Earth thrice during 1966
1967 Oct. 2	Pisces, near δ	South face of rings on view
1968 Oct. 15	Pisces, near ζ	
1969 Oct. 28	Between Pisces and Aries	
1970 Nov. 11	Aries, near δ	
1971 Nov. 25	Taurus, near Pleiades	
1972 Dec. 8	Taurus, near ι	
1973 Dec. 22	Gemini, near η	Rings, South face, widest open during year
(1974—no opposition in year)		
1975 Jan. 6	Gemini, between δ and ζ	South face of rings on view
1976 Jan. 20	Cancer, between ζ and μ	
1977 Feb. 2	Cancer, between δ and π	
1978 Feb. 16	Leo, near Regulus	
1979 Mar. 1	Leo, near χ	
1980 Mar. 14	Leo, near υ	Rings edgewise to Earth thrice during 1979–80
1981 Mar. 27	Virgo, near χ	
1982 Apr. 8	Virgo, near Spica	North face of rings on view
1983 Apr. 21	Virgo, near κ	
1984 May 3	Libra, near α	
1985 May 15	Libra, near κ	
1986 May 27	Scorpio, near Antares	
1987 June 9	Ophiuchus, near θ	
1988 June 20	Sagittarius, between λ Sgr and θ Oph	Rings, North face, widest open during year
1989 July 2	Sagittarius, near σ	North face of rings on view
1990 July 14	Sagittarius, near π	
1991 July 26	Capricornus, near π	
1992 Aug. 7	Capricornus, near θ	
1993 Aug. 19	Capricornus, near λ	
1994 Sept. 1	Aquarius, near λ	
1995 Sept. 14	Pisces, near κ	Rings edgewise to Earth thrice during 1995–96
1996 Sept. 26	Pisces, near ω	
1997 Oct. 10	Pisces, near ε	South face of rings on view
1998 Oct. 23	Aries, near ι	
1999 Nov. 6	Aries, between θ and γ	
2000 Nov. 19	Taurus, between Pleiades and Aldebaran	

(2) *Future prospects*. Saturn will be reasonably well placed for observers in the N. Hemisphere during the period 1964–84, the S. part of the disk and the S. face of the rings being on view from 1967 till 1979; but for about 8 years from 1985 onwards, when the N. part of the disk and N. face of the rings are on view, Saturn's S. declination will place it badly for observers in the N. Hemisphere, but of course better for those in the S. Hemisphere.

(3) Jean Meeus, of Kesselberg Observatory, Kessel-Lo, Belgium, who calculated the dates of passage of the Earth and Sun through

Saturn's ring-plane that will occur in 1966, has also calculated the following dates of passage for 1979–80 and 1995–96:

1979 Oct. 27	Earth (S. to N.)	1995 May 20	Earth (N. to S.)
1980 Mar. 3	Sun (S. to N.)	1995 Aug. 11	Earth (S. to N.)
1980 Mar. 12	Earth (N. to S.)	1995 Nov. 19	Sun (N. to S.)
1980 July 23	Earth (S. to N.)	1996 Feb. 12	Earth (N. to S.)

He points out that the Earth's passage on 1996 Feb. 12 will be hard to observe, as it will take place only five weeks before conjunction of Saturn with the Sun.

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Chapter Twelve

OBSERVATION OF MINOR PLANETS

J. L. White

Between the orbits of Mars and Jupiter thousands of tiny planets revolve around the Sun, and although the vast majority are too faint to be seen with small telescopes the brighter ones offer a wide range of interest to the amateur astronomer. There are probably comparatively few observers who have ever seen one of these inconspicuous members of the Solar System, principally because considerable effort and patience are needed to locate what looks just like a faint star—hence the alternative name of "asteroid".

The first minor planet (1) Ceres was discovered in Taurus on January 1, 1801 by Father Giuseppe Piazzi at Palermo while checking a star catalogue, and with a mean distance from the Sun of 2·8 A.U. it exactly filled the gap in Bode's Law. A most promising field of activity was then open to anyone with a telescope and great enthusiasm who was prepared to undertake the very arduous task of hunting for further asteroids, and three hundred and twenty-one more were discovered by 1891, in which year Max Wolf found (323) Brucia by photography. From then on the work of discovery passed more and more from the realm of the amateur to that of the professional observatories. Likewise the computation of orbits and ephemerides, which for so many years offered scope for the mathematical amateur astronomer, is now carried out by electronic computers. The Institute of Theoretical Astronomy at Leningrad publishes annually a volume of ephemerides of all minor planets coming to opposition during the year, together with the elements of all known orbits. In 1963 these numbered 1650.

Method of Working. The observer who wants to see a minor planet must first of all consult the published ephemerides to ascertain the date when one of sufficiently bright magnitude is visible and its position in the sky. The R.A. and Dec. of the first four asteroids, Ceres, Pallas, Juno and Vesta, are given for every day during the months they are visible in *The Astronomical Ephemeris*, together with dates of opposition, magnitude, meridian transit times, and distance from the Earth. These positions are of the greatest possible accuracy—far greater than that attainable by the amateur. Short ephemerides at ten-day intervals for a few weeks before and after opposition are given for these and other planets brighter than magnitude 9 in the *B.A.A. Handbook*. The Leningrad volume, in addition to the opposition ephemerides, also gives extended ephemerides at ten-day intervals over several months for planets brighter than magnitude 12. There were thirty-seven in 1973. It often happens that there is none brighter than magnitude 7·5. The favourite is (4) Vesta, which at favourable opposition reaches magnitude 6·0.

The next requirement is a map of the area in which the planet selected for observation is to be found. This should show stars of magnitude at least as low as that of the asteroid. The position is then marked in pencil on the map and appropriate groupings of stars between this and a naked eye star are noted. Then, starting with the telescope set on the latter, the observer slowly works his way to the marked area, looking alternately from the map to the eyepiece, which should be of the lowest power (and hence the widest field) available. A red cycle lamp hung round the neck is a convenient form of illumination. The planet will be recognized at once as appearing where no star is shown on the map. A second observation made on a subsequent night will reveal its motion and confirm that it had in fact been located and identified. *Webb's Star Atlas* gives stars down to the ninth magnitude, and is on the same scale as the much older Beyer-Graff charts, namely 10 mm to the degree, and its size and binding make it very suitable for this work. The *Bonner Durchmusterung* charts go down to the tenth magnitude and are 20 mm to the degree, but the atlas is too large for use at the telescope, so tracings of the required area must be made. The American astronomer C. H. F. Peters prepared a number of charts of areas near the ecliptic expressly for asteroid hunting in 1882, and he succeeded in discovering forty-three. The scale is 60 mm to the degree, and stars of the twelfth magnitude are shown.

It is important to take into account the effect of precession when using a map for this purpose, especially if the epoch is much removed from that of the ephemeris, which is usually for 1950·0. Precession diagrams for reducing one epoch to another are given in the *B.A.A. Handbook* for 1949. If a star catalogue is available the precessional variation given for any nearby star can be used. Quite good positions can be obtained for an asteroid by plotting its position on one of the larger scale maps and then measuring directly, often within one or two minutes of arc. A great deal depends on the surrounding stars, which sometimes make judgement of position easy, as when the asteroid lies exactly between two close stars, or forms an equilateral triangle with two near stars.

Once the minor planet has been located, the main interest lies in keeping track of it for as long as possible, and if this can be done beyond the last date of the ephemeris available there is a great sense of achievement, especially if clouds intervene and cause it to be lost for a time. It is particularly gratifying if one can continue to follow the planet after its magnitude has fallen below that of the faintest stars on one's chart. If this happens during a period of cloud, and particularly if the planet is changing its direction of motion, it will probably be recovered only by very diligent searching after the manner of the original discoverers. The excitement of the hunt is still there for those who have only a ten-day ephemeris and none of the star atlases mentioned. If the observer has *Norton's Star Atlas*, or something similar showing stars down to magnitude 6, he can select a date when the planet is due to be within a degree or two of a star which he knows he can pick up. He must then make his own chart of the stars seen in the telescopic field; a comet eyepiece is the most useful for this. It requires some practice to be able to position correctly the stars seen over an area of two or three degrees when only a small portion of that field can be observed at one time. In reviewing the field on subsequent nights he may spot the "star" which has moved quite easily or he may have to ring several suspects for further observations before he can be sure. The motion will be greater and more easily detected at times well away from the opposition date, but this also means that the magnitude will be lower.

If it is very near a star, the motion may be detected during the course of a single night. A quicker method is proposed by Wolfgang Malsch, a very assiduous observer of minor planets. A straight wire or bar is set in the eyepiece so that it is at right angles to the path of the stars drifting through the field. Several stars, including the suspect, are timed as they reach the wire. This is done again an hour later, when the intervals between the stars arriving at the wire will be the same, but if one of them is in fact an asteroid the interval will be shorter or longer, according to whether it is in direct motion or retrograding. Here again the difference will be greater away from opposition, and useless at the stationary points. A simple timing device, adequate for the purpose, is a cheap clock with the hairspring adjusted so that it ticks half seconds. While observing the transits one can make a series of short strokes on a suitably arranged board and paper, coinciding with the ticks heard, with a longer stroke every time a star crosses the wire. (2) Pallas may be given as an example of the change in right ascension in one hour. At opposition on January 5th, 1963, it was 2·5 seconds, on February 10th, 0 seconds, and on July 1st, 5 seconds.

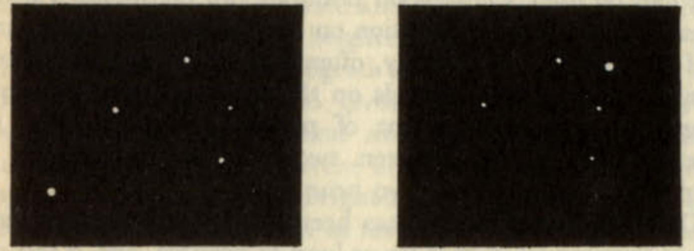

Fig. 20. Apparent shift of the minor planet Pallas over a period of 24 hours, observed by Patrick Moore using a 3-inch refractor.

If a star catalogue is available, such as the B.D., AGK2 or Yale, one can dispense with maps and prepare special charts by plotting suitable stars around the position given for the planet. This can be done quite simply on graph paper, and a big advantage is that one can choose any scale one pleases. Also the corrections for precession will be found against each

star position. Unfortunately many such special charts can be completely wasted if bad weather precludes their use during the periods for which they are drawn.

It might seem that in watching an asteroid move among so many stars one would be sure to see an occultation sooner or later. This is, however, a phenomenon very rarely seen, and no predictions are available. The *B.A.A. Handbook* gives the dates of very close conjunctions, described as appulses, and these could in certain circumstances be observed as occultations from some parts of the world. Certainly the observer can derive great pleasure from watching a close approach with the expectation of a possible occultation, which incidentally would provide an exact position of the planet if the time were accurately noted.

Observation of Changing Magnitude. Apart from watching the movement of a minor planet, another field of interest lies in noting the changing magnitude. The brightness of an asteroid depends upon its size, albedo, distance from the Sun and Earth, and the phase angle. The first four—Ceres 427 miles diameter, Pallas 280, Juno 150, Vesta 241—are among the largest (Ceres and Pallas are by far the largest of all), and it is upon these that estimates of the sizes of other asteroids are made from their brightness at a given distance. Short-period fluctuations in brightness suggest that the surfaces of some are uneven, and that others are of irregular shape. These planets are the fainter ones, and therefore less accessible to the observer with simple equipment. Moreover it requires great care to measure accurately the variations. Those able to assemble electronic apparatus may care to construct a photoelectric stellar photometer for this purpose, such as described by S. Archer in the *B.A.A. Journal*, Vol. 68, No. 7.

If the minor planet happens to pass through the field of a known variable star it is quite likely that a chart of suitable comparison stars is available, and these would enable the observer to make accurate estimates of the magnitude. The *B.A.A. Handbook* for 1962 contains a list of stars observed by the Variable Star Section, a few of which lie within the Zodiac and may therefore be approached from time to time by an asteroid. The *Atlas Stellarum Variabilium* of J. G. Hagen, in several volumes, contains a very large number of charts for such stars in all areas. These charts could also be used to locate and track for a short time planets too faint to be found with the maps already mentioned. It would be necessary to study the ephemerides and investigate the possibilities of this plan well ahead of the period involved, and above all to be fortified against the all too probable frustration resulting from cloudy skies on the critical dates. A report of an encounter with (20) Massalia in the field of the variable star X Leonis was given by F. M. Holborn in the *B.A.A. Journal*, Vol. 61, No. 5.

The greatest variation in brightness is due to the varying heliocentric and geocentric distances of the planet, and in a list of the elements of the orbits of minor planets the mean opposition magnitude m_0 is tabulated. This has been determined from many observations. Because many of the planets have orbits of marked eccentricity the magnitude of one particular opposition may differ greatly from another. Also tabulated is the constant g, which is obtained from the equation:

$$g = m_0 - 5 \log a\,(a - 1)$$

where a is the planet's mean distance from the Sun and 1 is one astronomical unit. Given this constant one can compute the magnitude at any time from the formula:

$$m = g + 5 \log r\,\Delta$$

where r is the distance of the planet from the Sun and Δ its distance from the Earth. Those who are interested in calculations of this kind can use the formula to determine many months in advance, perhaps at times right outside the limits of the available ephemeris, whether the planet will be bright enough for observation.

Remembering that Mars is gibbous at quadrature and that the unilluminated portion of the disk may be as much as one-seventh of the whole, it will be realized that phase has also considerable bearing upon the magnitude of minor planets, many of which lie only one astronomical unit further from the Sun. The phase angle q, Earth-planet-Sun, is given by the equation:

$$\cos q = \frac{r^2 + \Delta^2 - R^2}{2r\,\Delta}$$

where r is the radius vector of the planet, R that of the Earth, and Δ the geocentric distance of the planet. Having obtained q, the phase k is computed from:

$$k = \tfrac{1}{2}(1 + \cos q)$$

This is the value of the ratio of the illuminated area of the disk to the total area. It is also the value of the ratio of the illuminated part of the diameter at right-angles to the line of cusps to the whole diameter. The variation in the brightness of a minor planet due to phase can be from 0·5 to 1·7 magnitudes. The value of the phase angle and the phase can be approximately determined from geometrical scale drawings.

Computing. Minor planets have always offered special scope for the astronomer, amateur or professional, who is interested in mathematical astronomy; indeed it was the need to recover Ceres after its discovery and end of apparition that provided the incentive to Friedrich Gauss to produce his famous method of orbit computation. In spite of the fact that accurate and extended ephemerides are now published for the brighter asteroids, making location very easy, and that some yearbooks, such as the Swiss *Sternenhimmel*, give star charts showing the paths, making it easier still, many amateurs will prefer to rely more on their own resources. Some will even prefer to compute their own orbits, or at least their own ephemerides from published elements. Those who are attracted but perhaps overawed by such work could make a limited excursion into this field by extending a short ephemeris with the method described by H. E. Wood in the *B.A.A. Journal*, Vol. 36, No. 5; this requires that two geocentric distances be known. It gives tremendous satisfaction to find at the telescope that one's prediction, made months beforehand after hours of diligent calculation, is correct.

Photography. An interesting, though less arduous, field of activity is available for the amateur astronomer who is able to photograph minor planets. If the camera is carried on a clock-driven equatorial telescope set on to the area of the sky indicated by the ephemeris it cannot fail to locate the asteroid, revealed by its trail among the star points on the plate, after an exposure of two or three hours. An easier, though lengthier and more expensive method, is to photograph the area on two different nights and then examine the plates for the "star" that has moved. If the two plates are held in the hand superimposed towards the light and moved very slightly one against the other the stars all appear double, while the two solitary dots of the asteroid quickly catch the eye.

What has been written is intended primarily for the amateur astronomer who wishes to observe minor planets for his own satisfaction. If he wishes to undertake more serious work, such as the accurate determination of positions and magnitudes, he will find much guidance in the only book dealing exclusively with the asteroids, *The System of Minor Planets*, by G. D. Roth (Faber & Faber, 1962). The Minor Planet Centre at Cincinnati, Ohio, U.S.A., receives observations from all parts of the world and issues its *Circulars* to all observatories. The study of these reports may ultimately lead to a better knowledge of the nature of the asteroids and of the origin of the Solar System.

Chapter Thirteen

OBSERVATION OF COMETS

M. J. HENDRIE

THE OBSERVATION OF comets can be divided into three main branches: discovery of new comets and recovery of periodic comets, the accurate measurement of the positions of comets for the determination of their orbits, and the study of their physical aspects.

Fortunately professional astronomers are again taking a greater interest in comets, and some large instruments are in regular use for comet work. This means that the field in which amateurs can make contributions of scientific value is narrower than it was in the past; however, amateurs can supplement the work of the professional institutions by persevering with a few carefully chosen types of observation.

The estimated positions of periodic comets due to return to perihelion are published in the *B.A.A. Handbook* and in some other astronomical publications. Comets recently discovered are announced and their magnitudes, appearance and positions given in the *Circulars* of the B.A.A. and the *Circulars* of the International Astronomical Union. Comet observers need to have access to this information so that they know what comets are likely to be visible and where they can be found.

If a comet is likely to be bright enough to be seen or photographed with the equipment available, the position at each date can be plotted in *Norton's Star Atlas*. With a comet bright enough to be fairly easily seen in the telescope being used it is normally possible to find it quickly in a clear dark sky, but it is surprising how much difference a little haze, twilight or moonlight makes to the visibility of a faint diffuse object. Where an equatorial equipped with circles is used, these may be set directly to the comet's position, and in the case of a comet in twilight or too faint to be seen in the guide telescope being used for photography, this can save much valuable time.

Instruments. If a particular aspect of the study of comets appeals to the amateur he will need to have suitable equipment for that particular purpose. On the other hand, there is work to be done for which almost any telescope can be used so that the observer who already has some equipment and wishes to use it for comets should be able to do so without necessarily incurring additional expense. All optical equipment should be of good quality, but as high magnifications are not often used on comets, the ultimate in resolving power is not as essential as freedom from scattered light and a large fully illuminated field of view.

With binoculars and telescopes up to 3-inches aperture, comet-seeking is possible, and physical observations of the larger features in the heads and tails of comets brighter than about ninth magnitude can be made. Telescopes larger than 3 inches and up to 6 inches or so fall roughly into two groups: those with focal ratios smaller than *f*/5, and the remainder.

Short-focus instruments may be either refractors or reflectors, the refractor having the potentially wider field of view but the reflector probably being the cheaper of the two. For instance, a 6-inch aperture reflector with a focal ratio of *f*/4 could have a field of view of more than two degrees and should show comets to about eleventh magnitude in very good conditions. It would be very suitable for comet-seeking and the larger, fainter features of the heads and tails of brighter comets. The magnification used would be about ×30 to ×40, so that fine detail in the head of a bright comet might not be too well seen. Such an instrument would be light and very easily mounted, and therefore portable.

Long-focus telescopes usually have smaller fields of view, although often more than a degree in diameter. Reflectors are commonly *f*/6 to *f*/9, whilst refractors are *f*/10 to *f*/18. The rather higher lowest power used makes it easier to resolve faint star clusters that so often look like comets, and history has shown that successful comet-seeking has been carried out with many different types of telescope, some as small as 2-inch aperture and others with a field as small as one degree. Some have been equatorially mounted and others on simple altazimuth mounts. With these longer focal-length telescopes physical observations can also be made, of course, and if they are

mounted on good, solid equatorials they can be used for guiding for photography. Good slow motions on both right ascension and declination axes are essential, and a motor or clock drive is very desirable for long exposures, especially on comets which are also moving relative to the background of the stars. A permanent mounting is desirable free from vibration and accurately orientated with respect to the local meridian and celestial pole.

Observatory buildings, although not essential, do add greatly to the efficiency of a telescope. It can be left in position set up ready for use if the sky clears suddenly, and adjustments remain much more permanent if equipment is not subjected to movement. Although a dome provides better wind protection than a run-off type roof, it does restrict the amount of sky visible at one time. The run-off roof leaves the whole sky visible, and when engaged in visual comet seeking or using wide-angle lenses for comet or meteor photography this advantage may become a virtual necessity. In any case, walls should be built low enough to enable the telescope, and cameras if they are ever likely to be fitted, to reach the skyline without obscuration. (See Chapter 3).

Cameras faster than *f*/7 are necessary for satisfactory comet photography, and for the study of faint physical details *f*/5 is still not really fast enough. Unfortunately, as a general rule, the faster the camera the smaller the diameter of the field of sharp definition. Small sharp star images are essential, and a lens or mirror that will not produce them after careful focusing is of little value astronomically.

If a known comet is being photographed, it is usually possible to keep the image of its head within a degree or two of the optical axis. Portrait lenses of *f*/2·5 or slower and of 3- or 4-inches aperture often give good images up to some three or four degrees from the axis, but at twice this distance the images are large and unsymmetrical. Portrait lenses can still be bought cheaply and because of their simple construction transmit more light for their aperture than many lenses of more complicated design.

Where a wider field is required, as in searching for periodic comets or keeping in touch with a newly discovered comet before an orbit is available, aerial survey lenses give good results. Images are often usable up to 10° off the axis in those of 14- or 20-inch focal length working at *f*/5·6 or *f*/6·3. A focal-length of 14-inches gives a plate scale of almost 4° to one inch, and plate scale is proportional to focal-length.

Long dewcaps should be fitted to cameras, taking care that no light is cut off from the edges of the field of view by the dewcap or guide telescope. A lining of black blotting paper helps to prevent condensation in metal dewcaps, but a small electric heater is usually also necessary to prevent dew or ice from forming on the lens itself. Either is comparatively opaque, and will ruin a night's work. Resistance wire supported in a ring close to the front surface of the lens and connected to a car battery or transformer is very effective, but high voltages are best avoided in a damp observatory.

Reflectors offer a larger plate scale than lenses at comparable cost, but parabolic mirrors at *f*/5 or faster have small fields of sharp definition, probably less than a degree depending on what is considered acceptable. Schmidt-type systems overcome this limitation even at *f*/2 or faster but are expensive, and compared with lenses, the elements of which can be permanently mounted together, are difficult to keep in adjustment, and the curved focal surface is another complication.

Guiding a lens of up to 20-inches focal length will tax the patience of most amateurs, and it is much better to gain experience with a pair of lenses of about 12- or 14-inches focal length before tackling anything larger. In the section on guiding, the accuracy to which the photographic plate must be held relative to the sky will be considered. Problems increase greatly as the size and weight of photographic telescopes increase.

Guiding on a Moving Comet. A comet without a sharply defined central condensation can seldom be seen well enough to allow accurate guiding on the comet itself, and in most cases guiding must be carried out on a nearby star. This leads to a complication, as the comet is usually moving relative to the stars. Whether this motion is significant depends mainly on the focal length of the camera lens and length of exposure contemplated. Failure to make allowance for this apparent motion will result in blurring of the comet's image and longer exposure will only spread out the image over a larger area of photographic plate without increasing its density (see Fig. 21 and Plate 17).

In practice, the graininess of the photographic emulsion limits the minuteness of detail that can be photographed, the linear size of faint star images remaining almost constant regardless of focal length, although the angular size decreases with greater plate scale. For a lens of 14-inches focal length the plate scale is almost 1 degree = ¼ inch. The smallest star images are about 24 seconds of arc in diameter on fast emulsions or about 1/600 inch. It should be sufficiently accurate to keep any part of the comet's image within 12 seconds (1/1200 inch) of a fixed point on the plate throughout the exposure; the accuracy required is proportional to the focal length, so for a 7-inch lens it would be 24 seconds of arc.

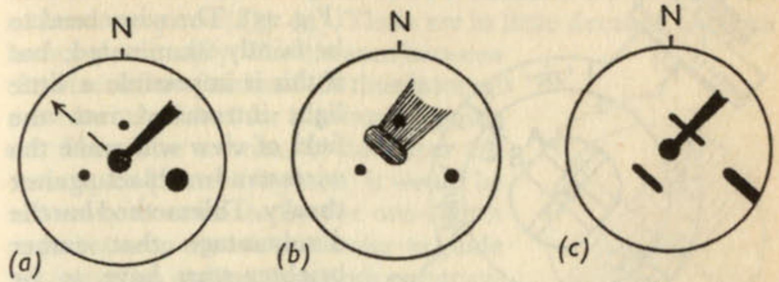

Fig. 21. (a) *A moving comet as it would appear in an instantaneous photograph.*
(b) *The same comet with a long exposure but with no allowance for its apparent motion.*
(c) *After allowing for apparent motion the comet's image is dense and sharp but the stars show trails equal in length to the comet's motion during the exposure.*

If a guide telescope of 42 inches focal length is to be used, 12 seconds in the focal plane will be about 1/400 inch: this then is the accuracy to which the guide star must be kept relative to the cross-wires. The importance of having the guide telescope and cameras rigidly coupled together can be seen, since movement between the two or bending in the guide telescope will ruin photographs even if of only a few thousandths of an inch.

If possible a bifilar micrometer should be used on the guide telescope; the fixed wires are set to the position angle of the comet's motion, and the movable wires a precalculated distance apart (Fig. 22). By moving the wires at intervals throughout the exposure and keeping the guide star in position by moving the whole telescope by means of the slow motions, a sharp photograph of a moving comet can be obtained (Fig. 23). The wires need to be faintly illuminated, but if this is impossible a little light introduced into the field of view will make the wires stand out black against the sky. This method has the disadvantage that rather brighter stars have to be used, but even so a seventh-magnitude star should be usable in a 6-inch telescope. The importance of adequate aperture as well as focal length is often overlooked for guiding on comets, but faint stars have to be used if there is no brighter star within a degree or so.

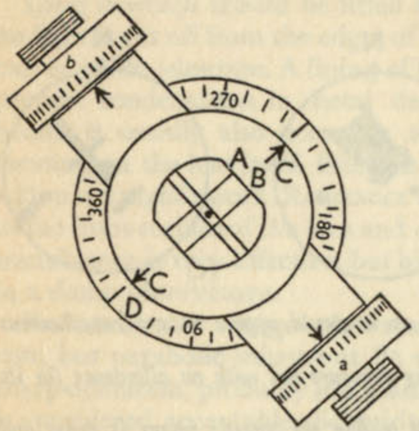

Fig. 22. The general appearance of a bifilar micrometer. The two drums a and b control fine screws moving wires A and B. The arrows C measure the position angle on the circular scale D. A magnification of 200 × on a guide telescope enables very small deviations during guiding to be easily detected.

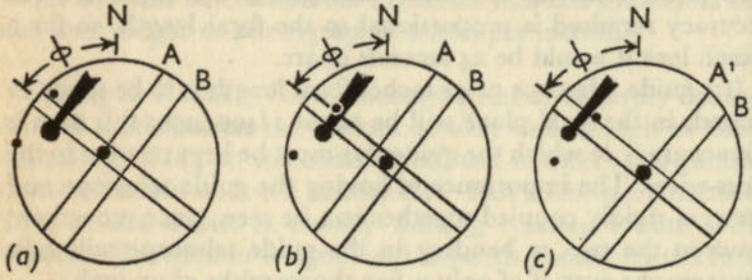

Fig. 23. Three positions of the comet (a, b, c) *amongst the stars are shown. Although the stars have moved relative to the field of the guide telescope the comet has remained fixed: as telescope and cameras are rigidly connected the resulting photograph should show a sharp image of the comet.*

When a comet is changing its position rapidly orbit computers often reduce the interval for which the ephemeris is tabulated, sometimes to one day. In some cases it may be advisable to plot $\Delta\alpha$ and $\Delta\delta$ against the dates given, and from the slope of the curves obtain better values for the proposed time of observation.

When a bifilar micrometer is not available it is possible to use a transit eyepiece (Fig. 24). These are in little demand and can be bought cheaply. The distance between the wires is now fixed and the time interval must be calculated for moving the guide star from wire to wire. If the wires are 1 mm apart (about 1/25 inch) it would be necessary to estimate by eye one-eighth steps between the wires in order to guide to 1/200 of an inch or 24 seconds on our 42-inch guider. For a 7-inch focal-length camera lens this would give quite good results and even for longer focal-length cameras would be a great improvement over ignoring the motion altogether. In any case it is usually preferable to estimate between the wires to a lesser extent, say thirds or quarters, even when using a bifilar micrometer, as it lessens the number of times that the telescope must be touched or a light used; this is especially important when a Newtonian is being used for guiding as the camera lens is behind the eyepiece. A simplified example for making the allowance for apparent motion is set out below (see Fig. 25).

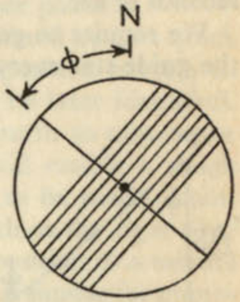

Fig. 24. The arrangement of the wires in a transit eyepiece. The position angle scale would have to be added, and, as with a bifilar micrometer, the angular distance apart of the wires on a given telescope is found by timing stars across the wires.

Example

	α	$\Delta\alpha$	δ	$\Delta\delta$
Jan 1	$6^h\ 30^m$		$+60°$	
		$+30^m$		$+180'$
Jan 11	7 00		$+63$	

$$\Delta\alpha' = 15\Delta\alpha^m \cos\delta = 15 \times 30 \times 0{\cdot}500 = 225'$$

$$\frac{\Delta\alpha'}{\Delta\delta'} = \tan\phi = \frac{225}{180} = 1{\cdot}250$$ where ϕ is the position angle of the comet's apparent motion.

Therefore $\phi = 51°\ 20'$

$$\frac{\Delta\alpha'}{\sin\phi} = d = \frac{225}{0{\cdot}781} = 288'.$$

where *d* is the angular distance moved by the comet in 10 days, in minutes of arc.

Therefore in 1 hour the comet moves $\frac{288 \times 60}{24 \times 10} = 72{\cdot}0$ seconds of arc.

We require to guide to 12 seconds, therefore we must move the guide star every 10 minutes.

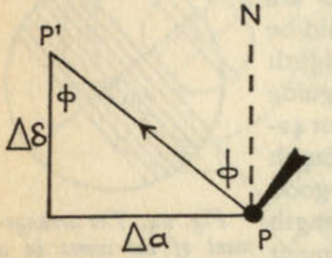

Fig. 25. *In this diagram φ is the position angle of the comet's motion and PP' is d, the distance moved by the comet along this direction in the interval corresponding to △α, the change in right ascension and △δ, the change in declination. To arrest the comet's motion the guide star must be displaced in the opposite direction at the same rate.*

If 1 revolution of the micrometer screw is 36 seconds of arc on the guide telescope used, two revolutions must be made per hour.

Therefore every 10 minutes the wire must be moved ⅓ of a revolution.

If it were decided to estimate thirds between the wires, the wires need only be moved every 30 minutes, or twice an hour.

Comet-seeking. This is of great importance, and is an aspect of observational astronomy that amateurs can do well. A bright comet is most likely to be seen near the Sun in the sky, which is why the twilight regions should receive special attention. This is difficult photographically, and photographers should concentrate on the darker parts of the sky.

Experience with the instrument being used for observing nebulæ, clusters and, of course, comets is perhaps the most important requirement for comet-seeking. This applies also to photography, as every lens produces its own special brand of images and ghosts, especially near the edges of the field. Faults on photographs are unavoidable, and it is safest, and cheapest in the long run, to make two exposures, one of twice the length of the other, on the same plate with a separation of about 3 minutes of arc. It is unlikely that any fault will have an exact twin, and the shorter exposure is long enough to confirm the reality of any image. A lens with a wide field of view in good definition and preferably not slower than *f*/4·5 or of shorter focal length than 12 inches is desirable. These are hard to come by, but whatever lens is used study the appearance of all types of objects all over the plates. Once an area has been photographed a "chart" is available for next time with all the permanent comet-like objects in their proper places.

If a suspect is found the visual observer should make a quick sketch of the stars and object, and fix the position roughly in the sky so that the field of faint stars may be later identified. Usually a comet will show signs of movement in 30 minutes or so; and if it has moved, another sketch will enable a rough position and estimate of apparent motion to be made. Comparison with a chart showing faint stars such as the *Beyer-Graff Stern Atlas* (to about $9{\cdot}3^{m}$) should enable a position to a minute or two of arc to be obtained. The procedure is similar for photographers and both can benefit from the *Atlas Coeli and Catalogue*, which gives nebulæ and clusters not shown on the *Beyer-Graff* or *Bonner Durchmusterung*. The epoch for charts should be noted: 100 years' precession may be as much as half a degree.

Periodic comets are usually recovered with large telescopes, often when as faint as twentieth magnitude. Sometimes, however, the position is too uncertain for large instruments, and if the comet is expected to be bright enough amateurs can join in the search. The procedure visually is to sweep very carefully that part of the sky in which the comet could be, noting all suspicious objects for subsequent elimination. Photographically the area is covered with overlapping exposures; it is usually advisable to allow for the comet's apparent motion if it is likely to be very faint, otherwise the image may be too spread out to be recorded. Either twin cameras or double exposures should be employed on each night. A blink-microscope is useful for searching the plates, which, it is only fair to say, can take a great deal of time.

Positional work requires special apparatus and access to star catalogues giving positions of great accuracy. Computers will not usually find use for observations which give the comet's position to a lesser accuracy than about 2 seconds of arc. This requires a plate scale of upwards of ½-inch to 1 degree and very careful measuring and reduction of the plate. However, when a comet's position is in doubt an estimate of its position, even to a few minutes of arc, can be useful.

Physical Observations. The most obvious observation to make is that of the measurement of total brightness. Unfortunately this is often very difficult, because there is no other object in the sky quite like a particular comet. This is partly solved by using a telescope that shows the comet as an almost starlike object. For instance, magnitude estimates on a sixth-magnitude comet would probably be more consistent if made with a 2-inch than a 6-inch telescope. Putting the star images out of focus helps, but the scientific usefulness of accurate measures made in white light has been questioned. Rough ones, by which is not meant carelessly made ones, are useful for the history of a comet, and these can well be made visually. It has always been difficult to deal with comet magnitudes photographically, and photoelectric measures are likely to be much more accurate. Photoelectric work requires considerable observational experience, but is not necessarily beyond the reach of the amateur either in cost or complexity: experience is best gained through work on variable stars.

It seems then that estimates in integrated light to a few tenths of a magnitude are required, but accurate measurements should be made in limited regions of the spectrum; this usually requires a larger telescope and is, perhaps, the province of the professional.

Apart from the brightness, there are the other physical features described in any book on comets. These may be carefully drawn or photographed and may show changes from hour to hour. Again continuous watch on all comets is desirable and this recording work, although unlikely to lead to a major advance in our understanding of comets, is none the less important. Photographically filters may be used to isolate the light from emission bands. Gelatin filters may be used if placed in front of the emulsion rather than in front of the lens, and by suitable selection can pass 80 % of the light in a narrow region of the spectrum. By means of these filters it is possible, for example, to tell whether a comet's tail is composed mainly of CO^+ or dust, and the images taken in different parts of the spectrum

may show quite different features. The motion of these features can sometimes be studied in the brighter comets, even with small lenses (Fig. 26).

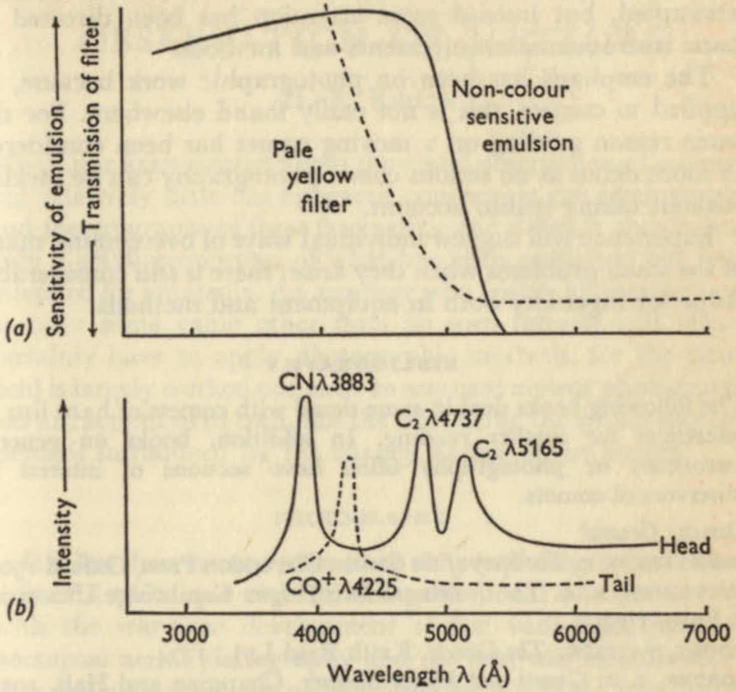

Fig. 26

(a) *An example of choosing a filter/emulsion combination to isolate a small region of the spectrum without recourse to narrow-cut filters with their low transmissions. The combination shown allows the comet to be photographed almost entirely in light of* C_2 *at* 4737 Å. *Removal of the filter admits the CN band also.*

(b) *The principal molecular emission bands in comets are shown: some comets show a continuous spectrum which may swamp these emissions.*

Spectrography is beyond the scope of amateur work, except perhaps for the occasional objective prism spectrogram of a bright comet. Useful work requires large instruments and carefully standardized processing and measuring conditions.

Special astronomical plates should be used where possible for long exposures: both Kodak and Ilford make them and both issue data sheets or booklets describing their characteristics. X-ray developers are useful for increasing the effective contrast.

Conclusion. It is, of course, impossible in the space of one short chapter to provide complete instructions for observing comets, even with small instruments. This has not therefore been attempted, but instead some attention has been directed to basic instrumental requirements and methods.

The emphasis has been on photographic work because, as applied to comets, this is not easily found elsewhere. For the same reason guiding on a moving comet has been considered in more detail as no serious comet photography can be tackled without taking it into account.

Experience will suggest individual ways of overcoming many of the small problems when they arise: there is still considerable scope for ingenuity both in equipment and methods.

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Chapter Fourteen

OBSERVATION OF METEORS

H. B. RIDLEY

MUCH HAS BEEN written about the visual observation of meteors, but relatively little has appeared concerning the photography and spectrography of these fascinating and difficult objects, and only a small proportion of what has been published has been intended for amateurs. An amateur who wishes his meteor work to have some value other than its own interest will almost certainly have to apply photographic methods, for the visual field is largely worked out now. In any case meteor photography has attractions of its own, not the least being the strong sporting element introduced by the chancy nature of the results.

PHOTOGRAPHY

It is less than twenty years since meteor photography became a fruitful technique even for the professional astronomer; but with the war-time development of fast wide-field lenses for nocturnal aerial photography and the post-war formulation of very fast emulsions, the meteor observer was given instruments and materials equal to the very severe demands of his work. The more recent design of special Schmidt cameras has enabled meteors to be photographed down to the fourth magnitude, but although these instruments are beyond the reach of the ordinary amateur he can, by using lenses readily available at low cost, record meteors as faint as second magnitude. This limit will give a substantial yield whenever the hourly rate of the meteors is high—that is, during the maxima of the major annual meteor showers.

A meteor camera can be reduced to the basic requirements of any camera: a box with a lens at one end and a plate at the other. The lens must be fast; anything slower than $f/2{\cdot}5$ is of little use. The effectiveness of a lens for meteor work is proportional to the product of aperture and the reciprocal of the focal ratio; of two equally fast lenses, the one with the larger aperture will give better results. A wide field must be covered in reasonable definition, but the standard required of the latter is less exacting than for most astronomical purposes; in particular the axial definition need not be first-class, and has to be sacrificed to some extent to achieve acceptable performance in the outfield. These requirements are well met by many aerial lenses that can be bought for a few pounds on the surplus-goods market.

Of all such lenses the one that has given the best service in my experience is the Kodak Aero-Ektar. This comes in two sizes: one of 7-inches focal length and the other of 12-inches, both working at *f*/2·5. These are seven-element lenses, the later ones being hard-coated, and some of their speed is lost by absorption, but even so they are superior to any others that have been given long-term trials. A slower lens that runs the Ektar fairly close is the Ross Xpres Wide Angle of 5-inches focus, and although it works at *f*/4·0 it gains by greater transmissivity and excellent marginal definition on a 65° field.

The camera body must be really rigid, and although wood is easier for constructional purposes, metal is to be preferred—the best procedure is to buy the aerial camera complete and adapt the body to take the largest plates that can be used. The plates should be big enough to accept the whole circle of illumination of the lens, which means using whole-plates or even 10 × 8 inch. These plates are expensive, but the increased yield reduces the cost per meteor photographed—a specious argument, of course, if one cannot afford them.

The fastest panchromatic emulsions are the best to use, though we have to consider not only speed, but also "reciprocity failure" and "spectral response". Reciprocity failure is a serious disadvantage when making long exposures on faint objects such as nebulæ and comets, but it is all to the good for meteor work, for it suppresses the build-up of sky fog without impairing the speed of the plate to the momentary exposure presented by a meteor.

The most successful plates that I have used are Ilford HPS. Kodak Royal X Pan have been tried, but they are in no way superior to HPS, and they suffer from the fact that they are not readily available in large plate sizes. High-speed oscillograph recording paper gives results comparable with HPS, but it is

blue-sensitive and not suitable for spectrography, and the difficulties introduced by paper negatives leave their cheapness as the only advantage.

Whatever the emulsion used, it should be fully developed with a vigorous contrasty developer. Excellent results are given by Kodak D19b, an X-ray film developer, and its Ilford equivalent. Normally the plates are given seven minutes development at 15°C (68°F).

So far no mention has been made of the 35 mm camera, which may seem to be the obvious thing to use if it has a very fast lens. I have never possessed one myself, but there is no reason why such a camera should not give good results. Many splendid meteor photographs have been taken with them in the U.S.A., but for some unknown reason nobody in Great Britain seems to have had much success—clearly there is an opportunity here for somebody to do some useful work.

Focusing and squaring-on are carried out in the usual way as for any astronomical purpose, and accurate focusing is of great importance, for without it many of the fainter meteors that make up the bulk of the bag are lost. It should be noted, however, that if the lens has any slight field-curvature it is better to sacrifice the central definition to some extent, for very few meteors are photographed at the middle of the plate.

One small addition to the basic camera is really indispensable—a heater to prevent dewing of the lens. This can consist of part of an ordinary electric-fire heating spiral mounted round the front of the lens and run either through a transformer from the mains or by a 12-volt car battery. The current need not exceed ½ ampere—the least value is soon found by experience. A large lens-hood should be fitted to keep off stray light, and this will also reduce the danger from condensation if it is suitably lined.

If no power-driven equatorial mounting is available the camera may simply be propped up in the required direction, taking care that it cannot be vibrated by the wind. It should be supported above ground level, where it is less likely to be kicked over, and should be painted white for easier visibility in the dark. Avoid trailing cables where they may be tripped over. A driven camera does not get more meteor trails than a stationary one, but the subsequent measurement and reduction of the plates is a great deal easier; also one may go indoors to warm up or to take some refreshment while the exposure is going on, but this should be avoided as far as possible and a visual watch should be kept on the field while the camera is operating.

Another adjunct that may usefully be added is a rotating occulting shutter, driven either by a synchronous motor or a non-synchronous motor in conjunction with a stroboscope or some other device by which the speed can be accurately controlled. The motor mounting must be independent of the camera body to avoid vibration, and for the same reason the bearings must be in good condition, the shutter disk accurately centred and the blades perfectly flat. The shutter will chop a meteor trail into a number of distinct segments, and from the speed and dimensions of it the duration and angular velocity of the meteor can be determined. Any persistent wake of the meteor will cause the shutter-breaks to be partly filled in—this led to the discovery of the "faint-meteor anomaly" at Harvard. The shutter will also reduce sky-fog on the plate, because the effective exposure time is less, but the effect is not pronounced (see Fig. 27).

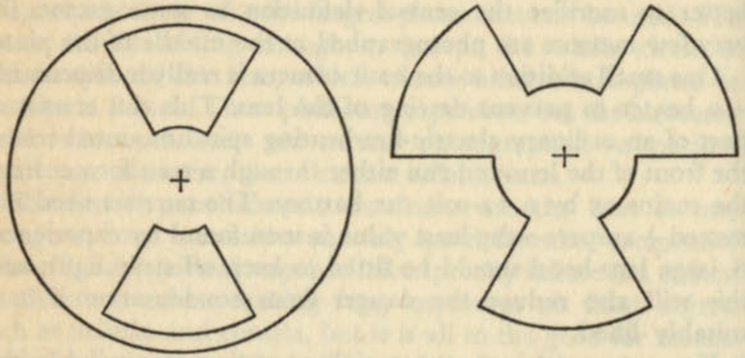

Fig. 27. Two forms of rotating shutters. One large multiple-bladed shutter can be arranged to occult several cameras on one mounting.

Exposures are best restricted to nights when a meteor shower is known to be active—work on sporadic meteors is apt to be somewhat heart-breaking, and I have come to the conclusion that the results rarely justify the effort and expense. Only the Super-Schmidt cameras can make this type of work really worthwhile.

When photographing a known meteor shower the camera should be pointed towards the radiant, for not only is there a concentration of meteors in this region but their angular velocity is less and the likelihood of recording them correspondingly greater. If the radiant is at a low altitude it may be necessary to aim above it to avoid the lower half of the plate taking in the horizon and the region of heavy absorption immediately above it.

The useful length of an exposure depends largely on the sky conditions. Using HPS plates with an $f/2{\cdot}5$ lens, exposures of an hour or more can be made without undue fogging provided that the sky is really dark, but even a small amount of twilight, moonlight, haze or reflected town-lights reduces this drastically. If clouds drift over the field the lens should be covered unless the sky is free from scattered light. Exposures of more than an hour with stationary cameras should be avoided because the star-trails run into each other, and measurement and reduction become very difficult.

Visual monitoring of the exposures is essential with stationary cameras and desirable even when the camera is driven. In the former case, the time of beginning and end of the exposure and the time of appearance of any meteor likely to have registered on the plate must be recorded with the greatest possible accuracy. The visible track of the meteor with respect to the background stars should also be noted, either by one of the methods used by the B.A.A. for visual meteor recording, or by plotting directly on an atlas or a prepared chart of the field. Many potentially valuable results have been discarded because it has not been possible to identify the trail on the plate with any recorded meteor; a trail cannot be reduced if the time of appearance is not known.

When the camera is driven, visual records are still of value, as it is useful to know the visual equivalents of photographed meteors. It is a useful—and sometimes humiliating—exercise to compare the photographed trail with the visually recorded track, and to know from experience how bright a meteor must be to yield a trail on the plate. Meteor cameras are equally suitable for photographing artificial satellites which, together with aircraft, are apt to produce trails that can easily be mistaken for meteor images.

The technique of observation giving the greatest amount of useful information is accordance work by two or more cameras separated by a baseline of 15–60 miles. When a meteor is photographed from two such stations the true path in the atmosphere, and the radiant, can be derived, and if rotating shutters have been used the geocentric velocity can be measured and the space orbit computed. Unfortunately this is the most difficult type of work for amateurs to do, for it involves the co-ordination of exposure times and directions, and requires simultaneous good skies at both stations. It is surprising how rarely these conditions can be fulfilled; in the visual field, for example, Alcock and Prentice had to wait for twenty years before they were able to get one good night of accordance work on the Quadrantid shower, observing from Peterborough and Stowmarket respectively. This is an extreme case, but the fact is that very little of this kind of photographic work has been done by amateurs in Great Britain.

Single-station work can produce results that enable the radiant of a shower to be determined with accuracy and certainty, and most of the B.A.A. photographic work has been directed to that purpose. There is still plenty of work to be done on light-curves, colour-index and persistent trains, and there is much room for experimentation with improved instrumentation and observational techniques.

SPECTROGRAPHY

Most meteor photographers will wish to try their luck at spectrography, for it requires only one addition to the equipment and can produce results of unquestionable scientific value, though at the cost of more time, money and patience. A recent survey of world meteor spectra by P. M. Millman gives the following scores for various countries:

Canada	252
U.S.S.R.	116
U.S.A.	72
Great Britain	28
Czechoslovakia	25
Others	3
World Total	496

The British contribution has been entirely the work of amateur members of the Meteor Section of the B.A.A. during the past eight years. The light of a meteor gives a bright-line emission spectrum, and as the image of a meteor on the plate is linear, a dispersing unit in front of the lens will produce a series of parallel images corresponding to the various wavelengths of the emitted light. A direct photograph of a bright Perseid meteor and its corresponding spectrogram are illustrated on Plates 18 and 19. There are two means of producing the required dispersion: objective prisms and transmission diffraction gratings. Each has its advantages, but for the amateur it is mainly a question of what he can get—prisms and gratings are usually rather expensive.

The great problem in meteor spectrography is to obtain sufficient dispersion while retaining the wide field and high speed needed to obtain an effective number of results, and unless impossibly large plates are to be used, short focus lenses must be retained. This means that the prism or grating must give the maximum dispersion itself. In the case of a prism the refracting angle should be large, but this in turn leads to excessive absorption at the thick end, and the best compromise is an angle of about 30°, the glass being dense flint. The 7-inch focus Ektar needs a prism 4 inches square to cover it, but the 12-inch calls for a 6-inch prism; a formidable item. The little Ross Wide Angle lens is less demanding, needing only a 2½-inch square prism-face to cover it, and some good spectra have been secured with it. An indication of the performance of the 7-inch Ektar is given by the spectrum of the Taurid meteor on Plate 20; the original image is 6 mm wide and 25° off axis.

If a grating is used, it should have 5000–10,000 lines per inch and be blazed to throw most of the light into the first order and the blue end of the second order. In general, the loss of light in a grating is less at high dispersion than in a prism of the same performance, with the added advantage that the dispersion is almost linear, thus making the reduction easier and above all avoiding the compression of the red end of the spectrum inseparable from the use of a prism. Good replica gratings of fair size can now be obtained at reasonable prices, and it is likely that gratings will supersede prisms in most future work on meteors.

There is no point in driving meteor spectrographs; they are always used on stationary mountings. The trailed star spectra rarely cause any trouble, and are useful as references for reduction. Orientation of the spectrograph in relation to the flight direction of the meteor is of great importance, for if that direction is parallel to the direction of dispersion, the lines will be superimposed on each other; the ideal case is to have the meteor travelling at right-angles to the dispersion. If the angle between the meteor track and the dispersion is θ the separation of the lines is proportional to sin θ. The effect of the inclination is shown in the Taurid spectrum on Plate 20, the angle in this case being 65°; the Perseid meteor was even more favourably placed.

In the case of sporadic meteors one can have little idea as to their probable direction of flight, but experience shows that the brighter ones tend to descend at steep angles, and for these the refracting edge of the prism, or the lines of the grating, should be vertical. When a shower is being observed, the position of the radiant is known and the flight-directions of the meteors can therefore be anticipated. The best results are obtained when the radiant is just off the plate to one side, as shown in Fig. 28.

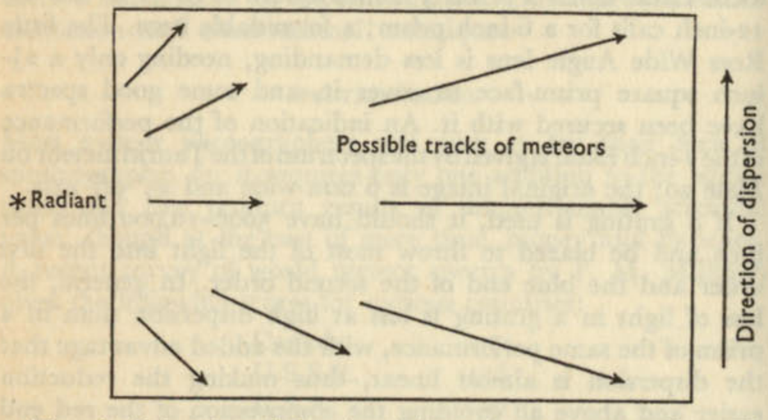

Fig. 28. *Orientation of plate in relation to known meteor radiant. The meteors are bound to move at a reasonably favourable angle to the dispersion.*

When pointing the spectrograph in the desired direction it must be remembered that the path of the light is deviated by

the dispersing unit, and one must aim off to compensate for this. My method is to put in an old plate, keeping the back of the camera open, and point the spectrograph at the Moon so that the image is central on the plate, then adjust an open bead-sight on the camera-body until it is aligned directly on to the Moon. Then if one sights on to a particular star, that will be at the centre of the plate. If the prism or grating is mounted so that it can be rotated, the sight must be on the moving part of the mounting. The optical paths and positions of the dispersing units are shown in Fig. 29.

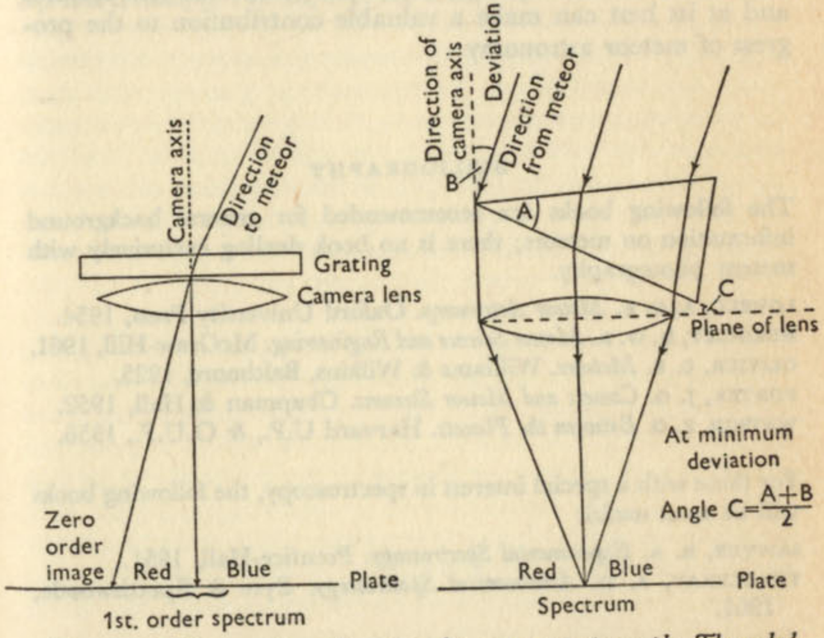

Fig. 29. Left, *mounting of grating for meteor spectrograph. The ruled surface is next to the camera lens.* Right, *position of prism for meteor spectrograph. Although set for minimum deviation of Sodium D, the angle is not critical for this type of work.* (*In both diagrams the outline of the camera lens is purely symbolic.*)

With an *f*/2·5 lens, a 30° prism and an HPS plate, the faintest meteor that will give a useful spectrum is of magnitude −1, depending on the spectral distribution of the light and the angular velocity of the meteor. Clearly, one cannot expect to get many spectra, and in fact I have found that an average of twelve hours of exposure has been needed for one spectrum, but until recently a great many of the exposures were on non-shower nights, and if work was restricted to shower nights only, the average would probably be about eight hours per spectrum. A rotating shutter may usefully be employed with a meteor spectrograph in order to record the spectrum of the meteor wake if it has one.

Meteor spectrography and photography provide the amateur with an interesting, challenging and rewarding discipline which at the very least can produce some rare and beautiful pictures and at its best can make a valuable contribution to the progress of meteor astronomy.

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Chapter Fifteen

THE AURORA

James Paton

The light in the night sky that we call aurora is emitted mainly by the atmosphere itself at heights over about 100 km above the Earth's surface. It is caused by the entry into the upper atmosphere of a fast stream of charged particles consisting mainly of protons and electrons, originating in the Sun. It is the bombardment of the atmospheric gases by this solar stream that causes them to emit visible light. The process is similar to that which occurs in the sodium and mercury discharge tubes used, for example, in street lighting. At the low pressures existing in the upper atmosphere (and in the discharge tubes) certain gases can be stimulated to emit light when submitted to bombardment by fast moving particles.

The Colour of Auroral Light. The colour of the emitted light is characteristic of the gas itself; sodium light seen in discharge tubes, for example, is yellow. Spectroscopic examination shows that auroral light is emitted mainly by atomic and molecular oxygen and nitrogen. A predominant line in the spectrum is in the green (5577Å) and is emitted by atomic oxygen. Red light may also be emitted by atomic oxygen, while molecular nitrogen may contribute to the spectrum in bands both in the red and the blue. The observed colour of the aurora at any point in the sky depends on which of the atmospheric gases there are stimulated to emit light. Very frequently, the brightness of the emitted light is below the threshold of colour perception of the eye so that the aurora appears as greyish-white. Colour is perceptible therefore only in brighter auroræ. If, in a particularly bright and active aurora, the red, green and blue emissions occur together, all combine to give the impression of a bright white colour. The auroral spectrograph disperses the light into its constituent lines and bands, whose origin can be identified by comparing them with the spectra of different gases produced

in the laboratory. Aurora thus serves as a natural probe for investigating the composition of the atmosphere at the levels where its light is emitted.

The Geographical Distribution of Aurora. Aurora is not seen uniformly over the whole globe. It is observed, however, on almost every clear dark night in two circular zones (one in the northern, the other in the southern hemisphere) centred on the Earth's magnetic poles and at an angular distance of 20° to 25° from them. The northern auroral zone is situated just south of Greenland and Iceland, in the extreme north of the North American Continent and just to the north of the northern seaboard of the Eurasian continent. The regions on the equatorial side of the auroral zones are known as the cis-auroral zones, while those on the polar side, over the polar cap, are called the transauroral zones.

Since aurora occurs at a height of over 100 km, it may be visible in clear conditions at a distance of over 1000 km from the place where it is overhead, which is, normally, in the auroral zones. In the cis-auroral zones, it is therefore seen usually as a glow, resembling dawn, on the poleward horizon. The glow is simply the top of the display which is at a sufficiently great height to project above the cis-auroral observer's horizon; the main portion of this display can be seen only by observers in and nearer the auroral zone, where the display is overhead. The name aurora borealis or northern dawn was first used by the French philosopher, Gassendi (1621), and is an appropriate description of the usual appearance of the "northern lights" when they are observed in cis-auroral latitudes. Later the "southern lights" were called aurora australis.

The Cause of the Geographical Distribution of Aurora. It is the magnetic field of the Earth which is responsible for the concentration of aurora into the two zones. When a stream of charged particles moves into a magnetic field, the particles are constrained to move either directly along the lines of force or to travel along and around the lines of force in a spiral movement. The lines of force of the Earth's magnetic field terminate at the north and south magnetic poles, so that any incident stream of charged particles will suffer deflection towards the poles and will arrive at the levels at which aurora is excited in high latitudes. (It is now known that incident charged particles remain trapped for a time by the Earth's magnetic field in the radiation belts, whose existence was first discovered during the IGY from the recordings of the Geiger counters carried by the American satellite Explorer I. Eventually the particles must escape from the horns of the belt, which project down towards the auroral zones. The influence of the radiation belts in determining auroral characteristics is not yet understood.)

Aurora, however, is not always confined in or near the auroral zones. At times of great solar activity, generally following the occurrence in the Sun of a great flare or eruption, aurora becomes visible in latitudes often far below the auroral zones; on rare occasions it has been seen in the tropics. Exceptional occurrences of this kind invariably occur near the time of maximum in the 11-year sunspot cycle. The last maximum occurred in 1968–9. Around the period of sunspot minimum aurora seldom extends far from the auroral zones. The next minimum is expected to occur in 1975–6.

The Appearance of Aurora. In the cis-auroral regions, aurora is most frequently seen merely as a glow on the poleward horizon (Fig. 30*a*); the glow is simply the upper portion of a display, which is overhead in or near the auroral zones. It is only when aurora moves equatorwards at times of great solar activity that observers in the densely populated regions of middle latitudes

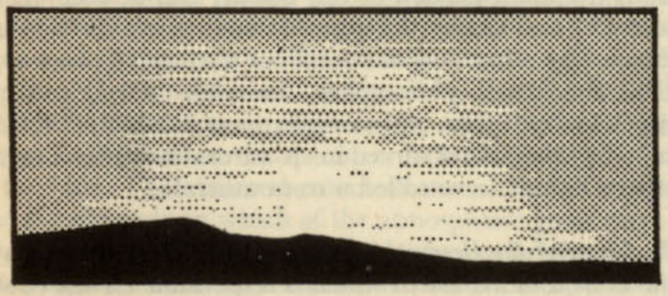


Fig. 30a. *Aurora Borealis means "northern dawn". This name was given because from middle latitudes it most frequently appears as a dawn-like Glow along the northern horizon. The word "glow" is to be used only when the auroral light is down on the horizon (qHN).*

see those parts of the display which, being below their horizon, are so frequently concealed from them. Aurora now belies its title. No longer is it an unspectacular glow on the horizon, like dawn; it is now more aptly called "the Merry Dancers", the name by which it is known in the northern isles of Britain.

It is quite impossible to predict the course that will be followed by any particular display, but a great display not infrequently exhibits a fairly well-defined sequence of events.

The display may begin with the usual glow along the poleward horizon. The glow then ascends from the horizon to form a quiet *arc* (Fig. 30*b*) extending in the form of a regular bow in an approximately E-W direction. The lower border of an arc is usually much more sharply defined than the upper border. An arc may remain quiescent for hours, drifting slowly northwards or southwards. Suddenly it may brighten here and there along its length and become still more sharply defined at its lower border, while *rays* begin to shoot upwards at right angles to its length (Fig. 30*c* and Plate 21). The arc is then likely to fold and so to lose its regular bow shape and to form an irregular *band* (Fig. 30*d*). If the rays are very long, the band assumes the appearance of a great drapery, waving like a curtain in the sky. If the rays extend overhead, they appear to converge towards a point. This indicates that the rays are parallel, the apparent convergence being the effect of perspective. The direction of the

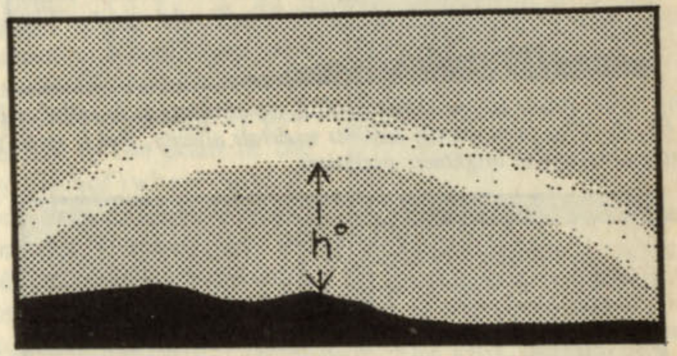


Fig. 30b. *Aurora often takes the form of an Arc (A) extending east-west across the sky. There is an area of clear sky below the lower edge, which is usually more clearly defined than the upper edge. When an arc has no vertical ray-structure it is called a Homogeneous Arc (HA).*

rays lies along the lines of force of the Earth's magnetic field. As the display dies down, waves of light may surge upwards from the horizon in quick succession, causing existing auroral forms to brighten as they pass over them. This is called *flaming*. At this phase of the display a continuous glow may extend over a large part of the sky (*veil*), serving sometimes as a background to the active forms; at other times diffuse *patches* (Fig. 30*e*) of light closely resembling clouds appear here and there.

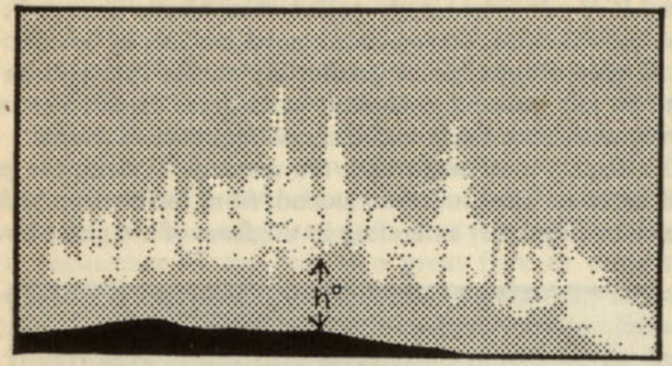


Fig. 30c. *When an arc shows vertical ray-structure it is called a Rayed Arc* (R_1A). *This form usually exhibits moderate activity, that is small movements and irregular brightness variations.*

Fig. 30d. *When a band shows ray-structure it is called a Rayed Band* (R_1B). *If the rays are long it may resemble a curtain or drapery waving in the sky.*

The cause of the various shapes assumed by aurora remains largely unexplained. Since auroral rays always lie in the direction of the lines of magnetic force, it seems likely that rays are the visible manifestation of the incidence of a concentrated stream of fast charged particles. As the particles move down the lines of force, they encounter denser air as they approach auroral levels and cause the air to emit light before they are slowed down by collisions; they leave a line of emitting atoms and molecules in their wake. When there is a bundle or cluster of long rays close together, then, since all are aligned along the lines of magnetic force, they are parallel to each other and so appear to converge by perspective to the point in the sky (Fig. 30*f*) where the magnetic lines of force intersect the celestial sphere, i.e. the point in the heavens to which the axis of a freely suspended magnetic dip needle would point. This point is known as the magnetic zenith, and

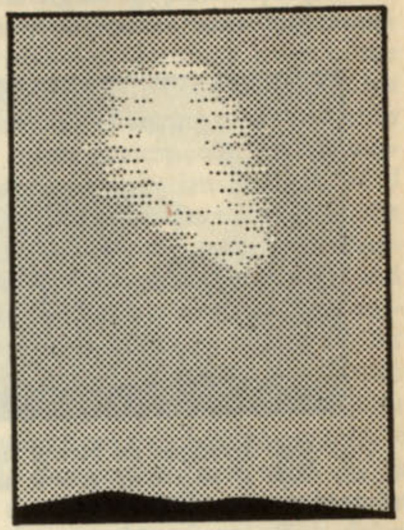


Fig. 30e. *Sometimes there are patches of auroral light without distinct boundaries, in clear sky* (*so that it is not the effect of obscuring clouds*) *and well up from the horizon* (*so that it is not a Glow*). (*HP*)

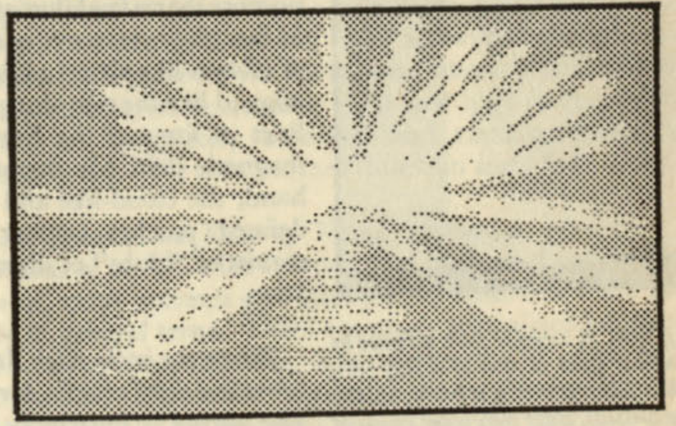


Fig. 30f. *When rays or other forms pass overhead, perspective causes them to converge to a point to form a crown or corona.* (cR_2R).

the shape assumed by the cluster of rays resembles a crown or corona. In those parts of the cis-auroral regions where aurora is likely to be seen, the magnetic zenith is situated about 20° on the equatorwards side of the true zenith.

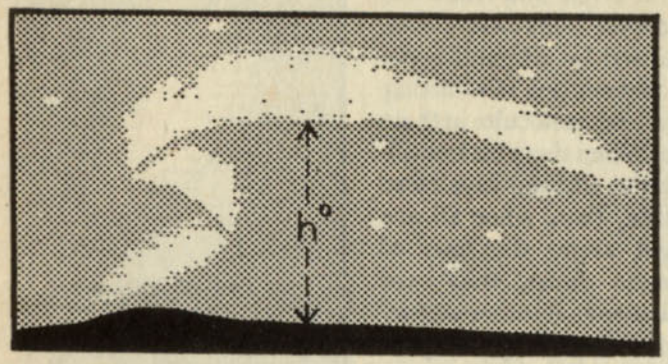


Fig. 30g. *Sometimes the auroral light forms a Band (B) without the regular shape of an arc. If there is no ray-structure in it this is called a Homogeneous Band (HB).*

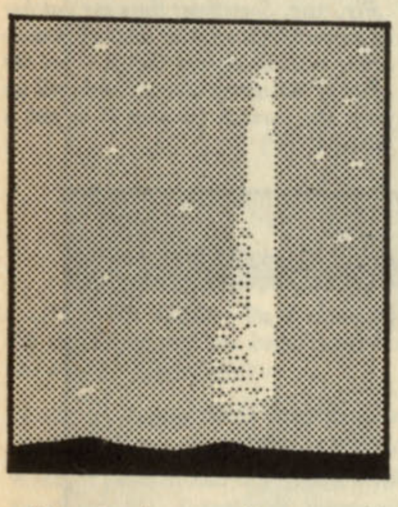


Fig. 30h. *A common form assumed by the auroral light is that of a Ray (R), which is like a searchlight beam, usually nearly vertical. Rays may occur singly or in bundles.* (R_2R).

When arcs and bands have been observed to pass overhead, it is seen that their width (transverse to their length) is usually quite small, sometimes no more than a few kilometres. In fact, they are seen to consist of ribbon-like sheets of light, aligned like the rays along the lines of force of the Earth's magnetic field. On the other hand, the cloud-like and ill-defined patches appear to consist of "blobs" of illumination.

Phenomena in the High Atmosphere Associated with the Aurora. The aurora is invariably accompanied by other observable events that are produced by the same cause, namely the entry into the upper atmosphere of a stream of charged particles. The solar stream of particles ionizes the air through which it passes; that is, it removes electrons from the atmospheric atoms and molecules. This increase in the electrification at auroral levels in the upper atmosphere increases the electric current systems that are caused to flow there. The continually changing magnetic fields associated with these varying upper atmospheric electric currents are strong enough to produce perturbations in the trace of a magnetometer, recording the Earth's magnetic field at the Earth's surface. This association between the aurora and magnetic disturbance has been known for over two centuries, and the onset of such disturbance in the Earth's magnetic field during the day has served as a warning to observers to look out for aurora on the succeeding night. The magnetic disturbance during a great aurora is so intense as to be called a *magnetic storm.* At the same time, induction from the changing magnetic field causes electric currents to flow in the Earth itself. These *earth currents* may flow under a potential difference as high as 1 volt per kilometre, and have been used to trigger off an alarm bell and so to arouse an observer at the onset of an aurora.

A further effect of the great increase in ionization of the upper atmosphere (the ionosphere) is the fade-out, or black-out, of radio communications. Since radio waves travel in straight lines, long distance radio-communication is possible only because of the existence of reflecting layers in the ionosphere. The source of auroral light lies within the ionosphere, and during a great aurora the concentration of electrons in the ionospheric layers becomes so great that high frequency radio-waves are completely absorbed and radio communication breaks down. This is sometimes called an *ionospheric storm.*

The Purpose and Value of Visual Observations of Aurora. The relations of aurora with sunspots and flares and with magnetic storms, earth currents and ionospheric disturbance are known only in general terms. There are many specialized problems in the study of these relations, the investigation of which requires the detailed information of auroral characteristics that can be supplied only by the practised visual observer. Certainly the all-sky camera, operating automatically, can provide a more complete record of an extensive display than can be noted by the visual observer, but this camera has serious disadvantages. It does not record the varied effects of pulsing, which will be described later, and features in rapid motion appear blurred and unrecognizable. Diffuse forms like patches and veil are not easily recognized on an all-sky film. Visual observations are therefore an essential supplement to the records of an all-sky camera.

The purpose of the visual observer is to record as fully as possible the nature and course of each display. Observers must become familiar with the appearance and characteristics of the different auroral forms so that they may quickly identify and record these forms during a display. But if their report is to be of scientific value, then the observations must be made according to a definite plan and reported in a systematic manner. The system of auroral observation which has been adopted internationally since 1964 is outlined in the paragraphs that follow.

The Method of Reporting Auroral Forms and their Characteristics. The visual observer must first identify the auroral forms that are present at the time of observation recorded to the nearest minute of U.T.

The form is simply the general outline or shape of a particular auroral feature. In reporting forms and their characteristics, it is convenient to use symbols, usually the first letter of the name of the form or characteristic.

(a) The Forms have been described in an earlier paragraph and are illustrated by the sketches.

The forms are:	Arc	A	Figs. 30*b* and *c*
	Band	B	Figs. 30*d* and *g*
	Patch	P	Fig. 30*e*
	Veil	V	A continuous glow, not readily illustrated.
	Rays	R	Fig. 30*h*

Sometimes an observer may be well aware that an aurora is present but it may be impossible to identify its form because of extensive cloud cover, moonlight, twilight, etc. This difficulty may also occur when the identifiable parts of the display are

below the horizon and only a diffuse glow appears above the horizon (Fig. 30*a*). It is then convenient to use the symbol N signifying "not identifiable".

Once the observer has identified the forms he may add further information concerning the nature and behaviour of each form by appending symbols before and after the symbol denoting the form.

(b) The first of these refers to Structure of the form and is placed immediately before the symbol representing form. Two kinds of structure are defined here—

1. *Homogeneous*—H. The brightness of the form is uniform, e.g. Fig. 30*b* represents a homogeneous arc, HA, and Fig. 30*g* a homogeneous band, HB.

2. *Rayed*—R. Rays aligned along the lines of force of the Earth's magnetic field appear within the form. Subscripts may be used to indicate the length of the rays. R_1, R_2 and R_3 represent, respectively, short rays, rays of moderate length and long rays. Fig. 30*c* shows a rayed arc, R_1A, and Fig. 30*d* a rayed band, R_1B, each with short rays.

(c) One or more of three Qualifying Symbols may, when relevant, be placed immediately before the symbol representing structure.

1. *Multiple*—m. Two or more forms of the same kind appear together, e.g. m_2HA signifies two parallel homogeneous arcs.

2. *Fragmentary*—f. Only a portion of an arc or band is present, e.g. fRB signifies a fragment of a rayed band.

3. *Coronal*—c. When any rayed form is viewed in the direction of the lines of magnetic force, i.e. when it is situated in the magnetic zenith, the rays appear to converge and to assume the shape of a fan or crown (corona). Fig. 30*f* shows rays of medium length forming a corona, cR_2R. See also Plate 21.

(d) Condition describes the behaviour of a form or of the whole of a display and is represented by one of three symbols preceding all the other symbols.

1. *Quiet*—q. A quiet form is one that undergoes only very slow changes in position or shape, e.g. qHA, a quiet homogeneous arc, may remain stationary for some hours.

2. *Active*—a. An active form is one which moves or changes its shape rapidly. A rayed band is generally active, aRB.

3. *Pulsing*—p. This describes a condition of fairly rapid and

often rhythmical fluctuation in brightness. Two kinds of pulsing may be seen in displays in middle latitudes, e.g. in the British Isles.

(i) *Pulsating*—p_1. The affected form displays a variation in brightness, the phase of which is uniform throughout the form. It may be displayed for example by a fragmentary arc, p_1fHA, when the brightness and length change rhythmically, or by a patch, p_1HP, when its brightness and area show similar variations.

(ii) *Flaming*—p_2. This kind of pulsing extends over a large area of the sky, which appears lit by surges of light sweeping upwards over it. The brightness of existing forms waxes and wanes as the waves of flaming pass over them. Though the name suggests red coloration, flaming is usually colourless. It commonly occurs in the late stages of a bright and active display.

Brightness and Colour. The brightness of an auroral form is given in terms of the following scale:

1. Weak, comparable with the Milky Way.
2. Comparable with moonlit cirrus clouds.
3. Comparable with cumulus clouds.
4. Much brighter than 3.

Colour is recorded using the following symbols:

a. Only upper portion of form red.
b. Red lower border.
c. White, green or yellow.
d. Red
e. Red and green.
f. Blue and purple dominant.

The symbols for brightness and colour follow immediately *after* the symbol for form, e.g. RB2e signifies a rayed band of brightness 2 and red and green colour.

The Use of the Symbolic Notations in Reporting Auroral Forms and their Characteristics. The Table shows the symbols that have been defined in the foregoing paragraphs, arranged in colums in the order in which they are used in reporting

Table 3

Condition	Qualifying Symbols	Structure	Form	Brightness	Colour
q	$m_{2,3,}$ . .	H	A	1	a
a	f	$R_{1,2,3}$	B	2	b
$p_{1,2}$	c		P	3	c
			V	4	d
			R		e
			N		f

An example of the full use of these symbols to describe an auroral form is

acfR_2A3e

This signifies a fragment (f) of an active (a) red and green (e) rayed arc (R_2A) of brightness 3, whose rays are of medium length (R_2) and form a corona in the magnetic zenith (c). It will be observed that ambiguity resulting from the use of c (which represents both coronal and a colour class) is avoided by the position in which these symbols appear in the sequence.

An observer may not have the time, or even the inclination, to give his report in this detail. He may restrict himself to giving only the most important parts of the information, namely the form and its brightness, RA3, or may add any further detail, say fR_2A3e, that he has the wish and time to record.

The system of notation has in fact been devised so that it is as nearly competent as is possible to describe all the varied character and behaviour of auroras that may be observed and yet may also be abridged to any extent to meet the conditions of the observer and the requirements of the organization to which he is attached.

The Actual Report of an Auroral Display. The name and position of the station and the date of the observations (always specified by two dates whether or not the observations are all before or all after midnight) are given at the top of each sheet of observations.

The forms existing at each particular time of observation given to the nearest minute U.T., are entered against the time as in the example below. The interpretation of the symbols is given beside the report.

1964 March 15–16 Station X	56°50′N 3°10′W	
2020 U.T.	qHN1 ↗ 15°	Glow of brightness 1 on horizon extending to an elevation of 15° above the northern horizon.
2035	qHA2 h=10°↗28°	Quiet homogeneous arc of brightness 2 with the highest point of its lower border at elevation 10° and the highest point of the upper border at elevation 28°.
2042	R_2A3 h=15°↗40° HP2 50°↗65°	Quiet arc has changed to active rayed arc of brightness 3, lower border at 15°, upper border up to 40°; also a patch of brightness 2 between elevations of 50° and 65°.

and so on.

The stated angles refer to angular elevation of the form above the north horizon (or S. horizon in southern hemisphere). These are measured using an alidade, supplied by the organization for which the observations are made, or they may be roughly determined using an ordinary foot rule. When held vertically at arm's length, the rule subtends an angle of about 25° at the eye, so each inch corresponds to about 2°. When the elevation refers to that of the highest point of the lower border of an arc or band (Figs. 30*b*, *c* and *g*) the symbol h is used. This is a very important measurement, since it enables the precise geographical position of the arc or band to be determined from the fact that the height of the base of arcs and bands is almost invariably within a few kilometres of 100 km.

Chapter Sixteen

OBSERVATION OF DOUBLE STARS

M. P. Candy

The observation of double stars is a particularly fascinating business for the observer. It is an exacting pursuit, making considerable demands on his patience and skill. It can give great satisfaction, too, to find good internal agreement between one's measures made on different nights, or between another observer's measures and one's own. There is, of course, no reason why an observer should not make a few casual measures of double stars for his own interest. However, if he would like to make a real contribution to astronomy it is essential that he should make many measures over a period of *some years*. One professional astronomer has said that a double star observer's results cannot be trusted until he has made a thousand observations. The writer thinks this is an exaggeration, but at least a hundred or so measures would be needed to allow a judgement to be made.

It is as well to be frank about the potential contribution of the amateur astronomer to this field. The instrumental needs are rather exacting in that for good observations the telescope should be accurately equatorially mounted, preferably with a clock drive. The aperture of the telescope should not be less than about 6 inches, and could be 12 inches or more with consequent improvement in the results. It is also necessary to have a measuring device, usually a filar micrometer.

Double star astronomy is at least as important today as ever it was. After all, a high proportion of all stars are involved in binary or multiple systems. Current advances being made in the study of stellar evolution and structure lean heavily upon the double star measures made in the past. Perhaps the most important "raw materials" for the astrophysicists are the masses of the stars and these are provided primarily by studying those double stars whose orbits can be calculated.

A considerable debt is owed to the early observers of double stars, particularly the Herschels, William and John, and the

Struves, F. G. W. and Otto, and nearer our time people such as Burnham and Aitken. Amateur astronomers were active in this field, too, and from a long list two names, Dawes and Dembowski, stand out from the rest. Both used small telescopes, in the range 4- to 8-inch aperture, and, because of the great care and skill with which they made their measures, their work compares quite favourably with that achieved with much wider apertures during the same period.

The Telescope. There is currently a shortage of observers of double stars, and there is plenty of scope for the amateur to work in this field. But he must exercise quite as much stubborn perseverance and attention to detail as the professional, if he wants his results to be accepted.

On the average it is the closest double stars which have the greatest interest and importance. Therefore the larger the aperture of the telescope used the better. The usual competition between refractors and reflectors exists in this field as in most others. Given identical observing conditions, Van den Bos states that a reflector must have fifty per cent greater aperture to give comparable results with a refractor. That is, an 8-inch refractor will give as good results as a 12-inch reflector.

The limit of separation for a particular aperture was determined observationally by Dawes for refractors, and is given as $\frac{4''\cdot 56}{a}$, where *a* is the aperture in inches. Dawes' limit applies to a pair of 6^{m} stars; fainter pairs will have a higher limit, and so will those pairs where the components have a large difference in magnitude. Values other than $4''\cdot 56$ have been suggested for the numerator in Dawes' limit, but we find Dawes' limit satisfied exactly by the 28-inch refractor, at the Royal Greenwich Observatory, Herstmonceux, with which it has been possible to measure a few pairs as close as $0''\cdot 16$. For any particular telescope the most reliable measures are made for separations which are two or more times the limiting separation.

The telescope should have a variety of eyepieces so that a power suitable to the "seeing" can be chosen. It pays to have some provision for changing the eyepieces quickly, usually by having them all fit the same holder with a push-fit. One does

not want to be pestered with "crossed threads" during the excitement of a period of good seeing.

With the 28-inch the powers most frequently used are (including ×2 for a Barlow lens) ×400, ×700, ×1400. These powers are respectively 15*a*, 25*a*, 50*a*, where *a* is the aperture in inches. There are higher powers, 70*a* or 80*a*, which could be used, but on those rare occasions when the seeing is good enough to use them they show little advantage over the power of 50*a*. Pairs at the limit of separation can be measured with 50*a*.

Astronomical seeing is a very difficult thing to describe, but any observer habitually using high powers will soon become familiar with all its aspects. Ideally the image of a star seen in the eyepiece of a telescope should be a small disk (the Airy disk) surrounded by concentric rings. When the seeing is good the brighter stars have this appearance. In general, with fair seeing, a star image appears as a small blob with a nucleus. If the seeing is bad then the nucleus disappears and the size of the blob increases. On some nights variable seeing occurs and one has fleeting glimpses of a nucleus. When measuring double stars such glimpses can be very useful. A setting is made as the result of one glimpse and checked at the next glimpse, altered if necessary and checked again and so on. If the glimpses occur at wide intervals this sort of measuring certainly taxes the endurance of the observer. It has to be a most fascinating binary to merit this attention. It is easy to make measures when the seeing is good, but this is not often. If one defines a good night on the 28-inch as being one where it is possible to measure at least one pair with a separation of $0''\cdot 5$, then there are about fifty good nights in a year. It is a waste of time to make measures when the nuclei are invisible. The poor results which follow will do more harm than good.

Bad seeing is generally caused by atmospheric turbulence, somewhere between the upper limits of the atmosphere and the housing of the telescope. But the observer should also beware of turbulence due to the existence of dome-currents, tube-currents and, in the case of Newtonian reflectors, observer currents. Some of these effects can be reduced by opening the dome sometime before starting to observe. This allows the temperatures of the dome and telescope to get nearer to the outside temperature.

It is interesting to try and correlate the state of the seeing with the time of day or the weather conditions. At Herstmonceux, experience shows that quite often there is an hour after sunset when the seeing is good. On the other hand we hardly ever get good seeing when there is a north-east wind. So far as general weather conditions go, anticyclones usually give the best seeing, especially when the barometric pressure is high and slowly decreasing. Similar correlations will apply to most observatories, and can be a help in catching the elusive good seeing.

A complete observation of a double star consists of the date, the position angle of the fainter component with respect to the brighter, and the distance between the components. To avoid errors in the position angle the polar axis should be well adjusted.

Measuring. The most common means of measuring double stars is with a filar micrometer. Filar micrometers differ somewhat in design, but the basic principles of use are the same. The whole micrometer should be rotatable so that all position angles can be measured. It should have two exactly parallel wires, one fixed and the other movable and able to pass by the fixed wire. These two wires are used to measure the distance between the components. They may also be used to measure position angles or, alternatively, two extra fixed wires at right-angles to the first pair may be used specially for the purpose. The wires have to be illuminated so that they can be seen in the eyepiece and the intensity of the light should be variable with a rheostat. Generally the fainter the illumination the better.

The position angle of the fainter component with respect to the brighter is measured from the north point round through east, see Fig. 31 *(a)*. If the pair is reasonably bright then the best results are obtained by bisecting each nucleus as in Fig. 31 *(b)*. This may be impossible for faint pairs, and these are best placed between the parallel wires to obtain a symmetrical position as in Fig. 31 *(c)*.

The zero error of position angle may be determined by letting a star trail along the wires while the telescope is fixed.

The micrometer is rotated to be parallel to the star's motion. A number of measures are made, and the mean taken. The values should of course be 90°, but if it comes to be 89°·0, for instance, then all the mean position angles must be increased by 1·°0.

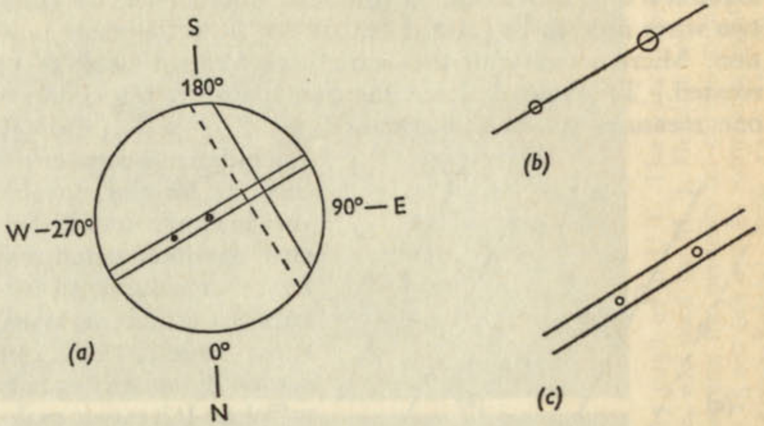


Fig. 31a. *Setting for position angle; in this case about* 300° (b) *and* (c). *Measuring the position angle of a bright and a faint pair of stars, respectively.*

To get the best results the observer's eyes should be parallel to the wire through the double stars, though some observers prefer a position at right-angles to this, and some others use both. The new observer should experiment to see which gives the best result for him.

Between each measure of position angle the micrometer should be rotated well away from the previous setting and the next setting made without being biased by the previous one. If there is good agreement between the first two settings, within 1°·0 say, then there is little point in making further measures as the mean will give a good result, unless the pair is a very unequal one. If consistent measures cannot be made then the whole observation should be rejected, unless a large aperture is being used on a critical pair and even an elongation would be valuable.

A reversing prism is useful in eliminating errors in position angle, which can be very troublesome for unequal pairs. The size of such an error without a prism may be estimated by setting on a suitable unequal pair near the zenith and rotating the *observer* through 180° between each measure. A series of about ten measures will show the effect quite clearly.

Once a satisfactory value for the position angle has been found it is time to measure the distance. (Micrometers with only two wires need to be rotated exactly 90° from the mean position. Micrometers with the extra wires do not need to be rotated.) To avoid deriving the zero point in the distance, one measures the double distance, see Fig. 32 (*a*) and (*b*). The difference between the readings for the movable wire gives the double distance. It will be found that further measures of distance on the same night will agree closely, and one double distance is usually sufficient. It is easy to make a mistake in reading the micrometer heads, but there is a check which may prevent gross errors. It is simply to *add* mentally the two readings, the result being a constant. This constant is twice the reading where the fixed and movable wires coincide, and will soon be memorized when several pairs have been measured.

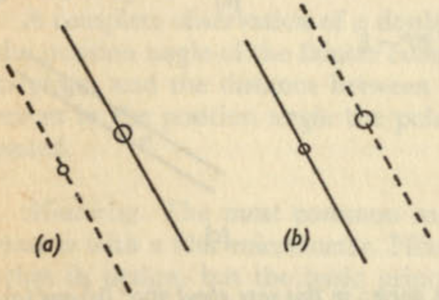
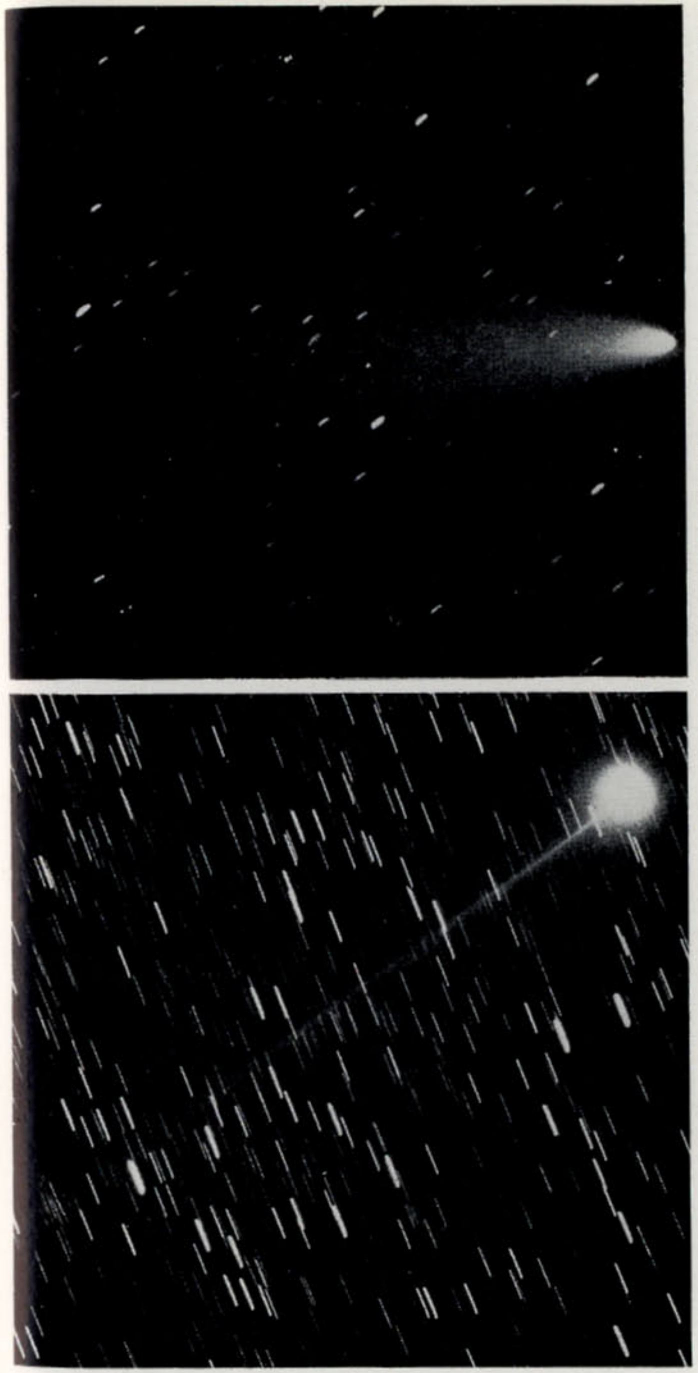


Fig. 32a *and* b. *Measuring the double distance. The dashed line represents the movable wire, which is attached to the reading head of the micrometer.*

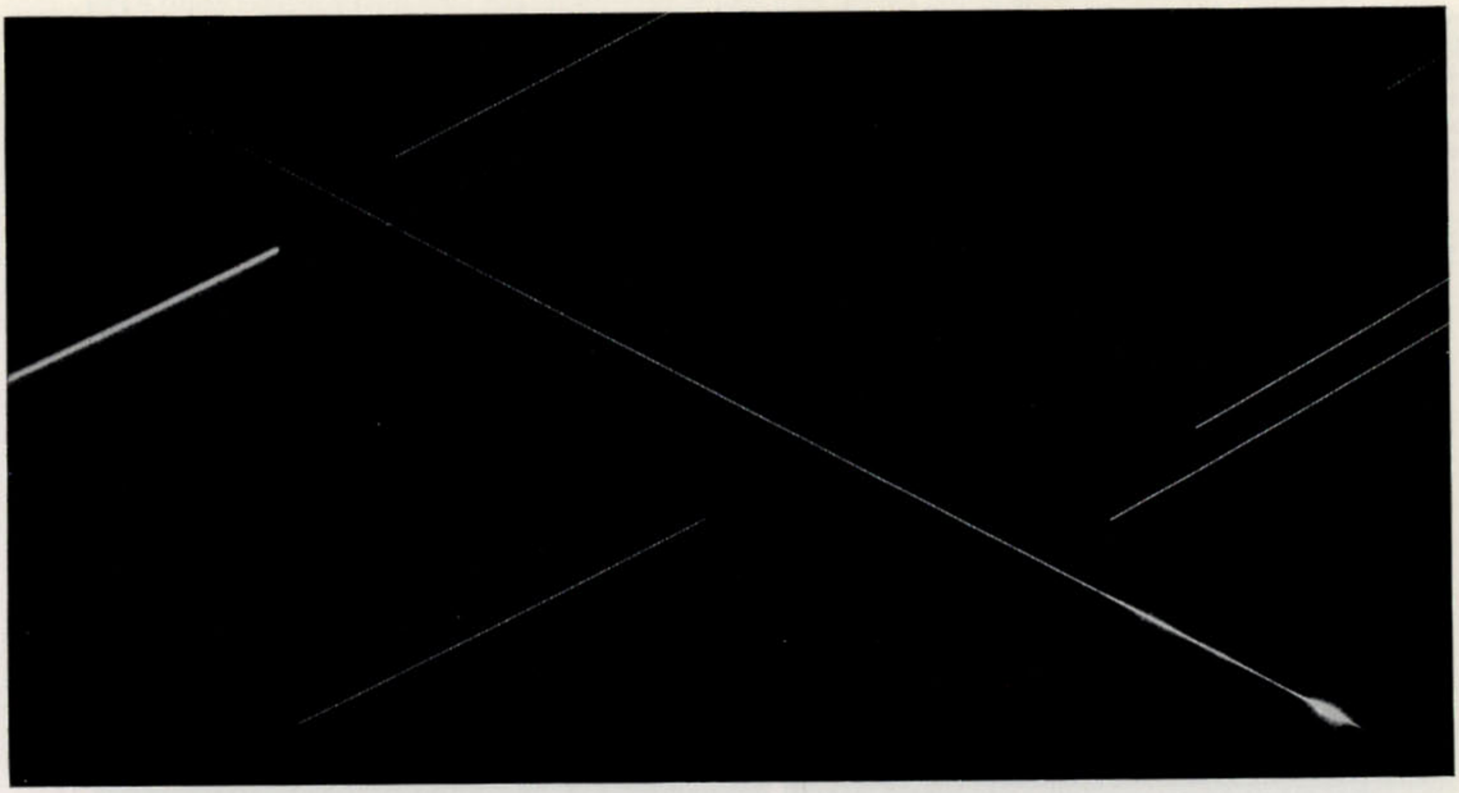
As one might expect, the distances of close pairs are difficult to measure with a filar micrometer. One way round the problem is to place the wires beside the stars and try to make the separation of the wires match that of the stars. This is a more difficult measure to make, but with experience the results are said to be more accurate.

The double distances found as above are in arbitrary units and to convert them to seconds of arc the *screw value* of the micrometer has to be found.

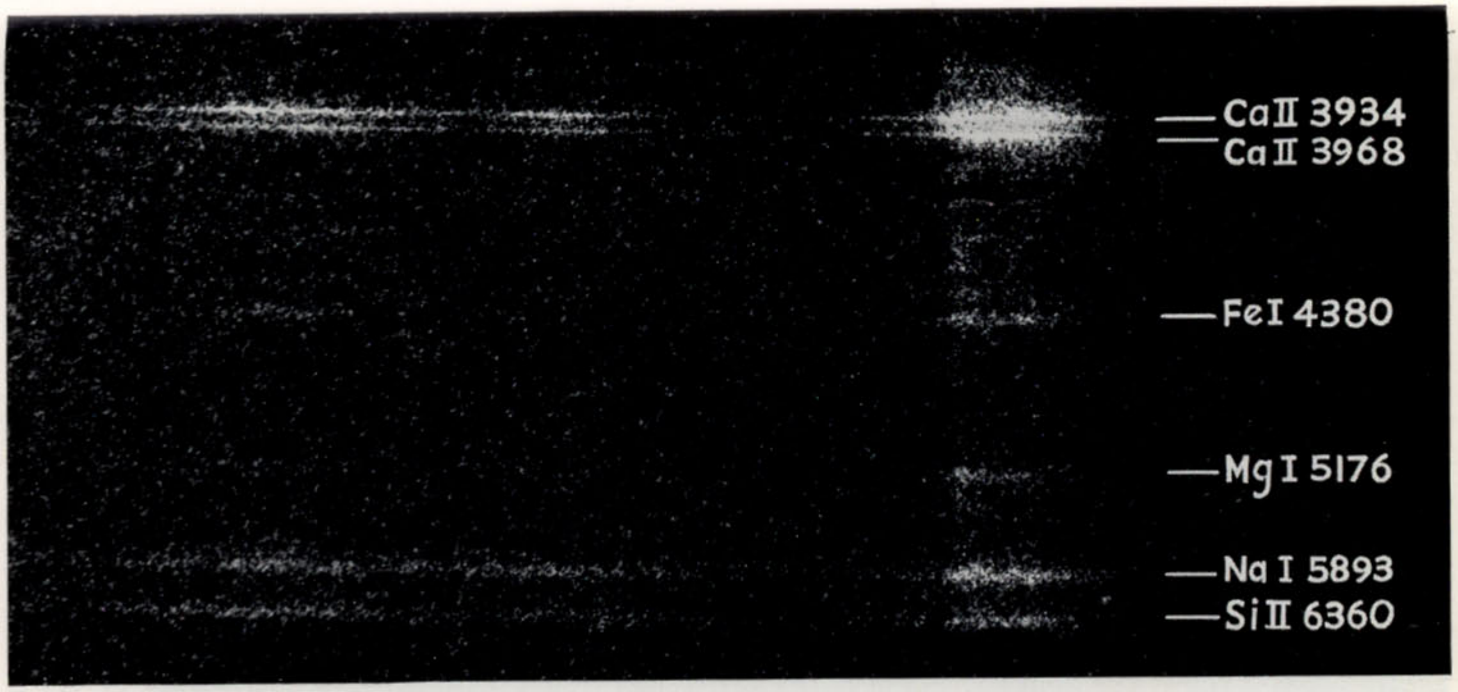
One way of finding the screw value is to separate the wires to each side of the field of view and time transits across them of a

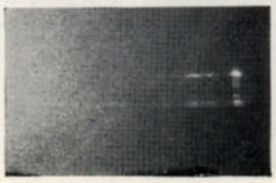


17. Comets. *Left*, Comet Burnham 1959k, 1969 Apl. 27 0238–0258 U.T. The 6-inch aperture Cooke lens (*f*/4·4) at Dr. R. L. Waterfield's observatory at Ascot, Berkshire, was used by M. J. Hendrie and H. B. Ridley to take this photograph in blue light on a Kodak Oa–O plate. It illustrates the necessity for careful guiding and allowance for the comet's apparent motion. The telescope was shifted every 15 seconds and by estimating eighth steps between the wires these were only moved every two minutes. *Right*, Comet Arend-Roland 1956h, 1957 Apl. 29 2050–2120 U.T. This 30-minute exposure was made with an *f*/5·6 aircraft lens of 14-in. focal length on an Ilford HP3 plate with an Ilford Micro 5 orange filter, the combination being sensitive to light of wavelength between 5700 and 6800 Å. In this case the comet's tail had a strong continuous spectrum and photographs in blue light showed little difference in general appearance.

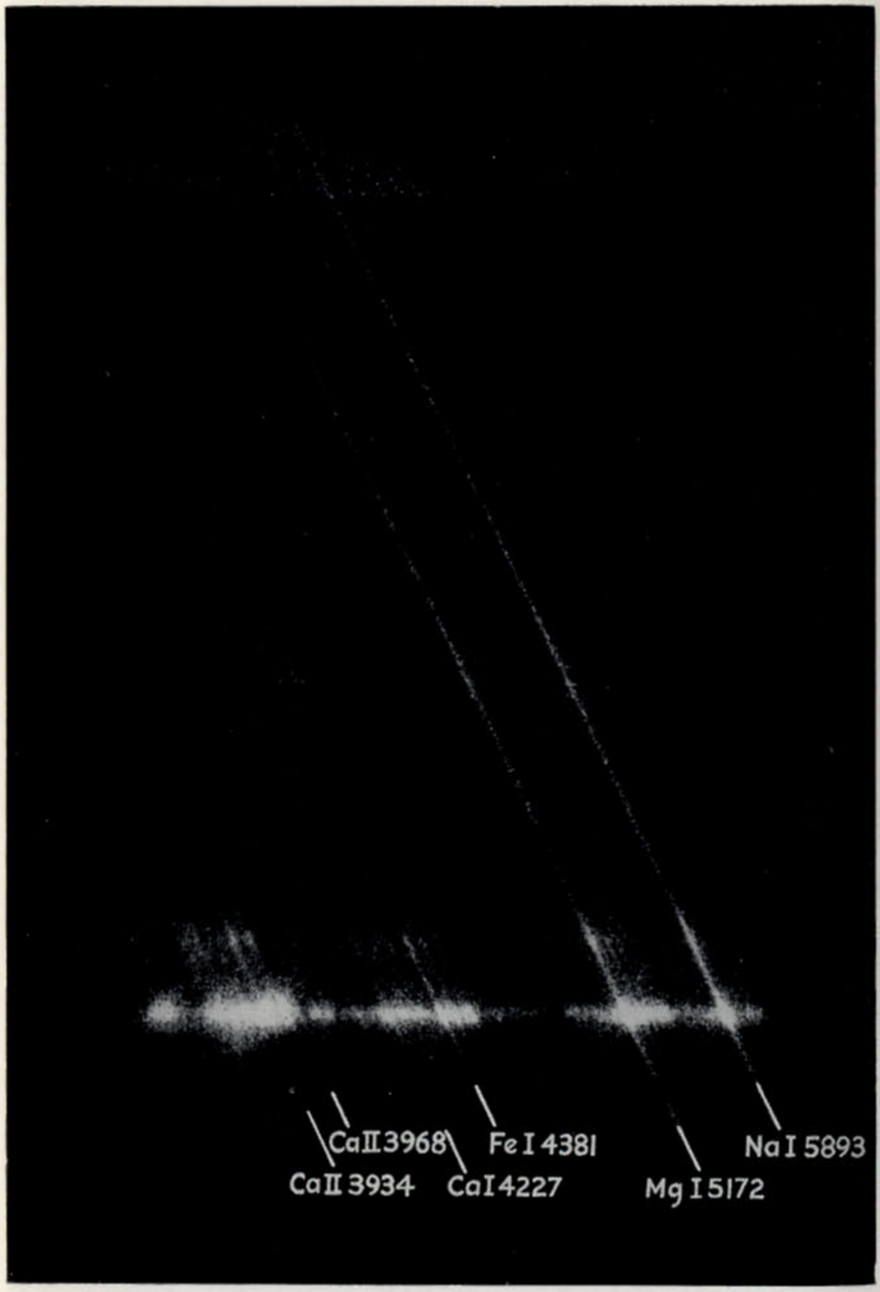


18. Trail of Perseid meteor, mag.–2, 1958 Aug. 15. Taken with Kodak Aero-Ektar, *f*/2·5, 12 in. focus. A non-Perseid meteor, mag. + 1·5, can be seen just below the Perseid; the bright star-trail, left, is of α Andromedæ. Enlargement × 4 from part of a whole-plate (photo by H. B. Ridley).

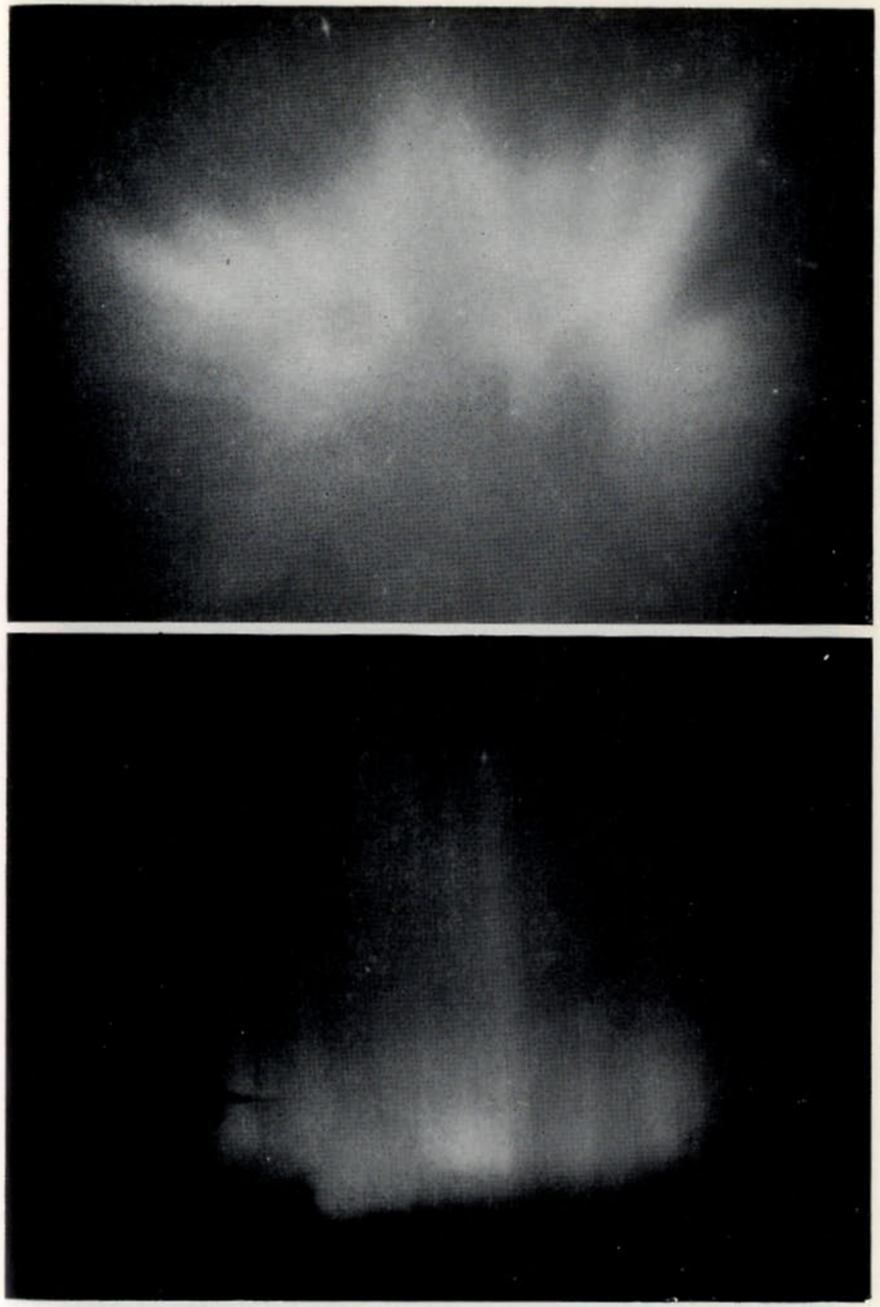




19. Spectrum of the meteor shown in Plate 18. The main emission lines are the close pair Calcium H and K. The meteor was moving almost exactly perpendicularly to the direction of dispersion. Kodak Aero-Ektar, *f*/2·5, 7 in. focus, with 30° dense flint objective prism. Enlargement × 17. The detail, *left*, is a contact print from part of the original plate. (Photo by H. B. Ridley.)

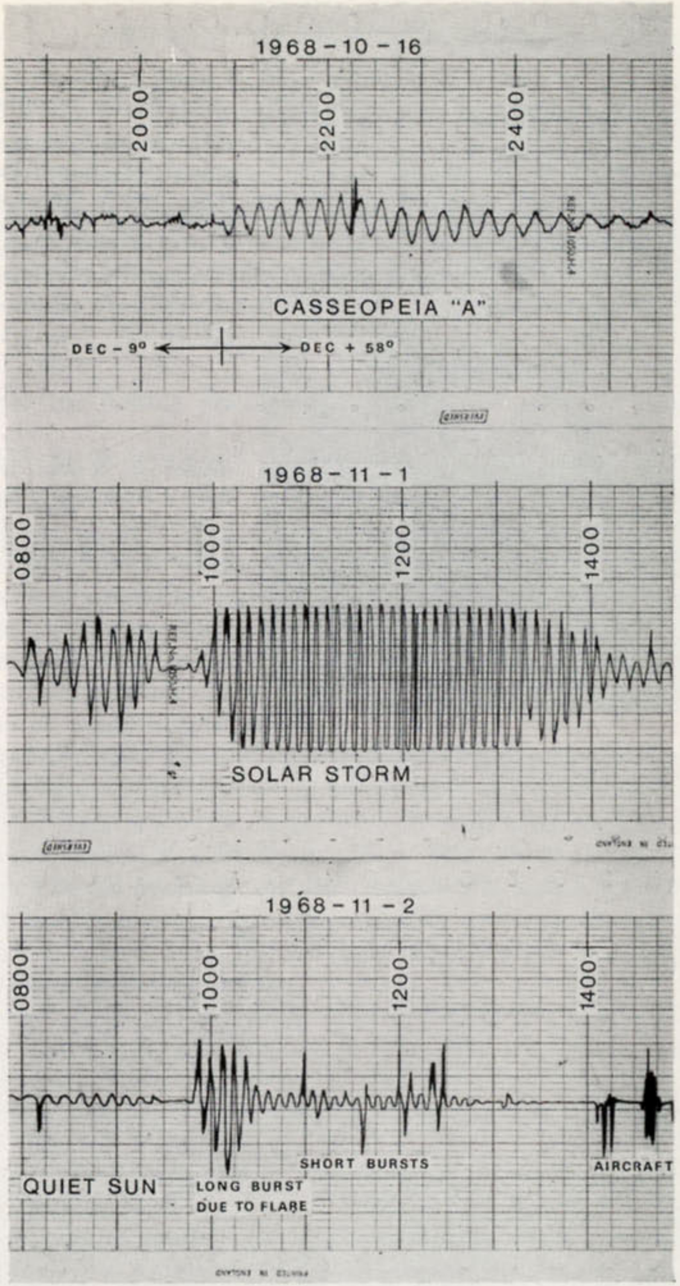


20. Spectrum of Taurid meteor, mag.–4, 1954 Oct. 29. Instrument as for Plate 19. Star spectrum top right is δ Tauri in the Pleiades. The meteor was moving at 65° to the dispersion. 56 lines were measured and identified in this spectrum. Enlargement × 20. (Photo by H. B. Ridley.)

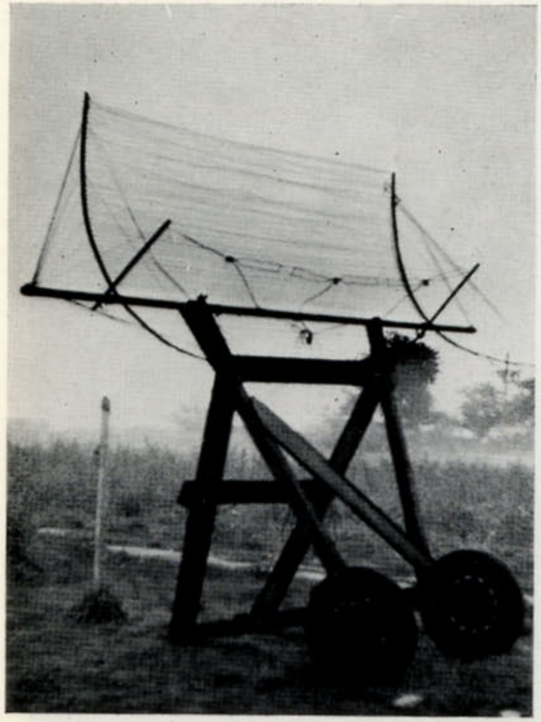


21. Photographs of Auroræ taken at Abernethy, Perthshire by James Paton. *Above*, Auroral corona. *Below*, part of Rayed arc.

22. Satellite Echo 1961/3/2, passing through Orion. (Photo by F. Kea).

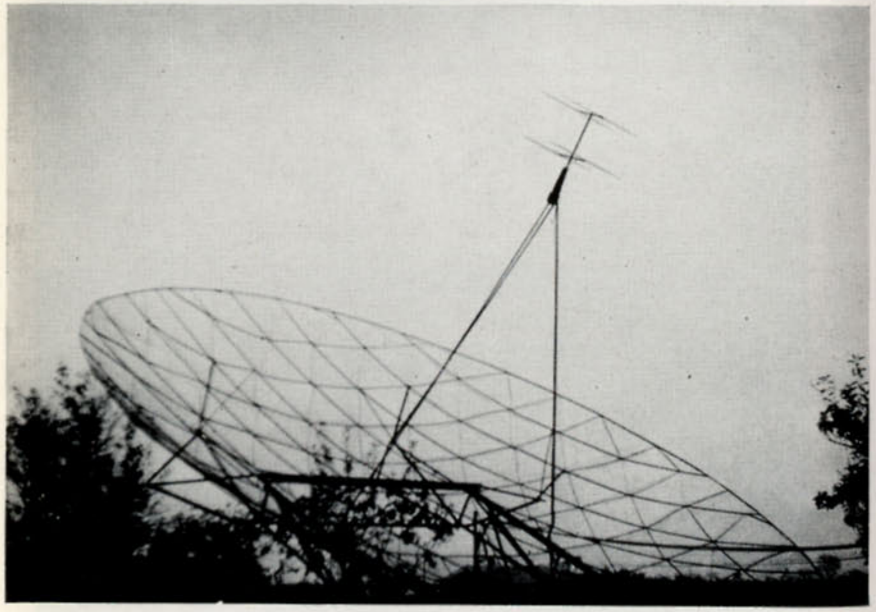


23. Radio astronomy. Phase-switched interferometer pen recordings made with the aerial shown in Plate 24 (*top*). *Top*, Cassoepeia "A"; *Centre*, Solar storm; *Bottom*, Quiet sun and "bursts".



24. Radio astronomy.

Left, a 10-foot by 8-foot cylindrical parabolic aerial with three half-wave dipoles. One of a pair used with a phase-switched interferometer for routine daily observations of the Sun at 136 MHz.



Below, a 30-foot diameter fully steerable parabolic aerial for 50 MHz to 3,000 MHz nearing completion.

star of known declination, near the meridian, with the telescope fixed. A number of such transits are timed and the mean taken! the reading of the head of the movable wire is also recorded. The wires are then transposed and the whole process repeated. If the mean time difference from the first and second sets of measures are t_2-t_1 and t_4-t_3, respectively, and the difference in the readings of the movable wire head is N revolutions, then the screw value S is given by the formula

$$S = \frac{15 \cos \delta \ (t_2-t_1+t_4-t_3)}{N} \text{ seconds of arc per revolution.}$$

Because the double distance is measured for the binary the distance to be published is equal to $\frac{S}{2} \times$ double distance in revolutions.

Another method of finding the screw value is to measure a pair of stars, of known positions, with nearly the same R.A. but differing by a suitable amount in declination. It may be necessary to use intermediate stars if the wide pair cannot be viewed in the field at the same time. In this case there is a straight comparison between the number of revolutions and seconds of arc, so no complications arise.

There are other forms of micrometer which do not use wires. One of these, the double image micrometer, splits the image of each star into two parts, either by a divided O.G. or Barlow lens, or by means of a Wollaston prism. The double images are observed in the eyepiece and their separation varied until the brighter component in one image exactly overlaps the fainter component in the other. The variation is achieved by movement of the image splitting device.

Another form of micrometer without wires is the comparison image micrometer. This projects an artificial pair of stars alongside the real pair in the eyepiece. The pair of artificial stars is formed by projecting light from a pinhole through a Wollaston prism. Their separation is varied by adjusting the distance of the prism from the pinhole. The absolute and relative intensities of the artificial stars can be made to match the real stars by rotating, independently, two small crossed Nicols in the optical path. A comparison image micrometer has been used for some years with the 28-inch at Herstmonceux, and is popular with the observers there, nearly all the measures being made with it. We find the most accurate procedure is to measure position angles with the filar micrometer and the distances only with the C.I.M.

It has been suggested by Worley that a skilled observer could attempt the construction of a filar micrometer. In the writer's opinion a person with such skill could just as easily make a double image or comparison image micrometer, with probably greater advantage to his double star work.

It is also possible to measure double stars with an interferometer, but as this is difficult to do and is anyway only suitable for the larger telescopes, it will not be discussed further here.

A new observer entering this field can compare with some profit his measures with the published ones of observers with long experience. The writer often uses Van Biesbroeck's measures for this purpose. The results of the comparison may or may not be encouraging, but at least the observer will be able to gauge the value of his own measures himself. Once the observer has satisfied himself that confidence in his measures is justified, he should get them published, about every three years.

When publishing measures, to help the workers who keep a card catalogue of all double star observations, it is desirable that the 1900 position of the pair is given as well as the ADS number and name. This helps to eliminate errors of identification which might otherwise occur if a copying error should be passed over. A sample layout for one star could be:

ADS	Name	R.A.	Dec.	Date	P.A.	Dist.
		1900·0				
		h m	° ′		°	″
8119	Σ1523	11 12·8	+32 05	1961·225	146·4	2·27
				·261	145·9	2·20
				·278	145·6	2·21
				1961·255	146·0	2·23

The most useful pairs to measure are those which are moving quickly and whose orbits have been or soon can be calculated. There is not much point in making a lot of measures of pairs wider than 3″, as these can be dealt with most accurately by photography. All the same, it is likely that some of the faint wide pairs are being neglected. An amateur could check over the neglected faint pairs with profit. Most will prove to be practically stationary, but any exhibiting motion would be

particularly interesting. Also of special interest are pairs where one component is a variable and too bright most of the time for the fainter companion to be seen. One such pair is Mira, ADS 1778, which is just entering a critical orbital phase. Observations over the next ten years or so could be very useful.

The following list contains some useful pairs to be measured and also some pairs to practise on. Where the period, P, is greater than 200 or 300 years it is necessarily unreliable. Some of the slow-moving pairs are useful in comparing one observer with another.

Table 4

ADS	Name	RA	Dec.	Mag.	Sep^{n}.	Notes
		1950·0				
		h m	° ′	m m	″	
61	Σ 3062	0 03·5	+58 09	6·9 8·0	1·3	P = 107 years
221	OΣ 4	0 14·1	+36 13	8·1 8·8	0·5	P = 112 years
416	β 394	0 28·0	+47 15	8·2 8·4	0·9	
434	OΣ 12	0 29·0	+54 15	5·6 5·9	0·5	λ Cas
746	OΣ 20	0 51·9	+18 55	5·9 7·0	0·4	P = 205 years
755	Σ 73	0 52·3	+23 22	6·2 6·8	0·6	36 And P = 165
862	OΣ 21	1 00·1	+47 07	6·9 8·2	0·7	P = 120 years
940	OΣ 515	1 06·6	+46 59	4·9 6·5	0·4	P = 300 years
1254	Σ 138	1 33·4	+ 7 23	7·3 7·3	1·6	
1538	Σ 186	1 53·3	+ 1 36	7·2 7·2	1·4	P = 158 years
1631	Σ 208	2 00·8	+25 42	6·2 8·4	0·5	P = 500 years
1709	Σ 228	2 10·8	+47 15	6·7 7·6	0·7	P = 145 years
1778	Joy 1	2 16·8	— 3 12	Va. 10·0	0·7	Mira. Measurable only when Mira is comparatively faint.
2004	Σ 285	2 35·9	+33 12	7·0 7·7	1·7	
2034	OΣ 43	2 37·8	+26 25	7·2 8·8	1·0	
2257	Σ 333	2 56·4	+21 08	5·7 6·0	1·6	ε Ari
2377	OΣ 50	3 07·6	+71 22	7·5 7·5	1·4	
2446	OΣ 53	3 14·5	+38 27	7·2 8·0	0·7	P = 118 years
2612	Σ 400	3 30·9	+59 52	7·0 8·0	0·6	P = 221 years
2616	Σ 412	3 31·5	+24 18	6·6 6·7	0·4	7 Tau P = 600 years
2668	Σ 425	3 37·0	+33 57	7·3 7·3	2·0	
2726	β 535	3 41·2	+32 08	4·0 8·5	0·9	o Per
2799	OΣ 65	3 47·3	+25 26	6·5 6·8	0·5	P = 62 years
2963	Σ 460	4 01·4	+80 34	5·2 6·1	0·9	49 Cep P = 500 years
3082	OΣ 77	4 12·8	+31 34	7·5 7·5	0·7	P = 200 years
3093 BC	Σ 518	4 13·2	— 7 41	9·2 11·0	7·5	o^2Eri 105°, 83″ from $4^{\mathrm{m}}\cdot 0$ star (40 Eri). The close pair are dwarfs, one white, one red. P = 248 years
3169	OΣ 82	4 19·9	+14 56	7·0 9·0	1·2	P = 225 years

Table 4—cont.

ADS	Name	RA	Dec.	Mag.	Sepⁿ.	Notes
		1950·0 h m	° ′	m m	″	
3330	Σ 567	4 33·8	+19 24	8·5 9·0	2·0	
3390	Σ 577	4 38·8	+37 25	7·7 7·7	1·1	
3672	OΣ 95	5 02·6	+19 44	6·6 7·2	0·9	
3711	OΣ 98	5 05·2	+ 8 26	6·0 6·8	0·8	14 Ori P = 163 years
3956	Σ 677	5 20·0	+63 21	7·7 8·0	1·0	P = 400 years
4208	Σ 749	5 34·0	+26 54	7·1 7·2	1·0	
4472	β 1053	5 50·1	+37 20	7·5 9·5	1·4	
5197	Σ 932	6 31·5	+14 48	8·2 8·3	1·8	
5234	OΣ 149	6 33·3	+27 20	6·5 9·0	0·6	P = 116 years
5400	Σ 948	6 41·8	+59 30	5·2 6·1	1·8	P = 700 years
5423	AGC 1	6 43·0	—16 39	—1·6 8·4	9·0	Sirius P = 50 years
5586	OΣ 159	6 53·0	+58 29	5·1 6·2	0·9	15 Lyn
5871	Σ 1037	7 09·7	+27 19	7·1 7·1	1·2	P = 116 years
5958	OΣ 170	7 14·9	+ 9 23	7·5 7·8	1·5	
6117	Σ 1093	7 26·5	+50 05	8·2 8·2	0·7	
6175	Σ 1110	7 31·4	+32 00	2·7 3·7	2·2	Castor P = 400 years
6263	Σ 1126	7 37·5	+ 5 21	7·2 7·5	0·9	
6623	Σ 1187	8 06·4	+32 22	7·1 8·0	2·7	
6650 AB	Σ 1196	8 09·3	+17 48	5·0 5·7	1·1	ζ Cnc P = 60 years
6993 AB—C	Σ 1273	8 44·2	+ 6 36	3·8 7·8	3·1	ε Hyd AB is a close pair, 0″·2
7071	Σ 1291	8 51·2	+30 46	5·9 6·4	1·4	
7203	Σ 1306	9 06·0	+67 20	5·0 8·2	2·4	P = 700 years
7307	Σ 1338	9 17·9	+38 24	7·0 7·2	1·2	P = 400 years
7704	OΣ 215	10 13·6	+17 59	7·0 7·2	1·2	P = 550 years
7730	Σ1426	10 17·9	+ 6 41	7·8 8·3	0·9	
7929	OΣ 229	10 45·2	+41 22	6·7 7·1	0·8	
8119	Σ 1523	11 15·6	+31 49	4·0 4·9	2·1	ξ UMa P = 60 years
8148	Σ 1536	11 21·3	+10 48	3·9 7·1	1·0	P = 180 years
8197	OΣ 235	11 29·5	+61 22	6·0 7·3	1·0	P = 73 years
8575	Σ 1647	12 28·0	+10 00	7·5 7·8	1·3	
8630	Σ 1670	12 39·1	— 1 11	3·0 3·0	5·1	γ Vir P = 172 years
8708	OΣ 256	12 53·9	— 0 41	7·2 7·6	0·9	
8804	Σ 1728	13 07·6	+17 47	6·0 6·0	0·7	α Com P = 26 years
8974	Σ 1768	13 35·2	+36 33	5·7 7·6	1·7	25 CVn P = 240 years
9031	Σ 1785	13 46·8	+27 14	7·2 7·5	3·0	P = 155 years
9167	Σ 1820	14 11·4	+55 33	8·2 8·5	2·4	
9182	Σ 1819	14 12·8	+ 3 22	7·9 8·0	0·8	P = 360 years
9229	Σ 1834	14 18·5	+48 44	7·1 7·2	1·1	P = 320 years
9343	Σ 1865	14 38·8	+13 57	3·5 3·9	1·1	ζ Boo P = 123 years
9418	OΣ 287	14 49·6	+45 08	7·5 7·6	1·0	
9494	Σ 1909	15 02·2	+47 51	5·2 6·1	1·0	44 Boo P = 282 years
9578	Σ 1932	15 16·2	+27 01	5·6 6·1	0·8	P = 191 years
9626 BC	Σ 1938	15 22·6	+37 31	6·7 7·3	2·0	μ Boo P = 260 years

Table 4—cont.

ADS	Name	RA	Dec.	Mag.	Sepⁿ.	Notes
		1950·0 h m	° ′	m m	″	
9716	OΣ 298	15 34·3	+39 58	7·0 7·3	1·2	P = 56 years
9909	Σ 1998	16 01·6	—11 14	4·9 5·2	0·8	ξ Sco P = 46 years
10075	Σ 2052	16 26·7	+18 31	7·5 7·5	0·8	P = 217 years
10087	Σ 2055	16 28·4	+ 2 06	4·0 6·1	0·9	λ Oph P = 132 years
10157	Σ 2084	16 39·4	+31 41	3·0 6·5	1·1	ζ Her P = 34 years
10235	Σ 2107	16 49·8	+28 45	6·5 8·0	1·1	P = 262 years
10279	Σ 2118	16 56·2	+65 07	6·4 6·9	1·1	20 Dra P = 700 years
10345	Σ 2130	17 04·3	+54 32	5·0 5·1	2·1	μ Dra P = 2000 years
10728	Σ 2218	17 40·0	+63 42	6·5 7·7	1·8	
11005	Σ 2262	18 00·4	— 8 11	5·0 5·7	2·0	τ Oph P = 224 years
11046	Σ 2272	18 02·9	+ 2 32	4·1 6·1	4·7	70 Oph P = 88 years
11111	Σ 2281	18 07·1	+ 3 59	5·7 7·2	0·5	73 Oph P = 400 years
11468	A 1377	18 32·8	+52 19	6·0 6·0	0·3	P = 185 years
11479	OΣ 359	18 33·4	+23 34	6·6 6·9	0·5	P = 191 years
11483	OΣ 358	18 33·6	+16 56	6·8 7·2	1·8	P = 300 years
11635 AB	Σ 2382	18 42·7	+39 37	4·6 6·3	2·8	ε¹ Lyr P = 1000 years
11635 CD	Σ 2383	18 42·7	+39 37	4·9 5·2	2·2	ε² Lyr P = 600 years
11640	Σ 2375	18 43·0	+ 5 27	6·2 6·6	2·5	
11871	β 648	18 55·2	+32 50	6·0 8·2	1·2	P = 60 years
12447	Σ 2525	19 24·5	+27 13	7·4 7·6	1·5	P = 500 years
12880	Σ 2579	19 43·4	+45 00	3·0 7·9	2·3	ζ Cyg P = 500 years
12889	Σ 2576	19 43·6	+33 30	7·8 7·8	1·2	P = 244 years
12972	OΣ 387	19 46·8	+35 11	7·2 8·2	0·5	P = 157 years
13723	OΣ 406	20 18·2	+45 12	7·1 8·0	0·5	P = 96 years
14296	OΣ 413	20 45·5	+36 18	5·0 6·3	0·7	λ Cyg P = 400 years
14360	Σ 2729	20 48·8	— 5 49	6·3 7·6	1·0	4 Aqr P = 155 years
14421	OΣ 418	20 52·8	+32 31	7·3 7·4	1·1	
14499	Σ 2737	20 56·6	+ 4 06	5·7 6·2	0·9	P = 101 years
15270	Σ 2822	21 41·9	+28 31	4·7 6·1	1·5	P = 500 years
15971	Σ 2909	22 26·3	— 0 17	4·4 4·6	2·1	ζ Aqr P = 360 years
15988	Σ 2912	22 27·4	+ 4 11	5·8 7·2	0·9	37 Peg P = 150 years
16057	Σ 2924	22 31·6	+69 39	6·8 7·3	0·5	P = 226 years
16173	Ho 296	22 38·4	+14 17	5·5 5·5	0·3	P = 21 years
16428	OΣ 483	22 56·7	+11 28	6·2 7·7	0·7	52 Peg P = 300 years
16665	β 80	23 16·3	+ 5 08	8·9 9·9	1·3	P = 108 years
16836	β 720	23 31·5	+31 03	6·0 6·0	0·5	72 Peg P = 218 years
17149	Σ 3050	23 56·9	+33 27	6·5 6·5	1·5	P = 800 years

The true path of the fainter component of a binary with respect to the brighter is an ellipse with the brighter component at one focus. When viewed from the Earth the effects of projection will be to alter this "true ellipse" to the "apparent ellipse", which is what is observed. There are many ways in which the orbits of binaries can be derived, and the interested reader will easily find references. However, there is no shortage of orbit computers, but there is a shortage of double star observers and it is the latter who should be encouraged. In the words of Aitken: " . . . an hour at the telescope on a good night is more valuable than half a dozen hours at the desk in daylight."

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Chapter Seventeen

OBSERVATION OF VARIABLE STARS

J. HEDLEY ROBINSON

THE STUDY OF variable stars is one of the departments of the science of astronomy in which the amateur can still do useful work. As is well known, variable stars fall into a number of classes according to their characteristics, and a large number of irregular and long period stars has for many years been observed by amateurs; their records have been made use of by the professional astrophysicists on many occasions. This alone is sufficient to demonstrate the value of variable star observation, which may not be spectacular nor attract the attention of the popular press, but is an essential to the understanding of stellar evolution and the fundamental structure of the universe in which we live.

Short-period variable stars and those with small magnitude variation are normally observed by the professional who can command instrumental facilities beyond the scope of the average amateur, but even in this specialized field the professional is sometimes glad of confirmation of his own observations by an amateur capable of making accurate records. It is, therefore, on the presumption that the basic facts regarding variable stars are already understood and it is desired to participate in useful observational work, that the following suggestions are put forward.

Satisfactory study of variable stars rests on a triple foundation of *Accuracy*, *Continuity*, and *Interpretation of Observations*, and it is proposed to treat the subject under these three headings without repeating the more elementary directions to be found elsewhere.

Accuracy. Accurate observation of stellar magnitudes by the usual visual methods is limited to about one-tenth of a magnitude by the inability of the normal human eye to differentiate between the brightness of stars having magnitudes less than one-tenth of a magnitude apart.

If an observer uses the Argelander Step Method, whereby the magnitude of a variable star is directly compared with that of a star of known magnitude, and the difference estimated in steps of about one-tenth of a magnitude, he must first ascertain the true value of his individual step, or minimum difference of magnitude he can appreciate, since any error will be multiplied by the number of steps he observes magnitudes to be apart. Thus, if his minimum step is really one-ninth of a magnitude (which he assumes to be one-tenth) and he observes a variable star as being six steps brighter than a comparison star of magnitude 8, then he will record the variable as mag. 8 minus six steps. This is equivalent to magnitude 7·4. But the true magnitude will be 8 minus six times one-ninth, or 7·33 mag., which for practical purposes produces a record carrying an error of one-tenth of a magnitude. Further complication arises from the fact that the individual step varies with fatigue and is also affected by the health of the observer.

An alternative is the Pogson Step Method in which the eye is trained to appreciate differences of one-tenth or one-fifth of a magnitude, much in the same way as the ear can be trained to appreciate tones and half-tones in music, as well as absolute pitch. This method, however, also carries the danger of error arising from fatigue.

To reduce error of observation in either of the above methods it is advisable to make a number of observations using different comparison stars, and to take the mean of all the observations as being an accurate estimate. It is true to say that given a large enough number of observations of any one star the resultant average value would be accurate, but the number of observations made of each variable star is limited by practical considerations, among which is the fact that the further from the variable any comparison star is situated, the greater is the chance of error arising in the comparison with the variable star. Thus an observation using a comparison star situated far from the variable is less reliable than one using a comparison star nearer to it. It is much easier to compare two stars symmetrically placed in the telescope field than it is to carry an estimate of the light stimulus from one field, while the instrument is being moved, to another; and it is evidently doubtful if this can satisfactorily be accomplished when the difference between the magnitudes is small. Confusion in the mind also

arises from seeing other stars pass through the field, especially if they are bright.

Another method that eliminates some of the foregoing difficulties is the Fractional Method, which is preferred by some observers on the ground that one measures the light interval on a scale that has both ends fixed. Using two comparison stars, one brighter and one fainter than the variable to be observed, the variable is then estimated as being so many steps from the brighter star and so many steps from the fainter one; and given comparison stars of say mag. 8 and mag. 8·5 with the variable to be placed somewhere on this scale of only half a magnitude in length, it is comparatively easy to place it fairly accurately. An estimate of the variable as exactly half-way between the two may on occasion be more accurate than the average of two step-method observations.

The choice of comparison stars as near the variable as possible in magnitude reduces even further the length of the scale, and the probable error in proportion thereto. Also, the shorter the scale between the comparison stars' magnitudes the nearer is the arithmetical difference to the true logarithmic difference between them, and hence the value assigned to the variable.

Objection is sometimes raised on the ground that the Fractional Method involves an additional factor through having two comparison stars instead of one, and the mind is thereby supposed to be hindered in coming to a satisfactory conclusion, as opposed to the Step Methods involving only one comparison star. If each comparison star is given good foveal observation (in difficult cases repeated a few times) and a suitable number of fractional intervals is mentally selected before attention is paid to the variable, other than for the purpose of selecting suitable comparison stars, it is actually comparatively easy to assign a position on the scale of intervals already visualized. The second comparison star in fact becomes an aid rather than a hindrance by providing a scale that can be visualized, as opposed to steps where only the starting point is fixed.

Observers vary as to the number of divisions they can reliably visualize on their scales, and in the ease or otherwise of assigning a true position to the variable star thereon. It has been stated with some authority that interval assessments of from

1:1 to about 1:5 can be made with sufficient accuracy to justify placing reasonable confidence in them, but mentally to divide a light interval into seven parts or more and to place the variable correctly within this range is too difficult for much weight to be attached to such an observation. This may be true, but practical observers will come across cases where perception of light interval is finer than a scale of only five intervals can accommodate. This is particularly so if the comparison stars are more than about half a magnitude apart. In such cases, to adopt Pickering's notation using ten intervals only serves to confuse the issue, since it is rather too long a scale for convenience, and two divisions on the ten-interval scale can easily be visualized as one division on the five-interval scale, and does not alter the scale interval values sufficiently to afford the accommodation of such estimates as say, 3:4. There is a case to be made for the occasional adoption of scales of more than five intervals when the observer is not satisfied that five divisions can give a true picture. Scales of six, seven, or even eight intervals sometimes enable observation to be carried to greater accuracy than five will allow, but there are dangers to be avoided, and each observer will in practice find his own way of expressing such light intervals when necessary. Fig. 33 illustrates the principle involved.

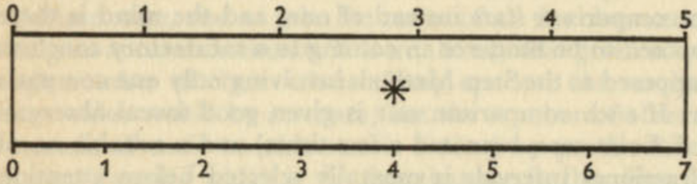


Fig. 33

The satisfactory course appears to be that of choosing comparison stars as near the variable in magnitude, and position, as possible, and to adopt a scale that will best express the light interval most accurately while using a scale of five intervals as a normal procedure. It follows that if the comparison stars are only about one-fifth of a magnitude apart, a scale of two intervals is all that can normally be expected.

Something needs to be said on the subject of retinal sensitivity and the necessity of so aligning the eyes that a line joining the stars passes through the plane of the observer's eyes. This is an elementary rule, but in actual observing conditions has its difficulties, especially in the Fractional Method, where two lines are usually involved; one joining the brighter, and one joining the fainter star with the variable (Fig. 34). A third line also joins the two comparison stars previously compared for the purpose of establishing the number of intervals to be adopted. If the pattern presents itself in such a way that turning the head to the required angles is not practical, there is little that can be done short of using an image rotator or becoming an acrobat. The prism image rotator is a luxury not often owned by the amateur, and has its own dangers, while a little perseverance will often overcome the trouble. Acrobatics at the telescope are not recommended, as they can have disastrous results both to the performer and the instrument.

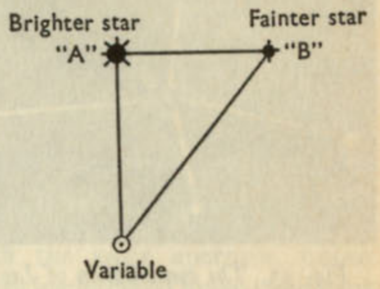


Fig. 34

Many variable stars are of a ruddy hue, while most comparison stars appear white or blue, partly by contrast and partly on account of their intrinsic colour. Since a red star appears to brighten during the time it is afforded a steady gaze, time for the eye to accommodate itself to the difficult task of dealing with both red and white/blue light must be allowed. Unless this is done the door is left wide open for error to creep in. Colour filters do not supply the answer in this case, since they give a false impression of the magnitudes of the comparison stars if red is used, and of the variable if blue is used. Since observers' eyes differ as regards colour perception and sensitivity, it becomes necessary for each to adopt his own accommodation period, which will not necessarily be of a constant duration but will require observing practice to establish on each and every occasion. The eye and mind can be trained to register relative brightness whether of white or red light, but it requires practice.

Observers can establish their own personal colour equation,

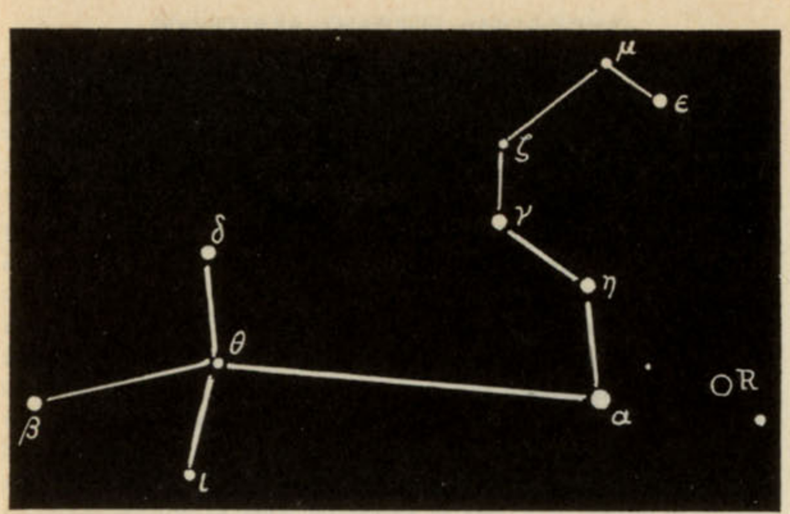
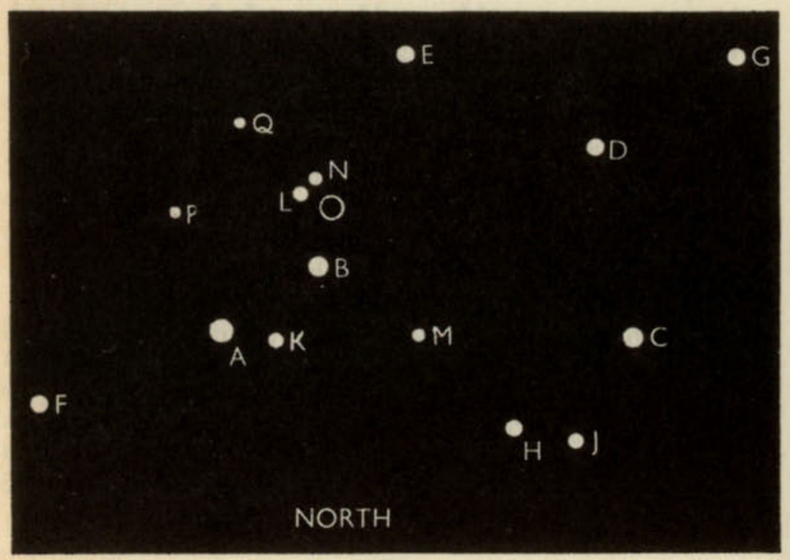


Fig. 35. *The constellation of Leo, showing the position of R Leonis as indicated by the open circle, while below is shown the inverted telescopic field. Magnitudes of comparison stars are:*

Star A	5·84	Star F	7·90	Star L	8·98
B	6·43	G	8·02	M	9·64
C	6·62	H	8·21	N	9·64
D	7·23	J	8·85	P	10·12
E	7·47	K	9·00	Q	10·45



which is an expression of the error created in the observation of red stars. This is done by observing red stars of known magnitude as compared with white or blue stars and plotting the error (true, minus observed) for various magnitudes, this will then be a guide in establishing the true magnitude of any red star subsequently observed. The maintenance of absolute accuracy will require occasional checking of this function, but in the case of team observation programmes it is not so necessary as will be shewn in the section on Interpretation of Observations.

Reduction of telescope aperture is sometimes recommended when a red star is bright with a view to reducing the error. This, however, introduces complication for the compiler of the records of a team of observers, but might be quite feasible for a lone observer. It is normal to use the same instrument throughout a programme, with the same aperture, unless variations are so great that the eye is unable to make consistent estimates. Then, something has to be done about it. The principle is that colour sensitivity decreases as intensity is reduced, when the eye becomes more sensitive to light differences. In actual practice the lack of dark adaptation helps in these cases of bright red stars, but no hard and fast rule as to the amount of dark adaptation allowable can be given, and each observer will find his own tolerance and optimum observing conditions.

Confusion and error can also arise when a bright star is situated near the variable or comparison stars. The impression is then often gained that the stars are brighter than they actually are. In such cases the bright intruder should be covered with an occulting bar or similar device.

Direct vision should usually be employed, and averted vision only when both variable and comparison stars are too faint to be seen otherwise. In such a case a note should be made in the record of the observation.

Occasionally a variable star will appear equal in brightness to a comparison star. When this happens there is usually some element of doubt in the observer's mind. While this can be removed, if the two stars appear alternately one brighter than the other for equal periods of time, there is now and again a case where the mind cannot be made up as to which star is really the brighter of the two. It is a good plan when this happens to put the stars slightly out of focus, when the brighter will be seen to present a larger spurious disk than the fainter one, but the stars should be symmetrically placed in the telescope field to avoid any error through spherical aberration.

The striving after accuracy is the motive behind the development of the photometer, of which there are many types, from the simple wedge to the photo-electric; and there is a quantity of literature on the subject. For the observation of long-period stars with wide fluctuations and for many irregular-type stars the human eye and brain provide a satisfactory photometer for the purpose, but short-period stars and those with small variations need something more elaborate. If the observer wishes to undertake this kind of work he must be prepared to face not only the construction of his photometer, but also to apply all necessary corrections to his observations to bring his results into line with other results. This is far from insuperable, but has its own pitfalls, and guidance should be sought before getting too far involved. The calibration of a photometer has to be carried out carefully to avoid systematic error, and in certain types of instrument adjustment for atmospheric absorption is also necessary as well as for colour and even moonlight.

It is well known that the eye is more accurate in matching two light sources for intensity than it is for estimating the difference between them. A visual photometer constructed on this principle will accordingly give better results, and the Zöllner type is a good example. Another type is illustrated in Fig. 36, but in this case care must be exercised in converting the milliamp readings into stellar magnitude since the scale will not be linear. The scale is best established by the repeated observation of stars of known magnitude and then plotting the curve of the readings against stellar magnitude. This curve is then used to convert milliamp scale readings into stellar magnitudes for future observations. It will be necessary to observe control stars each time to establish any correction required for atmospheric absorption; and variation in the electricity supply if the instrument is supplied by a battery. Atmospheric absorption will obtrude in the observations of red stars to a marked degree and must be guarded against.

Another simple form of photometer can be made by mounting two polaroid sheets, one to rotate, to cut down transmitted light progressively. Difficulty, however, arises since transmission

varies increasingly rapidly towards the extinction setting.

Continuity. One observation of a variable star by itself tells us very little indeed, but when compared with others reveals not only the amplitude of the variation, but the period and characteristic type of curve produced for the particular star observed. For this reason alone, continuity over a period of time is essential. There is a further reason in that sporadic observation, even over a long period, can give quite an erroneous picture of the true light curve of a variable star (Fig. 37). Poor observation of a short period variable can easily give an im-

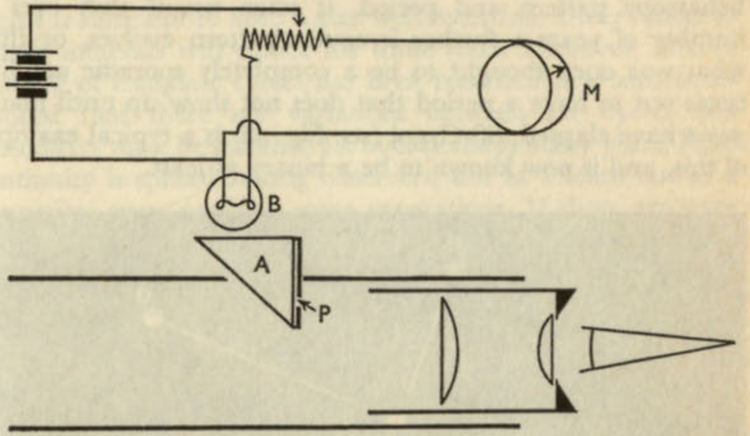


Fig. 36. *A visual photometer.* A, *Right-angled prism screened on side towards eyepiece;* B, *Pea bulb;* M, *Milliameter;* P, *Pinhole in screen on face of prism to produce an artificial star in the eyepiece.*

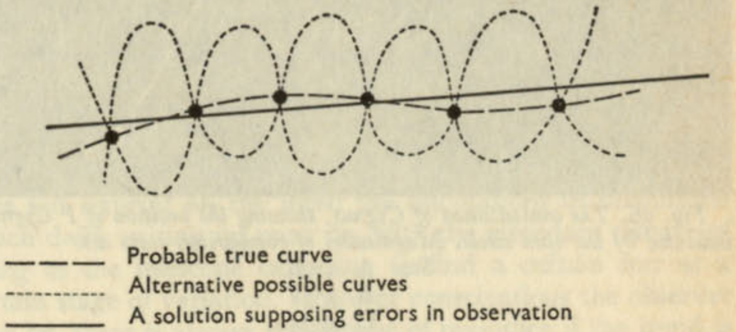


Fig. 37.

pression that it is an irregular, while similar misrepresentation of an irregular can suggest its being a long period star. Here continuity of observation has its obvious effect on interpretation.

There is, however, a further reason for continuity of observation. After a series of observations has established a star's behaviour pattern and period, it often occurs that over a number of years a further irregular pattern evolves, or that what was once thought to be a completely sporadic activity turns out to have a period that does not show up until many years have elapsed. SS Cygni (see Fig. 38) is a typical example of this, and is now known to be a binary at least.

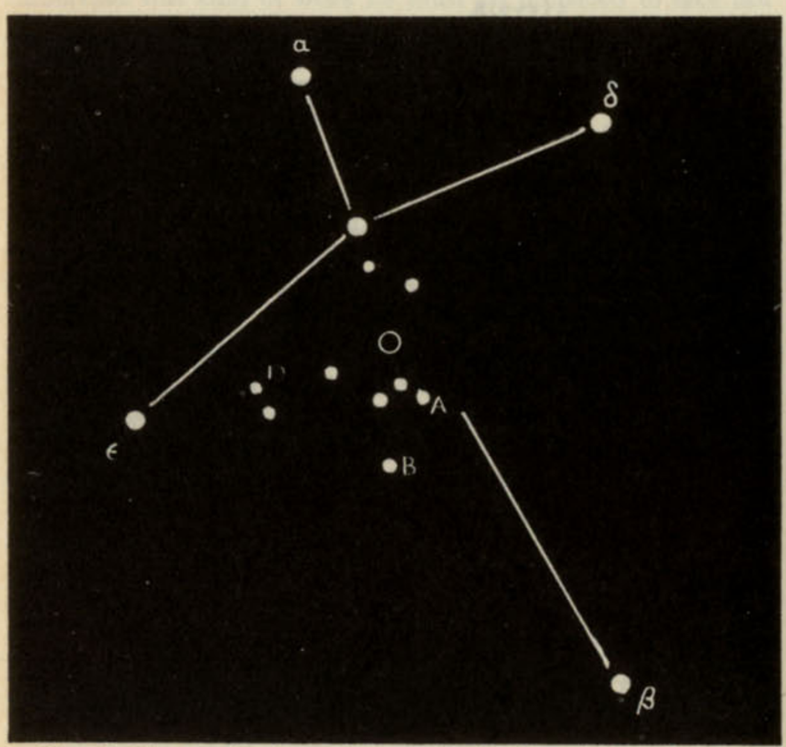


Fig. 38. The constellation of Cygnus, showing the position of P Cygni as indicated by the open circle. Magnitudes of comparison stars are:

Star	A	4·98
	B	5·52
	C	5·94
	D	6·30

Climatic conditions hamper continuity, and it is therefore an advantage for variable star observation to be undertaken by a team of observers geographically well spread, who pool their observations at regular intervals.

Long-period variation in magnitude is obviously slow, and unless anything unusual occurs, observation every four or five nights is sufficient to keep a star well recorded. Observation at longer intervals will suffice for some stars. However, after a number of complete cycles has been recorded, it is sometimes noticed that there are variations between the cycles and periodicity must be searched for over perhaps many years. Here continuity is spread among observers, not as a team but as a succession over, possibly, some generations. If there are gaps during this long period, a certain amount of guesswork is unavoidable, with the result that the reliability of the whole record is endangered. For the lack of a few observations the curve cannot be trusted, and an irregularity might have occurred which could contradict the periodicity exhibited during the remainder of the time under review. Happily this does not occur very often, and an extreme case has been envisaged for the purpose of accentuating the necessity of continuity in observation.

From the foregoing it will be appreciated that observation by various people must be reduced to a common form, and there is a good case for taking part in an observing programme already under way as against individual attempts in observing long period stars.

Interpretation. This will necessarily include the keeping of satisfactory records as the work progresses, and a standard form is usually adopted, such as that used by the B.A.A. Variable Star Section, with one sheet per star written up from the observer's notebook periodically. Some observers do this daily, while others prefer to leave it until a mass of observations has accumulated. The latter method is recommended because it does not imprint on the mind the fluctuations in magnitude which daily writing up must do, with the attendant danger of going to the telescope expecting to find a certain star at a certain stage of variation. However conscientious the observer may be, there is always the danger of prejudice if the trend is already known before an observation is made. The record sheet is all that the plotter has to rely on, and it should be as nearly accurate as possible.

When plotting observations in graphical form with magnitude plotted against date and time, it is the form of the curve that indicates the type of star under observation. Obviously, the curve of a long period variable with its rise characteristically shorter than the sometimes irregular fall, is quite dissimilar from the regular rhythm of an eclipsing binary or the sudden changes of an irregular of the R Coronæ type.

Colour correction will be necessary in cases where the personal colour equation shows itself in team work by one observer consistently over- or under-estimating the brightness of red stars as compared with his fellows. This correction can be established from the observations plotted and may reach a maximum of one magnitude, notably when a bright red star is observed by a red-sensitive eye. The personal colour equation of each individual observer will be smoothed out in the drawing of the mean curve of team observations, provided the team has no overwhelming bias as a whole. The resulting magnitude established for each plot will be the mean for the whole team, and not only personal colour equations, but any individual variations therein, will largely disappear from the final plot. Observers should not adjust their magnitude estimates when working as a team, but if they are aware of any large error should advise the plotter so that he may be cognizant of the danger of accepting them as true apparent magnitudes without correction.

The plotting of variable star observations is not in itself a difficult operation; more difficult is the establishment of a mean curve when there is scatter over a large area, or when blanks are occasioned by lack of observations. The former is a mathematical problem, while the latter may sometimes be filled in by inference if the characteristic curve of the variable is known already. If it is not known, then it is quite dangerous to attempt filling in, particularly in the cases of stars newly observed or of irregular habits. Experienced judgement will be the best guide as to the amount of intelligent guesswork considered prudent.

Having plotted the characteristic curve for a full sequence of

events, it remains to express the character of the variation as a mathematical formula, but observations must be continued long after this has been done, to check on the star's behaviour and to record any variation from the normal that may occur. As matters stand, one is already able to go further than merely to record the curve of a particular star's variation.

From the examination of a number of curves, it is apparent that variable stars fall into classes, notably the eclipsing binary types, the pulsating types, long-period variables and irregulars. The two latter classes may be regarded as including novæ. Each of these classes is sub-divided, and it will become apparent from time to time that it is necessary to transfer a star from one class to another.

The outstanding problem today is that of fitting variable stars into the cosmic scheme, rather than of interpreting their characteristics as a pointer to the solution of their structure, for this latter problem has largely been solved. Both statistical and individual studies are required for this purpose.

For statistical studies numerous catalogues are available, ranging from simple lists for the amateur observer to those covering the requirements of the more advanced astronomer, who needs something more comprehensive. A standard work is the *Atlas Stellarium Variabilium* of J. G. Hagen, which was published from 1899 to 1941 and contains charts and comparison stars for some 488 variables, but the more modern standard work is the *General Catalogue of Variable Stars*, which carries annual supplements in Russian, but with English translations of the introductions.

Studies have already been made of distribution in order of length of period as well as between spectrum, period and absolute magnitude. In general, the shorter the period, the earlier the spectral class, and the brighter a variable star is intrinsically. Further studies have been carried out relating colour and period, and period with range of variation. A study of colour change in relation to amplitude of variation could possibly provide information as also might a survey of colour variation in relation to period. It would be necessary to adopt a colour scale expressible in numerical form to facilitate graphical plotting of the observations.

Distribution in galactic co-ordinates and, less important perhaps, distribution according to constellations, have already been studied.

Broadly speaking, it appears that long period variables have a maximum frequency around 200 to 350 days period, while short period stars have a smaller range of variation.

Studies of the behaviour of individual stars have brought to light interesting examples of unusual conditions:

> *31 Cygni* has been known to possess a composite spectrum as a binary for some time. It is now clear that the secondary star suffers eclipse and shines through the atmosphere of the primary. These eclipses last for some months.
>
> *Y Y Geminorum* is a 20-hours-period eclipsing pair, but the stellar disks are patchy and so cause irregularities.
>
> *SS Cygni* shows emission and absorption lines varying out of phase, indicating binary motion, with a type G primary and a hot variable sub dwarf of type B, which do not eclipse. It is suggested that variation in colour is due to the variable importance of the B star relative to the G star.
>
> *Pleione.* Rotational instability appears to cause the star to shed a disk of material. This process of disk formation and disruption seems to be repeated.
>
> *ϕ Persei* is a spectroscopic binary, having the secondary apparently enclosed within the shell of the primary, which shell is compressed in front of the secondary, giving rise to increased emission and absorption in the violet-ward components of the H lines.
>
> *λ Andromedæ* appears to be a spectroscopic binary, but the inclination of the orbit plane is probably fairly low, and we see the pulsating component approximately pole-on.
>
> *TW Ceti.* is another binary system with the larger star having the greater luminosity but the smaller mass and being ellipsoidal. The small star is over-massive and under-luminous, and it is suggested that the behaviour of the binary system includes the transfer of mass from the larger to the smaller star.

Consideration of these few quoted examples of unusual variable stars and the suggestions that have preceded them, as well as to the Table that follows, may perhaps stir the imagination and encourage yet another observer to take up the study of variable stars. If so, the author's hopes will have been realized.

Table 5

LIST OF VARIABLE STARS FOR OBSERVATION

Name	*R.A.*		*Dec.*		*Mag. Variation*	*Remarks*
	h	m	°	′		
R And.	0	21·4	38	18N	6·1—14·9	
W And.	2	14·4	44	4N	7·4—13·7	
S Aql.	20	9·3	15	28N	8·9—12·4	
η Aql.	19	50	00	53N	3·7—4·5	Period 7·18 days N.
R Ari.	2	13·3	24	50N	7·5—13·7	
R Boo.	14	35	26	57N	6·7—12·8	
S Boo.	14	21·2	54	02N	8·0—13·8	E
γ Cas.	0	54	60	27N	1·6—3·2	E
ρ Cas.	23	52	57	18N	4·1—6·2	E Requires observation
R Cas	23	55·8	51	6N	5·5—13·0	
T Cas.	0	20·5	55	31N	7·3—12·4	
μ Cep.	21	42	58	33N	4·0—5·5	Long period. E. N.
o Cet.	2	16·8	3	12S	2—9	E
R CrB.	15	46·5	28	18N	5·8—14·8	Irregular E
P Cyg.	20	16	37	54N	?	Requires observation
R Cyg.	19	35·5	50	5N	7·5—13·9	E
U Cyg.	20	18	47	44N	7·2—10·7	
SS Cyg.	21	40·7	43	21N	Irregular	
R Gem.	7	4·4	22	47N	7·1—13·5	
U Gem.	7	52·1	22	8N	Irregular	
η Gem.	6	12	22	31N	3·2—4·2	E.N.Period 231 days
T Her.	18	7·2	31	1N	8·0—12·8	E
U Her.	16	23·6	19·–	N	7·5—12·5	E
R Leo.	9	44·9	11	40N	5·8—10·0	E
X Leo.	9	48·4	12	07N	12·0—15·0	
SV Lyn.	8	01·	36	30N	?	Requires observation
U Ori.	5	52·8	20	10N	6·3—12	
α Ori.	5	52·	7	24N	0·2—1·0	Irregular E. N.
R Peg.	23	4·1	10	16N	7·8—13·2	E
R Per.	3	26·8	35	30N	8·7—14·0	
β Per.	3	5·	40	46N	2·3—3·5	Eclipsing type. E.N.
λ Tau.	3	58	12	21N	3·8—4·1	Short period E. N.
R UMa.	10	41·2	69	2N	7·5—13·0	E
S UMa.	12	41·8	61	22N	7·8—11.7	
T UMa.	12	34·1	59	46N	7·7—12·9	
S Vir.	13	30·4	6	56S	7·0—12·7	

THE FOLLOWING STARS ARE ONLY OBSERVABLE IN SOUTHERN LATITUDES

RDor.	4 36	62 11S	4·5—7	Period 335 days N.
L_2Pup.	7 12	44 33S	3·1—6·3	Period 141 days
RCar.	9 31	62 34S	4·0—10·	Period 305 days
κ Pav.	18 52	67 18S	4·0—5·0	Short period. N.

E— Stars easily found or near lucid stars.
N— Stars observable by naked eye.

Reference should be made to J. S. Glasby's book *Variable Stars* (Constable, London 1968).

Chapter Eighteen

EARTH SATELLITE OBSERVATION BY AMATEURS

K. FEA

BEFORE THE FIRST satellites were launched a good deal of attention was paid, during the planning of the International Geophysical Year (1957–58), to the tracking of the proposed satellites. Three basic methods are available: the tracking of radio transmissions from the satellite; the tracking by radar reflection; optical tracking with telescopes and cameras while the satellite is lit by the Sun. All three approaches have been developed, and amateur observers have played an important part. Especially valuable were the early observations by amateurs of the radio signals of the first satellites, described by Heywood[1,2]. Radio tracking is now, however, with radar techniques, almost solely carried out by the efficient, world-wide net of American stations. The reception of telemetary is also adequately covered by these stations. Some useful Doppler tracking (the recording of radio frequency versus time during a pass of a satellite) is still undertaken by amateurs, particularly on objects which transmit on frequencies other than the standard 136 Mc/s. However, amateur interest centres primarily on optical methods, and the other techniques will not be discussed here.

Much of the early discussions on optical tracking remains valid, for example Zirker *et al.*[3] but it is useful to summarize again here the reasons for making observations of artificial satellites, especially since the emphasis has shifted during the last five years.

It is necessary to define "observation" in this context. This is usually taken to mean a statement of the apparent, celestial position of the satellite, for example in terms of right ascension and declination, and the time at this position. The data returned to the prediction centre should include: the position, the time, an estimate of the accuracy, the observer's latitude, longitude and height above sea level, and possibly the satellite's magnitude and fluctuations. Certain tracking devices yield also the angular velocity and direction of track, but we assume here that the aim is to obtain timed positions only. It can be said at once that, under almost all circumstances, the value of the observations increases with the accuracy and usually with the number of observations on each pass (or "transit"), on different passes, on different satellites and from different sites.

There are two fundamental reasons for obtaining observations. The first relates to locating a satellite in its orbit, relative to the Earth below, to make the data from the experiments on board more meaningful. For example, an experimenter may wish to know exactly where the satellite was when his experiment measured a sudden flux of energetic electrons—see, for instance, O'Brien[4]. Such a need for exact location at critical moments will become acute when the "ozone-absorption" experiment is flown in the second US/UK satellite. A similar experiment has been described by Twomey[5]. The experimenter must rely on the data sent to him by the prediction centre, and the centre requires a continuous flow of observations from as many sites as possible. It may be added here that there is scarcely now a danger of a satellite becoming *lost*, since the establishment of the American radar "fences"; the danger is, rather, of a loss of accuracy in locating a satellite in its path.

The second reason, which concerns us more closely, is that important information on the Earth's gravitational field (and therefore on the Earth's shape and internal structure) and on the structure of the atmosphere above about 200 km, can be obtained by studying the changes in satellite orbits with time. The orbit may be defined by six elements, illustrated in Fig. 39, and familiar to most. The elements define the shape and orientation in space of the elliptical orbit, and by obtaining values for the rates of change with time of the various elements, data on the Earth's figure and atmosphere are deduced. Clearly, and especially if the changes are rapid, numerous observations are needed to define the orbit continuously. And, if the changes are rapid, observations of relatively low accuracy may suffice; here the amateur observer can make very valuable contributions with modest equipment.

The three most important changes in the elements are illustrated in Figs. 40–42. First, it is seen that an elliptical orbit brings the satellite at perigee into denser air. On each passage through perigee, therefore, the satellite loses some energy through drag. The result is that the orbit steadily contracts, apogee falling more rapidly than perigee, until the orbit is nearly circular, when a general contraction occurs and the satellite re-enters the atmosphere and is destroyed. The fiery disintegration has been observed visually for about half a dozen satellites. Since Kepler's laws hold approximately for Earth satellite motion, the contraction of the orbit—or the decrease of the major axis—entails a shortening of the orbital period of

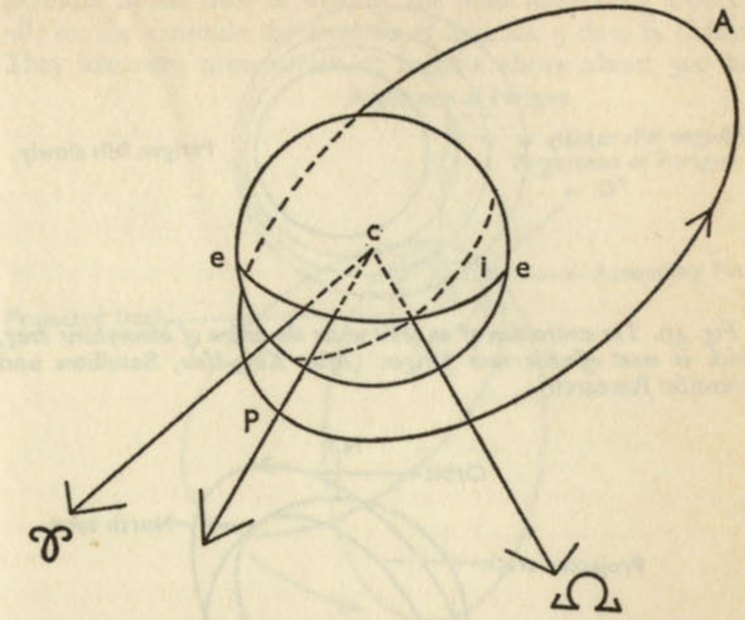


Fig. 39. *The elements of a satellite's orbit. The orbital ellipse projects into a great circle on the Earth's surface, cutting the equator,* ee, *at an angle,* i, *the inclination. The north-bound intersection of the orbit with the equator is termed the ascending node. The angle* γ C Ω *is the right ascension of the ascending node. The ellipse has a maximum diameter,* AP, *the major axis. The maximum distance from the Earth's centre,* CA, *equals* $AP(1 + \epsilon)$, *where* ϵ *is the eccentricity. The angle* Ω CP (*in the plane of the orbit*) *is named the argument of perigee. The time taken for one revolution relative to perigee is the anomalistic period.*

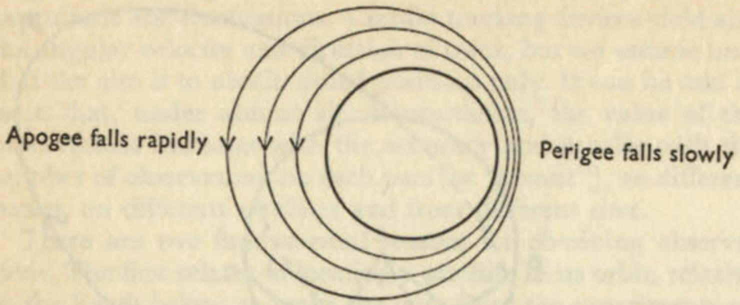


Fig. 40. The contraction of an orbit under the action of atmospheric drag, which is most effective near perigee. (After King-Hele, Satellites and Scientific Research).

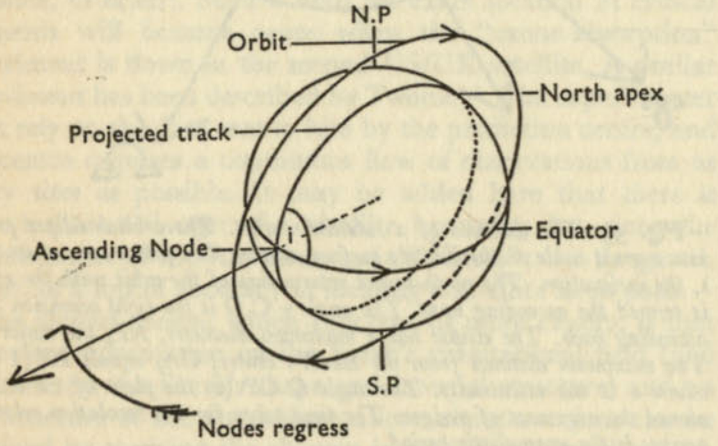


Fig. 41. The regression of the node, due to the Earth's equatorial bulge. The node moves in the opposite direction to the satellite's motion, that is westwards for a direct orbit. (Reproduced from Fig. 1.6 Mem. B.A.A., **39,** (2), 1961).

revolution. It is possible to deduce the air density in the region of perigee from the observed orbital period/time relation. The method has been simply described by King-Hele[6], and has been given in detail by Cook, King-Hele and Walker[7]. A recent review of air densities obtained by this and other methods has been given by Kallmann-Bijl[8], who discusses the variations of density and temperature at different heights due to diurnal, seasonal and latitude effects. These variations are perhaps, at the time of writing, the most interesting aspect of all; see for example the analysis of Sputnik 3 data 6, (May[9]). They are very pronounced at heights above about 500 km. For example, the density at a height of about 500 km appears to vary by a factor of ten from day to night. By studying different orbits these effects are slowly revealed. To elucidate the very large changes due to the 11-year cycle of solar activity, systematic observations over many years are needed. Here the perseverance of the dedicated amateur is of great value.

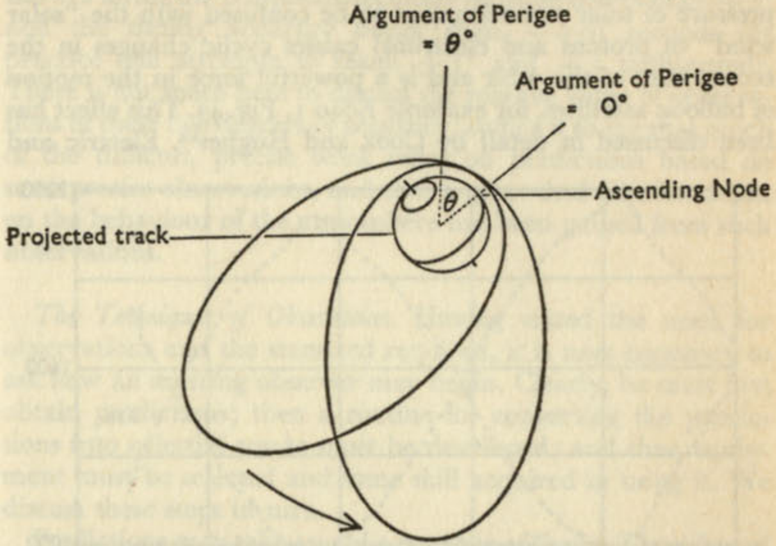


Fig. 42. The rotation of the orbit in its own plane, due to the Earth's equatorial bulge. Perigee moves in the same direction as the satellite's motion for inclinations less than about 63°, *but in the opposite direction for inclinations greater than* 63°. (*Reproduced from Fig.* 1.4 Mem. B.A.A., **39,** (2), 1961).

The two other changes in the elements are almost steady motions of the ascending node, Fig. 43, and of the argument of perigee, Fig. 44. The orbit both precesses in space about the Earth's axis and also turns in its own plane, due to the Earth's equatorial bulge, or polar flattening. A revised figure for the polar flattening, derived from orbit studies, has been given by King-Hele and Merson[10]. Another study of the Earth's gravitational field has recently been made by Smith[11], using observations mainly produced by amateurs. Again, a simple account of the effect on orbits of the Earth's non-symmetrical gravitational field has been given by King-Hele[6].

Other generally smaller effects disturb a satellite's orbit. The pressure of solar radiation (not to be confused with the "solar wind" of protons and electrons) causes cyclic changes in the eccentricity of the orbit and is a powerful force in the motion of balloon satellites, for example Echo 1, Fig. 43. This effect has been discussed in detail by Cook and Hughes[12]. Electric and magnetic forces also act on the satellites, especially on large, light objects, and have been studied by Beard and Johnson[13]. Rather precise observations are naturally needed however to obtain information on these processes.

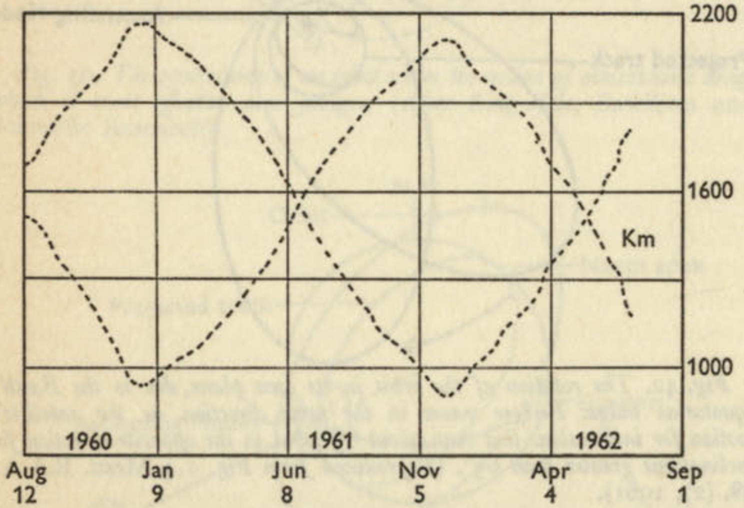


Fig. 43. *The oscillation of the orbital eccentricity for Echo* 1, *due to solar radiation pressure. The curves represent the heights of apogee and perigee. Note that the mean height is steadily decreasing, due to air drag; irregularities in the curves arise from variations in air density, and drag, and are closely correlated with activity on the Sun.* (*Reproduced from the Satellite Situation Report, July* 17, 1963, *of the Goddard Space Flight Center*).

The various catagories of observation accuracy have been defined in a report of the Royal Society[14]. Two of these catagories may be quoted here, as these give roughly the division between two areas of research. The "semi-precise" standard should be the aim of all amateur observers; this requires a positional accuracy of ± 10′ and a timing accuracy of ± 0·2 seconds (the aim should normally be ± 0·1° and ± 0·1 seconds). In the precise catagory, vital for studies of the Earth's form, the positional accuracy must be better than ± 1′ and the timing accuracy better than ± 0·01 seconds (in practice one attempts to reach ± 1″ and ± 1 millisecond). There is not space here to discuss the relative value of observations of these two degrees of accuracy; suffice it to say that much of the difficult, precise work relies on predictions based on semi-precise observations, and that a great deal of information on the behaviour of the atmosphere has been gained from such observations.

The Techniques of Observation. Having stated the need for observations and the standard required, it is next necessary to ask how an aspiring observer may begin. Clearly, he must first obtain predictions; then a routine for converting the predictions into celestial tracks must be developed; and then equipment must be selected and some skill acquired in using it. We discuss these steps in turn.

Predictions may take any of a number of forms. Those issued by the Goddard Space Flight Center or by the Smithsonian Astrophysical Observatory give the times of equatorial crossings (ascending node), the longitude of the sub-satellite point at this moment, and corrections to obtain the positions and times at other latitudes. The heights are given also at various latitudes and all equatorial crossings are tabulated for a week or longer. The observer in Great Britain will most likely obtain his predictions from the Satellite Section of the D.S.I.R. Radio Research Station (R.R.S.) at Ditton Park, Slough, Bucks. Here many satellites are continuously predicted, the data sheets issued including the times at apex (most northerly point) or at crossing latitude 50°N for polar satellites, the longitude at this point and a table of heights. Figures are usually given to enable the ground track to be plotted on a map, or else a track diagram is issued. Since the observer may not have access to these track diagrams, particularly if American predictions are used, a general graphical method is described here for plotting satellite tracks and obtaining apparent (predicted) celestial tracks. The method also applies to the diagrams issued by the R.R.S.

On a convenient projection, for example ordinary polar graph paper, take the north pole as origin and mark lines of latitude and longitude. Plot the observer's position as in Fig. 44. From this point we wish to draw the great circles that correspond to particular azimuths, say at 30° intervals. This is accomplished with fair accuracy by using the data of Table 8, which has been calculated for latitude 53·°oN. For other

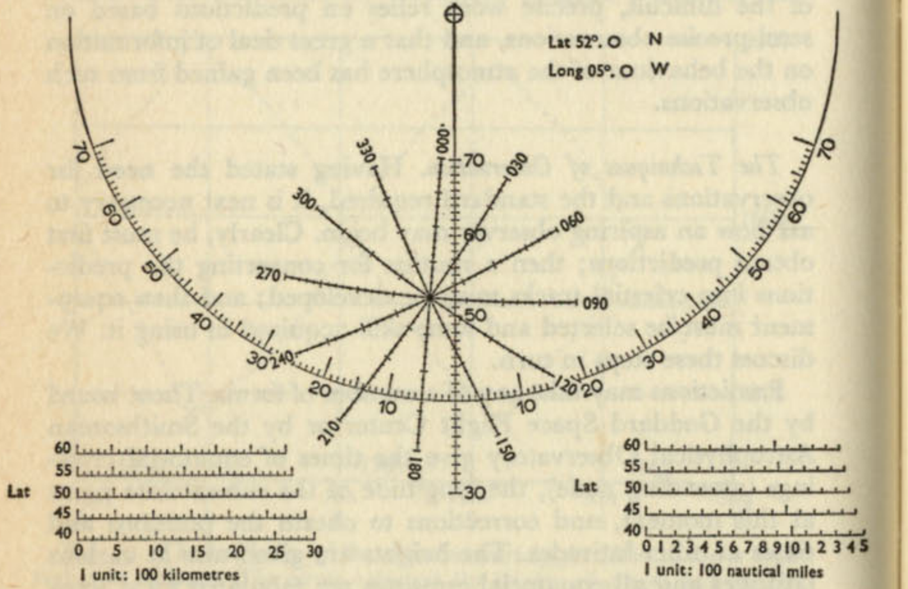


Fig. 44. *An example of a basic map, showing azimuth lines with range marks radiating from the observer's position. The projection in this case is polar stereographic* (*similar to that used in the R.R.S. diagrams*). (*Reproduced from Fig.* 12·2 Mem. B.A.A., **39,** (2), 1961).

latitudes within the British Isles the latitudes given in the Table should be corrected by the difference between the actual latitude and 53·0°N. The resulting curves may be smoothly drawn with a bent spline or ruler. The ground ranges along these selected azimuths, at intervals of 500 km, may be taken from the Table also. The divisions into 100 km intervals may be carried out by simple interpolation, or with proportional dividers.

Table 6

Azimuth/Range grid for latitude 53·00N.

Az	r	B	λ	Az	r	B	λ
000	500	57·50	00·00	090	2000	49·42	28·39
000	1000	62·01	00·00	090	2500	47·54	34·57
000	1500	66·51	00·00	090	3000	45·35	40·29
000	2000	71·02	00·00				
000	2500	75·52	00·00	120	500	50·58	06·15
000	3000	80·03	00·00	120	1000	47·87	11·66
				120	1500	44·93	16·61
030	500	56·84	04·12	120	2000	41·79	21·06
030	1000	60·50	09·15	120	2500	38·50	25·08
030	1500	63·94	15·42	120	3000	35·08	28·74
030	2000	67·03	23·34				
030	3500	69·61	33·35	150	500	49·05	03·43
030	3000	71·49	45·69	150	1000	45·01	06·36
				150	1500	40·90	08·89
060	500	55·06	06·82	150	2000	36·75	11·13
060	1000	56·71	14·30	150	2500	32·55	13·13
060	1500	57·87	22·36	3000	3000	28·33	14·96
060	2000	58·49	30·83				
060	2500	58·54	39·46	180	500	48·50	00·00
060	3000	58·01	47·98	180	1000	43·99	00·00
				180	1500	39·49	00·00
090	500	52·77	07·46	180	2000	34·98	00·00
090	1000	52·07	14·76	180	2500	30·48	00·00
090	1500	50·94	21·77	180	3000	25·97	00·00

The latitude, B, and longitude, *λ*, are given at various ranges, r (in kilometres), along azimuth lines, Az, at 30° intervals. The observer's position is taken at latitude 53·°00N, longitude 00·°00 (i.e. on the Greenwich meridian). For other latitudes within the British Isles correct the latitudes given by the difference between the actual latitude and 53·°00N. Similarly correct for longitudes other than 00·°00. Ranges between the points given may be linearly interpolated. Note that the azimuths to the west are symmetric with respect to those given, the latitudes being the same and the longitudes being west of the observer instead of east.

These figures are taken from a table computed and made available by D. E. Smith.

Having drawn this net, centred on the observer, the predicted positions of the satellite could be taken and plotted on the same map. It is more convenient instead to plot the track of the satellite on a second, transparent overlay, see Fig. 45. Then the overlay may be rotated over the basic map and pinned in the predicted longitude. Even if data are not available for plotting the satellite track, the orbital inclination is likely to be known and in this case Table 9 may be used. Inclinations below 70° are plotted relative to the apex point and those above 70° are plotted relative to the point of crossing of latitude 50°N.

Table 7

λ/i	40	41	42	43	44	45	46	47	48	49	
10	39·6	40·6	41·6	42·6	43·6	44·6	45·6	46·6	47·6	48·6	
20	38·3	39·3	40·3	41·3	42·3	43·3	44·3	45·3	46·3	47·3	
30	36·0	37·0	38·0	39·0	39·9	40·9	41·9	42·9	43·9	44·9	
40	32·8	33·7	34·6	35·6	36·5	37·5	38·5	39·4	40·4	41·4	
50	28·3	29·2	30·1	31·0	31·8	32·7	33·7	34·6	35·6	36·5	
λ/i	50	51	52	53	54	55	56	57	58	59	
10	49·6	50·6	51·6	52·6	53·6	54·6	55·6	56·6	57·6	58·6	
20	48·3	39·3	50·3	51·3	52·3	53·3	54·4	55·4	56·4	57·4	
30	46·0	47·0	48·0	49·0	50·0	51·0	52·1	53·2	54·2	55·3	
40	42·5	43·5	44·5	45·5	46·5	47·5	48·7	49·7	50·8	51·9	
50	37·5	38·5	39·5	40·5	41·5	42·5	43·7	44·7	45·8	46·9	
60	30·8	31·7	32·6	33·6	34·5	35·5	36·6	37·6	38·7	39·8	
λ/i	60	61	62	63	64	65	66	67	68	69	70
10	59·6	60·6	61·7	62·7	63·7	64·7	65·7	66·7	67·7	68·7	69·7
20	58·5	59·5	60·5	61·6	62·6	63·6	64·7	65·7	66·7	67·8	68·8
30	56·3	57·4	58·5	59·6	60·6	61·7	62·8	63·9	65·0	66·1	67·2
40	53·0	54·1	55·3	56·4	57·5	58·7	59·8	61·0	62·2	63·4	64·6
50	48·1	49·2	50·4	51·6	52·8	54·1	55·3	56·5	57·8	59·2	60·5
60	40·9	42·1	43·2	44·5	45·7	47·0	48·3	49·7	51·0	52·5	54·0
φ/i	70	71	72	73	74	75	76	77	78	79	
40	7·9	7·4	7·0	6·5	6·1	5·7	5·2	4·8	4·4	4·0W.	
60	13·4	12·4	11·5	10·6	9·8	8·9	8·2	7·6	7·0	6·3E.	
70	64·3	46·9	40·6	35·8	32·1	28·7	25·9	23·4	21·1	18·8E.	
φ/i	80	81	82	83	84	85	86	87	88	89	90
40	3·6	3·2	2·9	2·6	2·2	1 8	1·4	1·1	0·7	0·4	0·0W.
60	5·7	5·1	4·4	3·8	3·3	2·7	2·2	1·6	1·1	0·5	0·0E.
70	16·8	15·0	13·1	11·3	9·5	7·9	6·3	4·7	3·1	1·6	0·0E.

For various longitudes, λ, either east or west of the apex point (most northerly point) and for inclinations, i, between 40° and 70°, latitudes are given to enable the satellite ground track to be plotted. For inclinations other than the integral values shown the latitudes may be simply interpolated. For inclinations between 70° and 90° the longitudes relative to that at latitude 50°N are given for various other latitudes. Note that the designations "east" and "west" should be interchanged if the satellite is south-bound, as opposed to north-bound, and also if the orbit is retrograde, (i.e. if the inclination is greater than 90°). The figures given do not take account of the Earth's rotation during the passage of the satellite along the track.

The Table is extracted from *Mem. B.A.A.* **39** (2), 1961.

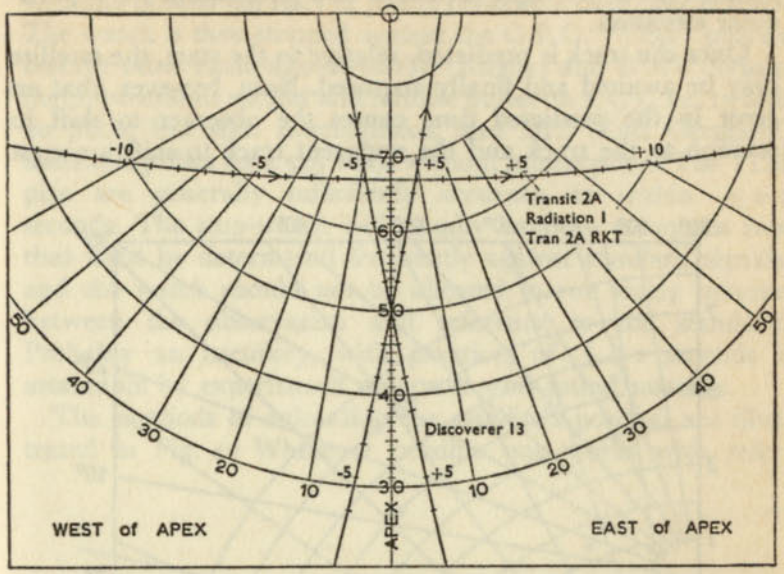


Fig. 45. An example of satellite tracks plotted from the data in Table 9. The time marks (minutes) are plotted from a knowledge of the orbital period. (Reproduced from Fig. 12.3 Mem. B.A.A., **39**, (2), 1961).

Pinned according to the predicted data, the satellite track cuts the azimuth lines in a number of places and the ranges may be read directly. The height of the satellite at each point may be extracted from the predictions, and also the time at each point. There remain two steps. First, a conversion from range and height to elevation is needed. This is done with the aid of charts given by Taylor[15] or by drawing a chart of this type, Fig. 46. Second, a conversion from the pairs of azimuth and elevation (and time) to right ascension and declination is required, unless a theodolite or similar instrument with azimuth and elevation scales is used. For the track must be known in relation to the stars in order to locate the satellite if it is faint. This last step can be tedious. Graphical navigation devices exist which can be modified to do this; or the conversions can be carried out with the standard formulæ of spherical trigonometry, for example as given by Smart[16]; or tables may be used, as described (with useful examples) by Turner and others[17]. Probably the best course, in difficulty, is to write to the Director of the Artificial Satellite Section of the British Astronomical Association, who will assist with advice. A special and easily calculable case is that of the meridian crossing. Knowledge of the local sidereal time (taken from the *B.A.A. Handbook* or from *The Astronomical Ephemeris*) and of the observer's latitude at once gives the right ascension and declination for a particular elevation.

Once the track is predicted, relative to the stars, the satellite may be awaited and finally acquired. Note, however, that an error in the predicted time causes the observer to shift in relation to the track and the apparent track to shift amongst the stars. It is wise to estimate the rate of change of altitude with time (both early and late) and to follow the predicted track accordingly. When the satellite has been located an observation is taken relative to known stars. A procedure adopted by many observers is as follows.

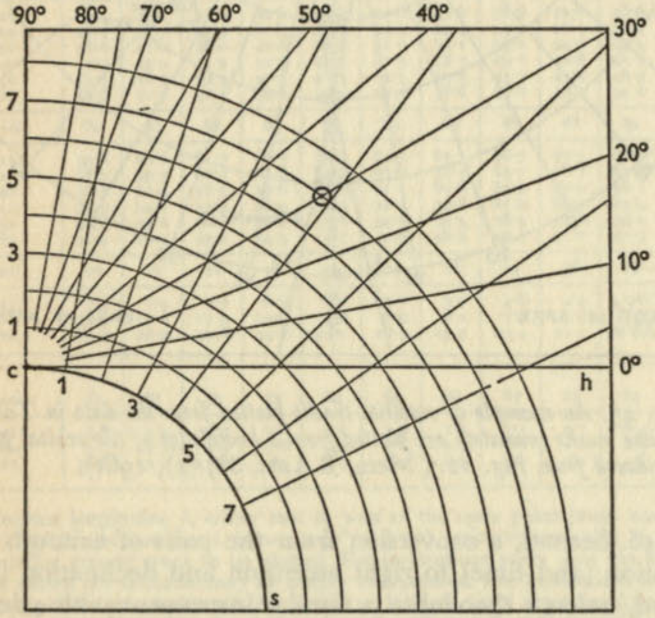


Fig. 46. An illustration of a height/range/elevation chart. Heights and ranges are in thousands of kilometres. The observer is at point C, the origin. The Earth's surface is CS, and Ch is the horizon. The point plotted at o, *as an example, has a height of* 7,000 *km and a ground range of about* 3,900 *km; the elevation is therefore* 30°·0. *This chart is for illustration only; observers should construct their own larger, more accurate charts.*

An accurate stop-watch is set running at the instant the satellite either passes close to a star (or, very infrequently, virtually occults the star) or passes between a close pair of stars. The watch is then stopped against the G.P.O. "TIM" pips or BBC or other radio signals—MSF (Rugby) and WWV (Washington) transmit second and minute pulses on 2.5, 5, 10, 15 and 20 Mc/s, but with interruptions, and DIZ (East Germany) transmits pulses on 4.525 Mc/s without interruption. The TIM pips are generally sufficiently accurate, to within ± 0·1 seconds. The stop-watch will usually have an erroneous rate that must be determined frequently against standard signals, and the watch should not be allowed to run many minutes between the observation and reference to the standard. Probably an accuracy, with practice, of ± 0·1 seconds is attainable by experienced observers with sound watches.

The methods of estimating the satellite's position are illustrated in Fig. 47 Wherever possible one works with reference to pairs of stars, and these should be quickly and certainly identified, or else an unambiguous sketch made on the spot. Since it is not possible to interpolate (or extrapolate slightly if necessary) to much better than ± 0·05 of the stars' separation, the separation should not much exceed 1°. This forces the selection of faint pairs, and therefore a good atlas is needed. The *Atlas Coeli, 1950·0*[18] has been found almost ideal, while the more elaborate *Atlas Eclipticalis, 1950·0*[19] is a useful adjunct. The

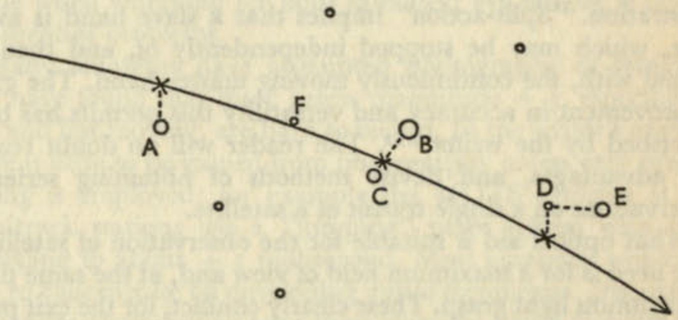


Fig. 47. Various ways of making observations of satellite positions relative to stars. The satellite may be timed when vertically above star A (the angular distance AX is estimated); when close to star F; when crossing the line joining stars B and C (the ratio CX:CB is estimated); or when on the line perpendicular to that joining stars D and E (the ratio DX:DE is estimated).

former covers the entire sky to magnitude + 7·75 and the latter the sky between declinations + 30° and − 30° to about magnitude + 9. Companion volumes to the *Atlas Eclipticalis* are in preparation to extend it to the rest of the sky. The other vital aid is naturally *Norton's Star Atlas*[20], which is invaluable for plotting predicted tracks. This atlas is not however suitable for reducing observed positions to right ascension and declination. If the other atlases are not available for this reduction, and they contain transparent grids that allow an accuracy of reading of at least ± 0·1°, then the observations should be returned to the prediction centre in their original form, relative to identified stars.

A split-action stop-watch is so much more valuable for satellite work than an ordinary stop-watch with a single hand, that it can almost be regarded as necessary. Such a watch, though a rather luxurious version, to be sure, is shown in the illustration. "Split-action" implies that a slave hand is available, which may be stopped independently of, and then reunited with, the continuously moving master hand. The great improvement in accuracy and versatility this permits has been described by the writer[21,22]. The reader will no doubt realize the advantages, and devise methods of obtaining series of observations on a single transit of a satellite.

What optical aid is suitable for the observation of satellites? The need is for a maximum field of view and, at the same time, a maximum light grasp. These clearly conflict, for the exit pupil diameter should not exceed the diameter of the observer's pupil (about 0·3 inches maximum), and this defines the minimum power possible, as described by Sidgwick[23]. The power must not fall below the point where the exit pupil expands beyond 0·3 inches. Hence, for a small objective aperture, a relatively low power and large field of view may be employed. But the light grasp will be small. A larger aperture, giving a greater light grasp, demands a higher minimum power and a smaller field of view. A compromise must therefore be sought between a large field and a large aperture needed for faint satellites. Note the relations:

Minimum power = O.G. diameter/Exit pupil diameter.
Maximum field (in sky) = Eyepiece field/Minimum power.

It has been found that two instruments suit the range of observable satellites best. For the low, usually bright, fast-moving and often unpredictable objects (Discoverer type satellites, for example) a wide field (up to 8°), small aperture (2 inches or less) "elbow" telescope is ideal. A pair of these has been mounted by the author as "elbow" binoculars, and it should be noted that a tripod is indispensable when searching for ill-predicted satellites over long periods. For fainter objects (below about magnitude + 7 and brighter than + 11) the four-inch reflector is ideal. The large eyepiece (of about 70° field) and the short focal length of the mirror (24 inches) allow a field of almost 4°. Elusive objects such as Explorer 8, Ariel 1, and the Tiros satellites are readily observed, and this instrument has been adopted for the six "advanced amateur" tracking stations sponsored by the Royal Society. Since this telescope is not a binocular, it is wise to cover the unused eye with a comfortable shade when searching for faint satellites; eye fatigue is one of the greatest problems.

Many amateurs have attempted photography of satellites, and have found that those below magnitude + 3, especially if low and fast moving, are hard to record. In the writer's opinion there is little to be gained from photography unless very precise timing is employed; for example the MOTS cameras at the Minitrack stations use a "jumping" plate system with time recording to about ± 1 millisecond. Most amateurs would do best to concentrate on developing visual techniques. Discussions of satellite photography have been given by Lloyd Evans[24] and Fisher[25].*

It is certain that the observation of earth satellites offers the amateur an almost unique opportunity to contribute to scientific research. It is hoped that many will be persuaded to take up this work, both with the patient visual approach and with the more complex and experimental methods of photographic and photo-electric recording.

*See Plate 22 and also Chapter 4 on the subject of meteor photography.

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Appendix

OBSERVING OF ARTIFICIAL SATELLITES

HOWARD MILES

FROM THE TIME Sputnik I was launched in 1957, members of the British Astronomical Association have played a very important rôle in providing the necessary observations required by the prediction centres. During the early stages, observations were sent to the Royal Aircraft Establishment, Farnborough, but since Sputnik III, all observations have been handled by the D.S.I.R. Radio Research Station, Slough.

Originally the Association's satellite work was handled either by the Radio and Electronics Section or by Gordon E. Taylor of Sussex, who has provided the predictions appearing on the B.A.A. *Circulars*. However, with more and more satellites being launched, it was found necessary to form a special section to deal solely with artificial satellites and space probes, and so in the Spring of 1961 the Artificial Satellite Section was formed.

One of the main aims of the Section is to train potential observers in satellite work in order to provide R.R.S. with sufficient observers to enable them to continue predicting for all the objects which pass over or near to Great Britain. This is being done by issuing simplified predictions for the brighter satellites, together with information sheets giving techniques and methods of obtaining local predictions.

B.A.A. Members have tracked and identified a very high percentage of the objects visible from Great Britain. Here is a typical example of the observations made by one of the experienced observers:

Observer: S. Milbourn July, 1962

		No. of Revs	*No. of Fixes*
1959 Iota 1	Explorer 7	1	1
1960 Epsilon 3	Sputnik 4	1	1

		No. of Revs	*No. of Fixes*
1960 Iota 1	Echo 1	6	16
1961 Alpha 1	Samos 2	3	5
1961 Delta 1	Explorer 9	2	7
1961 Epsilon	Discoverer 20	1	1
1961 Omicron 1	Transit 4A	1	1
1961 Omicron 2	Greb 3- Injun	1	2
1961 Omicron 3	Rocket fragments	1	2
1961 Rho 1	Tiros 3	3	5
1961 Rho 2	Tiros 3 Rocket	1	1
1962 Kappa 1	Midas 5	3	8
1962 Omega 1	Samos 6 ?	1	1
1962 Alpha-Alpha 2	Tiros 5 rocket	1	3
1962 Alpha-Epsilon 1	Telstar	3	7

Number of objects 15
Number of revolutions 29
Number of fixes 61

Several of the Section's experienced observers are included in the team of observers chosen to make accurate observations of Ariel 1, the first Anglo-American satellite. They have been issued with specially designed telescopes and much ancillary equipment.

The work of the Section, however, is not limited to the training of observers and the making of observations. As has been explained in the main article, the most common method of finding local predictions from those issued by R.R.S. involves the use of graphs. Quite often it is desirable to use a method which will give slightly more accurate results. This, in the past, has generally meant using time-consuming mathematical formulae. The Section is preparing a set of precomputed tables which will enable the observer to achieve quickly and easily the required accuracy without having to worry too much about his arithmetical ability.

Satellite observing, like all other branches of observational astronomy, involves skills which develop with experience. The technique used varies from one satellite to another, depending to a large extent on the magnitude and height above the Earth's surface. It is work of vital importance and is a very good example of where the amateur is working in close co-operation with the professional worker.

Chapter Nineteen

RADIO ASTRONOMY FOR AMATEURS

J. R. Smith

To most people a radio telescope looks something like that shown in Fig. 48. The parabolic reflector or "dish" focuses the incoming radio waves on to the aerial located at its focus in the same way as the speculum in an optical telescope can direct starlight on to a photographic plate placed at its prime focus. However, unlike the optical instrument, this type of radio telescope does not produce a picture of the sky directly. This must be done by scanning the required area of sky, measuring and recording the intensity of the radio waves from each small piece. The radio appearance is then plotted in the form of a contour map of temperatures or flux densities.

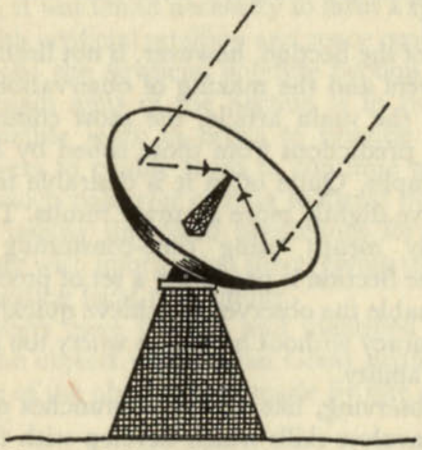


Fig. 48, Steerable parabolic reflector with aerial located at the focus.

A dish mounted so that it can be steered to any part of the sky, such as those at Jodrell Bank, has great versatility, but in spite of its enormous size is far inferior in resolving power when compared with the unaided eye, due to the very much longer wavelength of radio waves when compared with those of light. The resolving power of an aerial is approximately

$$\frac{57\cdot 3 \times \text{wavelength}}{\text{diameter of aerial}} \text{ degrees}$$

which is analogous to Dawes' Limit for an optical instrument

$$\frac{4\cdot 56}{\text{diameter of O.G. (inches)}} \text{ seconds of arc.}$$

The 250-ft. diameter Jodrell Bank instrument could on this basis resolve 10 minutes of arc at a wavelength of 20 cm, compared with 1 minute of arc by the eye at visual wavelengths. A smaller version is the 30-ft. diameter dish built by K. Tapping and the author (Plate 24, *bottom*).

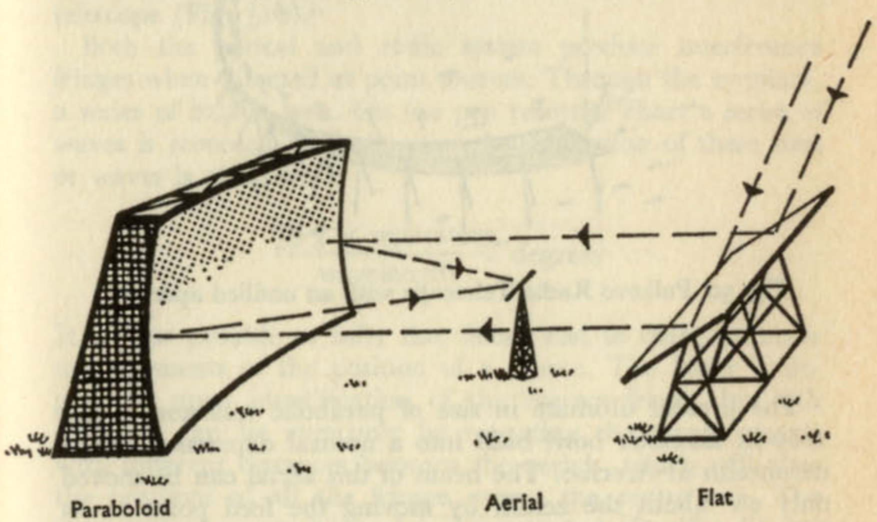


Fig. 49. Fixed paraboloid with flat movable in declination.

One variation of the single aerial system is the fixed paraboloid facing horizontally a movable "flat" (Fig. 49), as in the instrument at Nançay.

The Pulkovo Observatory uses an unfilled portion of a paraboloid to obtain high resolution of the Sun (Fig. 50).

A three-mile diameter ring of small dishes is used in Australia to obtain high resolution of the Sun in the same way as an optical mirror with the centre stopped out, leaving only a narrow ring at the edge.

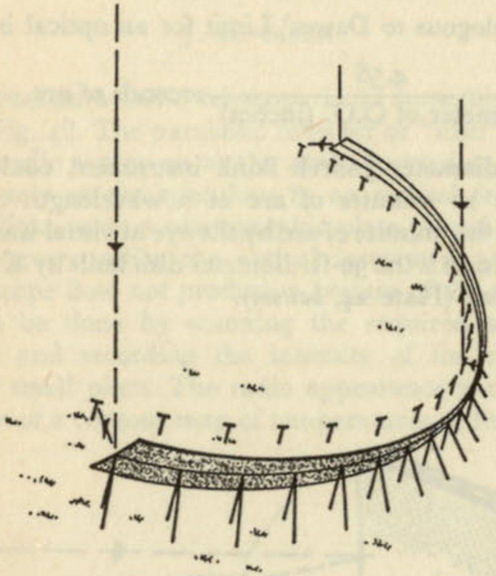


Fig. 50. Pulkovo Radio Telescope with an unfilled aperture.

The present ultimate in size of parabolic reflectors is the 1000-ft. diameter bowl built into a natural depression in the mountains at Arecibo. The beam of this aerial can be moved only 20° about the zenith by moving the feed point at its focus, as in the 218-ft. diameter fixed parabola used at Jodrell Bank, before the 250-ft. instrument.

Whilst the large steerable telescopes are extremely versatile, and are very useful for flux density measurements, spectrographic work and solar system radar studies, there is a practical limit to their resolving power and collecting area. These difficulties can be overcome by building simpler aerials covering larger areas of ground. If the observer can wait for his results, such an aerial can be pointed upwards at the sky at the required declination of the meridian and a scan can be made in right ascension by making use of the rotation of the Earth.

Where sensitivity is a prime need, the aerial can consist of rows and columns of smaller aerials connected together to cover a large area. A typical example is the 4½-acre array built by the research team at the Mullard Radio Astronomy Observatory at Cambridge under Dr. A. Hewish. This aerial was built to study the scintillation of quasars due to movement of interstellar gas clouds. It was with this aerial that the first pulsating sources or "pulsars" were discovered.

When resolving power is of greater importance than sensitivity, it is possible to use two aerials in conjunction to make an interferometer (Fig. 51a) similar to Michelson's stellar interferometer used on the 100-inch Mount Wilson telescope (Fig. 51b).

Both the optical and radio system produce interference fringes when directed at point sources. Through the eyepiece, a series of bars is seen. On the pen recorder chart a series of waves is recorded. In both cases the separation of these bars or waves is given by

$$\frac{57{\cdot}3 \times \text{separation}}{\text{wavelength}} \text{ degrees}$$

It is thus possible to infer fine detail and to make accurate measurements of the position of a source. The latter is dependent upon identification of the correct fringe, but this difficulty can be overcome by repeating the measurements with different distances between the aerials, which will alter the positions of all the fringes except the centre one. The same technique can be used to separate and identify adjacent sources in one direction.

Very long base lines have been used by means of radio links over tens of miles. Transcontinental distances giving resolutions of fractions of seconds of arc have been accomplished by means of tape recorders synchronised by atomic clocks. Perhaps the ultimate in resolution may be obtained with one aerial on Earth and the other on the Moon.

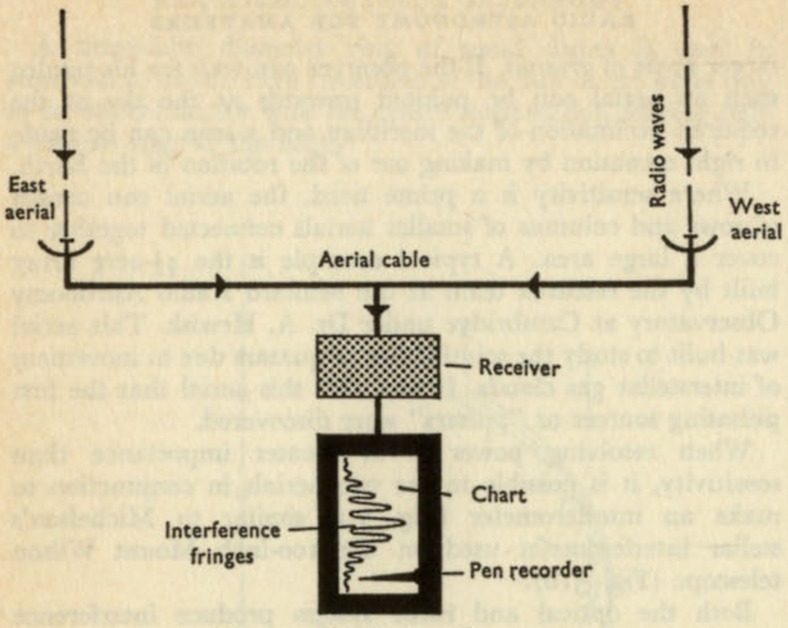


Fig. 51a. Radio interferometer.

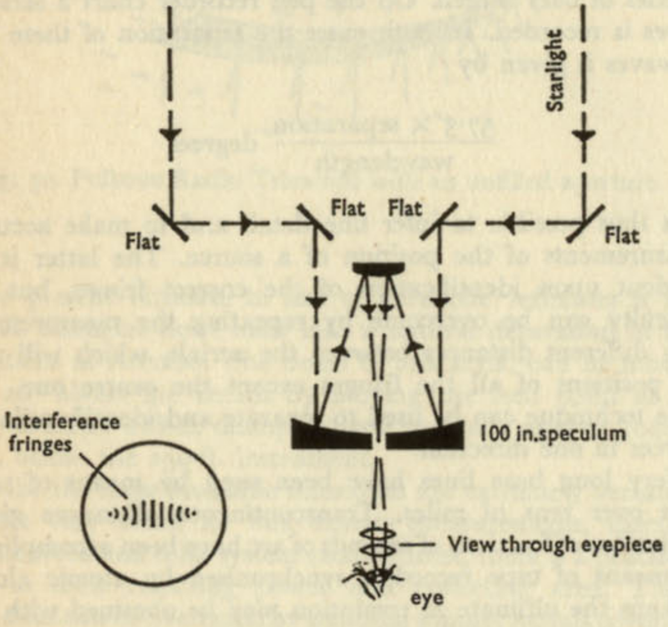


Fig. 51b. Optical interferometer.

However, if the direction of the line joining the two aerials is varied with respect to the sky, as well as their spacing, information can be obtained to build up a complete picture of the sky by summating the results of many observations, usually with the assistance of a computer. This method, originally devised by Professor Sir Martin Ryle at Cambridge, is known as "aperture synthesis", as the effective aperture of the system approaches the area of ground covered by one aerial in relation to the other.

Typical aperture synthesis systems are shown in Fig. 52.

Types of signals received. Most of the natural signals received from celestial sources have a completely random structure and have an extremely low strength. If all of the power received by the whole Earth in the whole of the radio spectrum from sources outside the Solar system could be collected, there would be barely sufficient to light an electric torch bulb.

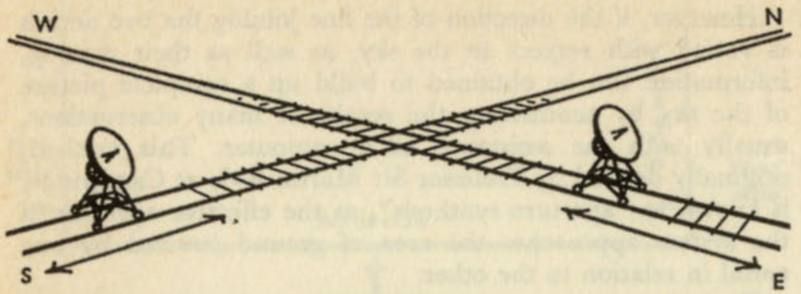
The power usefully fed to the receiver from an aerial 30 ft. diameter from the most powerful source outside the Solar system, Cassiopeia A, at metre wavelengths is approximately one hundred million millionths of a watt (10^{-14}W), or in the case of the newly discovered pulsars, one million million millionth of a watt (10^{-18}W).

If these signals are amplified sufficiently and fed to a loudspeaker, they sound like the hiss of a steam jet and are referred to as "noise". If the noise is spread evenly in all frequencies (pitches) it is known as "white noise". This hiss or noise has the same character as the unavoidable noise generated by the first stages of the receiver, about which more will be said later.

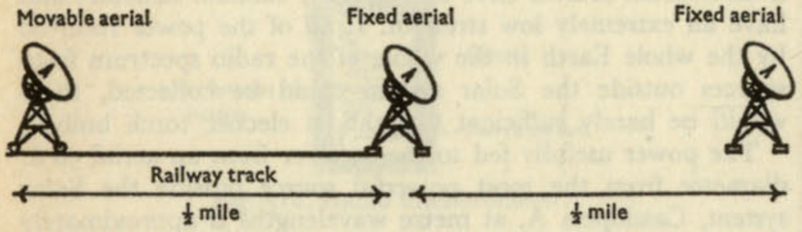
The noise generated by celestial sources can be generated in various ways, as described briefly below, and in all cases results from the acceleration of electrons.

I. THERMAL RADIATION

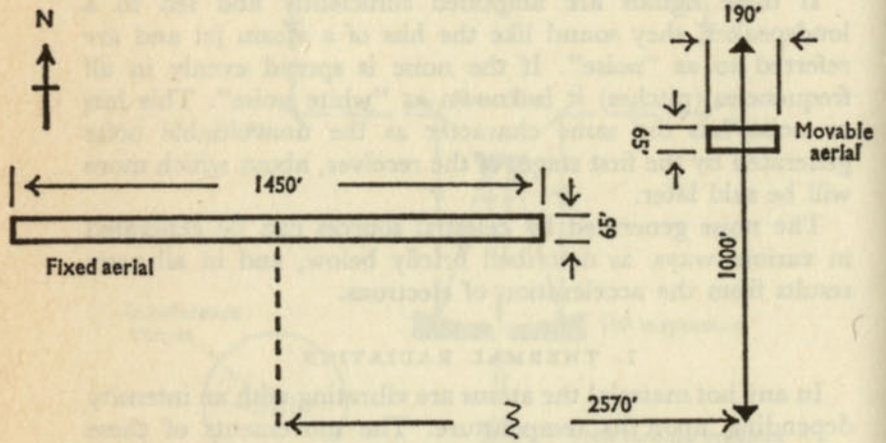
In any hot material the atoms are vibrating with an intensity depending upon its temperature. The movements of these atoms jostle their electrons and any free electrons in a random manner, thus causing them to radiate radio waves at all frequencies up to a maximum dependent upon the temperature.



Aperture synthesis interferometers of the Malvern and Owens Valley types.



Cambridge One-Mile Aperture Synthesis Interferometer. All three aerials are 60 ft. diameter and are equatorially mounted.



The Cambridge 178 MHz Aperture Synthesis Interferometer

Fig. 52. Typical Aperture Synthesis Systems.

2. SYNCHROTRON RADIATION

If electrons pass through a magnetic field, they are deflected so that they spiral around the magnetic lines of force, thus suffering acceleration. If they are travelling at relativistic speeds they emit a wide range of frequencies.

3. ČERENKOV RADIATION

Electrons or ions entering a cloud of disassociated atomic particles (a plasma) at high speeds above the velocity of radio waves in the plasma produce shock waves in it, again causing the electrons thus accelerated to radiate in certain directions.

4. SPECTRAL LINES

Neutral hydrogen atoms radiate at a wavelength of 21·1 cm if the direction of spin of their electrons is reversed. The neutral hydrogen line is the strongest yet discovered at radio wavelengths. The few other lines discovered are very weak.

Receivers. As already stated, the received signals from outside the Solar System are extremely weak, and the receiver produces its own noise, which has exactly the same character as these signals. The noise produced by the input end of a receiver of conventional type is typically 10^{-13} watts, which is of the same order as the signal from the powerful source given above. This means that the fainter sources will be lost in the receiver noise unless extremely large aerials are used. It is possible to improve matters by averaging the receiver output, or "integrating" over long periods, using a storage capacitor or a computer, and making a comparison between levels when the aerial is connected and disconnected. This process is rather like taking a time exposure of a moving crowd of people with only one person standing still. This person will be the only one recorded in the picture. However, the method is subject to considerable errors if the amplification of the receiver changes. These changes are due to variations in the power supplies, which can be cured, and to random changes in the circuit components, which cannot.

A major advance was made when R. H. Dicke devised a method of switching the receiver rapidly and continuously between the aerial and a known constant artificial signal. At one instant the integrating capacitor is charged in proportion to the wanted signal plus the receiver noise. At the next instant it is discharged in proportion to the artificial signal plus the receiver noise. The average charge over a period of time therefore corresponds to the difference between the celestial source signal and the known artificial signal, the receiver noise being mostly cancelled out. An important variation of this system is to reverse continuously the connections of one aerial at the switching frequency with respect to the other in a two-aerial interferometer system. The operation of the output circuits are as in the Dicke system, and this is known as a phase-switched interferometer. Typical recordings are shown in Plate 23, made by the Author using a pair of 5m^2 cylindrical paraboloids, one of which is shown in Plate 24 (*top*). The advantages are that diffuse sources, such as the Milky Way, are ignored, permitting the detection of distant small sources that would otherwise be swamped, also, that many forms of man-made unwanted signals are ignored. A disadvantage of the phase-switched system is that there is no direct comparison with a local standard signal source. The Cambridge aperture synthesis instruments are all phase-switched.

Novel use is made of this system by B. Y. Mills at Sydney, where two long aerials are set out in the form of a cross. One has a very narrow beam width in the east-west direction and a wide beam width in the north-south direction. The opposite applies to the other aerial. The two aerials are used as a phase-switched interferometer. As only a very small part of the sky is seen simultaneously by both aerials, this is all that will be recorded, thus producing a "pencil beam". The Mills Cross builds up a map of the radio sky by successive scans in declination, piece by piece. The aperture synthesis method, on the other hand, gathers information about a wide strip of sky over many days, but does not place individual sources on the map one at a time. The whole map of the strip is produced complete at the end of the survey by the use of a computer.

By switching between a pair of aerials which have their electric axes set at 90° to each other, it is possible to measure

the angle and degree of polarisation of the incoming waves. The aerials can be right and left-handed helices, or alternatively dipoles mounted at the focus of a dish. The former can detect circular polarisation.

RECENT DISCOVERIES

Radio astronomy has produced many surprises since its inception. It was predicted that the Sun should radiate at radio wavelengths with an intensity appropriate to the observed optical temperature of 5800°C in accordance with Planck's law. When actual measurements of the radio flux density at about 1 metre wavelength from the Sun were first made, it was found that they corresponded to temperatures of about one million degrees Centigrade, and even a million times greater than this during a solar flare. The former is in fact the temperature of the solar corona immediately above the photosphere. The coronal temperature remains high, out to very large distances. The lack of optical density prevents this high temperature producing intense light, in the same way as a sheet of red hot glass only radiates light feebly although it is still possible to see other objects through it. The very strong bursts of radiation from the Sun are not of thermal origin, but are due to the violent magnetic and mechanical shock waves occurring in a flare.

Radio waves from the Moon and the planets are feeble, and are due to their actual temperatures, except in the case of Jupiter, where powerful bursts lasting for a second or so at wavelengths between 10 and 20 metres are received. Their character is not unlike that of terrestial atmospherics due to lightning. As any lightning flash on Jupiter would have to be about a million times larger than a terrestial flash, this is an unlikely explanation. At first there appeared to be some correlation between their occurrence and the rotational speed of the planet. The agreement with the System I or System II periods was not exact, and a new period known as System III was devised. The latest analyses, however, show some connection with the motions of Jupiter's satellites, particularly Io, although the actual mechanism of generation of the radio waves remains a mystery.

Let us now turn to radio sources lying beyond our Solar System. If the stars are evenly distributed throughout space the number contained within a given sphere is proportional to the cube of the radius of the sphere. Also if all the stars are assumed to be of equal intrinsic brightness the maximum distance at which they can be seen above a minimum given apparent brightness is proportional to the square root of the distance. Hence the number that can be seen is proportional to the apparent brightness to the power of 1·5. If the number is plotted against the brightness on logarithmic scales they should fall on a straight line with a negative slope of 1·5.

Herschel employed this principle with his "star counts" using different sizes of telescopes to select different minimum brightness levels. He was thus able to show that the stars were not evenly distributed beyond a certain limit, which turns out to be the edge of our Galaxy.

Ryle followed the same reasoning for the radio sources known to be outside our Galaxy. He found that sources fell on a straight line, except for the very faint, and therefore very distant, ones. There appeared to be an increase followed by a decrease, which seems to indicate that the Universe has a fairly dense rim with little or nothing beyond, which favours the evolutionary (big bang) or the oscillating theories of the Universe at the expense of the steady state theory. The arguments either way, however, still continue vigorously.

Exploration of the Galaxy has been greatly developed by the observation of radio waves which can travel through the clouds of matter that obscure light from certain parts, particularly its centre.

The 21 cm hydrogen emission line can, by measurement of its Doppler frequency shift, give a measure of the velocity radial to the Earth of its source. Where background continuum signals pass through the intervening cold clouds of neutral hydrogen, absorption lines at 21 cm have Doppler frequency shifts appropriate to the radial velocity of each cloud impressed upon them. From this data it has been possible to draw a map of the spiral structure of our Galaxy.

Splitting of the 21-cm line by the Zeeman effect has made it possible to measure the magnetic field existing in the spiral arms. Measurements of the polarisation of emission at other

radio frequencies due to synchrotron radiation have given information about the movements of electrons, and thus the electric currents existing in the spiral arms. The indications are that the materials of the arms are held in position by what has been termed a magnetic bottle that locks the inboard ends to the rotating centre of the Galaxy, thus winding them up into spirals.

Early attempts were made to determine the nature of the solar corona and distribution of the Solar System gases by observing how distant sources with small apparent angular diameters, such as the Crab Nebula, vary or scintillate due to refraction caused by these gases. This effect is akin to the twinkling of stars due to atmospheric effects. The smaller the apparent angular size of the source, the greater the effect. It has been found by this means that the solar corona extends out to the Earth's orbit and beyond. This method was then extended to the examination of interstellar gas clouds. The converse is that some extremely small sources were discovered by scintillation, which appeared to have no optical counterparts and were termed "quasi-stellar radio sources". Subsequently some optical identifications were made, particularly with the 200-inch Mount Palomar telescope, and the name was shortened to "Quasars". These objects were found to be very faint and blue with large spectral red shifts. The latter would imply that their velocities of recession are high and that according to Hubble's law they should be at great distances. Some argument followed as to whether the red shifts were due to some other effect and that these quasars were nearer, possibly located within our own Galaxy. If this were so, they would be very small and dense, and could be white dwarf stars which have a mass similar to the Sun but a diameter similar to the Earth. The white dwarfs are stars that have run out of nuclear fusion energy and have collapsed under their own weight, due to the loss of internal radiation pressure. To permit this, the electron shells of its atoms collapse completely, thus forming matter with a density of several tons per cubic inch. This gravitational collapse provides the energy to heat the star to a high temperature, which has difficulty in escaping due to its small surface area. Due to the high gradient of its gravitational field and conservation of angular momentum, it can rotate approximately once every four seconds. If the speed is as fast as one revolution per second it could disintegrate.

Recent theories indicate that these stars could collapse even further to spheres of only 10 miles across if its protons and electrons are compressed to form neutrons, hence the name "Neutron stars". Due to their small size they would be very faint and unlikely to be seen optically making proof of the existence of such objects difficult. Being so small their rotational speeds would theoretically be high and of the order of about 1,000 revolutions per second.

At the beginning of 1968 Dr. Hewish and his team at Cambridge discovered some sources emitted extremely regular pulses of radio waves. The regularity was of the order of about 1 part in ten million million. These pulses were first thought to have come from deep-space probes, but from measurements of position this was disproved. They were shown to be at stellar or cosmological distances, which implied great transmitted powers that would have killed any "little green men" sending them.

Possible explanations were that these "pulsars" were white dwarfs or neutron stars that oscillated by radial expansion and contraction, or by alternate expansion on one axis in step with contraction on another axis. The extremely regular pulse rates in all cases are slowing down very slightly; none is increasing. According to one theory, pulsars are neutron stars. Two have been located in the Crab Nebula, and have been recorded visually as well as at radio wavelengths.

Other theories are that they are eclipsing binaries where one component occults active areas on the other similar to those on the Sun, or that the stars with active areas are rotating rapidly sending out the signals like a lighthouse beam. A recent theory by Hewish is that a plasma emitted by an active area is carried around the star by a magnetic field which rotates with and is locked to the star's rotation. Where the radius is such that the plasma is carried around at a speed near the velocity of light a hydro-magnetic shock-wave is produced in the surrounding gas, thus emitting radio waves. This would explain their strong observed polarisation.

Another possibility is that the waves are generated in the star's atmosphere by the presence of a companion in the same unknown way as the pulses from Jupiter are related to the motions of Io.

With all these theories there is the major difficulty that the pulse rates for different pulsars so far measured vary between 3 seconds and 1/30 second, which lies between the 4 seconds and 1/1000 second rotational speed postulated for the white dwarfs and the neutron stars respectively. If the present rapid rate of discoveries is maintained it is probable that some of the answers will have been found before this article is published, or that we will have even more questions to answer.

APPENDIX

Amateur radio telescope construction

This section is written assuming that the reader has some knowledge of radio technology and construction.

For those amateurs who would like to build a simple radio telescope the following design notes might be useful.

First, no radio telescope is simple!

The following qualifications are necessary:—

(i) patience and plenty of it;
(ii) space for aerials;
(iii) the ability to obtain enough components equivalent to that required to build a television set;
(iv) use of a pen recorder;
(v) enough knowledge *and* know-how to build a television set with the aid of standard text books, not using detailed plans;
(vi) possession of some simple test gear, such as the following:—
  a. small multi-range test meter,
  b. a simple modulated signal generator to cover the IF and RF frequencies.

The signal generator can easily be home-built and calibrated, using a lecher wire or known commercial stations as references. High accuracy is not normally necessary.

The following test equipment might be desirable, but is not essential.

a. Cathode ray oscilloscope for checking switching wave forms.

b. Diode valve noise generator for measurement of noise figures and sensitivity.

c. Wobbulator for alignment of RF and IF stages.

Assuming that only powerful sources are to be observed, e.g. the Sun, Cygnus A, Cassiopeia A and the Crab Nebula, the basic requirements are given below:

Suggested Frequencies:—30–200 MHz. 136–150 MHz covers many artificial satellites and is a good compromise between aerial size and receiver difficulties. Finding a clear band is a problem.

Aerials:—

Quantity is to be preferred to quality.

Cheap and easy to build:—Corner 'V', cylindrical paraboloid (Plate 24 *top*) and Kooman (broadside).

Difficult and awkward:—Yagi.

Expensive, versatile and photogenic:—Parabolic dishes. (Wind difficulties!) (Plate 24 *bottom*).

Useful for special purposes and with wide band width:—Helical and rhombic.

Receivers. These can be valve, transistor, integrated circuits or hybrids of these. About 20 stages are required.

Pen Recorders. These are expensive, but can be home-made. A chart speed of one inch per hour is useful for general purposes, although this should be chosen to suit the work in hand.

TYPICAL SPECIFICATION

Source to be detected:—Crab Nebula.

Flux density of source:—$2{\cdot}2 \times 10^{-23}$W Hz^{-1} m^{-2} (at 150 MHz).

Aerial collecting area:—5m^2.

Loss due to polarisation:—3db.

Bandwidth (B) say 4MHz.

∴ Power to head amplifier(s) $2{\cdot}2 \times 10^{-16}$ watts.

If receiver noise figure (N) is 5 the noise referred to head amplifier is N ktB, i.e. $5 \times 1{\cdot}37 \times 10^{-23} \times 293 \times 4 \times 10^{6} = 10^{-13}$ watts.

k = Boltzmann's constant.

t = Receiver temperature in degrees Kelvin.

∴ Signal to noise ratio = 0·0022.

If Recorder is 10 mA F.S.D. 3,000 ohms and deflection required due to signal is 10 per cent F.S.D., the recorder power is 3mW.

$$\therefore \text{Overall receiver gain} = \frac{3 \times 10^{-3}}{2{\cdot}2 \times 10^{-16}} = 1{\cdot}36 \times 10^{13}$$
$$= 131{\cdot}3 \text{ db}$$

But the output power due to noise is $1{\cdot}36 \times 10^{13} \times 10^{-13} = 1{\cdot}36$W, i.e. the recorder current would be 21 mA, i.e. 210% F.S.D., which is unacceptable as any gain drift would obviate the effect of backing off the recorder zero. This is avoided by Dicke or phase switching.

Typical Stage Gains

Stage	db
Head Amplifier	20
Feeder	−10
RF amplifier and frequency changer	20
IF amplifier	70
LF amplifier and synchronous detector	20
DC amplifier	11·3
Total	131·3

GENERAL

The gain of the RF stages should lift the *signal* level well above the mixer noise level.

The head amplifier gain should exceed the feeder loss.

The IF gain should be sufficient to produce several volts at the detector due to the head amplifier noise.

The LF amplifier should pass the signal at the switching frequency only and produce several volts at the synchronous detector.

The time constant after the synchronous detector would typically be 1 second for Solar bursts and 10 to 100 seconds for the Crab Nebula.

The switching frequency can be from 10 Hz to 10 kHz. Avoid odd harmonies of the mains supply.

Intense solar bursts can be detected with simpler equipment but these bursts are so rare that such equipment would be hardly worthwhile.

The example calculations given above are typical and can, of course, be varied at different points according to the design of the system.

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Chapter Twenty

ELEMENTARY ASTRONOMICAL CALCULATIONS

J. G. PORTER

THE AMATEUR OBSERVER is often called upon to do simple calculations to assist him in his observing, or in reducing his observations. Far too often this work is carried out in pencil, on any odd scrap of paper that happens to be handy, and with the use of an old set of log tables left over from school days. It is not surprising that the result is sometimes wrong, but unfortunately astronomical calculations are not like those sums we did at school, and answers are not provided.

The divergence of an answer from the correct result may be due to *errors* or to *mistakes.* The difference between the two is quite simple: errors are inevitable in any calculation, and result from the nature of the methods used and the limitations of the tables which are available; but mistakes are indications of a failing on the part of the computer, whether human or mechanical. (Here let it be said that there exists a curious delusion among some of the younger generation of computers that machines never make mistakes—a nice example of "famous last words"!) Now there is nothing to be ashamed of in making mistakes. Even the best computers make mistakes at times, but a good computer is always on the look-out for trouble; he knows the shortcomings of his methods, and he takes every possible care to guard against mistakes by applying checks at every stage of his work.

Checks. It is essential in any form of calculation to apply some sort of check on the working. It may not be possible to find a complete check, but it is not good enough to say that "it looks all right". Nor is it of the slightest use to repeat the calculation oneself. It is so easy to make the same mistake, not only twice but repeatedly, and this is particularly true if the computer is at all tired—and computing is a very tiring job. The most difficult work to check is that of a single calculation, although this is often possible in trigonometrical work because of the relationship between the different functions. The best kind of check on a single calculation is one which derives the same answer by a different route.

Most of the problems which we are called upon to solve are capable of being solved in more than one manner. The methods taught at school are probably the safest for general use, but the standard method is not always the most suitable. As an illustration of this, take the simple case of finding the hypotenuse c of a right-angled triangle, given the other two sides a, b. The obvious "best" way of doing this is to find the square root of the sum of the squares of the two sides, but although this is quite easy with a calculating machine, or with tables of squares, it is not a rapid process if logs have to be used. With logs (or with a slide rule) it is easier to find the angle A from $\tan A = \frac{a}{b}$ and then find the hypotenuse c from $c = \frac{b}{\cos A}$ or $c = \frac{a}{\sin A}$, whichever formula uses the larger numbers. In practice it would be best to use both, because the formula using the smaller numbers is then a check on the other solution. This is an illustration of the fact that the most suitable method depends on the computer, and on the means he has available for doing the work.

A long series of calculations, e.g. an ephemeris, giving the position of an object at equal intervals of time, is easily checked for consistency by examining the differences of the tabulated values. These should flow quite smoothly, without any sudden jumps up or down. But this check, which is an extremely powerful one, does not verify the absolute value of any particular entry; it merely tests the smooth running of the work as a whole. Thus even in this case it would be necessary to check the actual figures for two or three of the tabulated values. Sometimes a long series of values is calculated from some simple formula of the type $a + bt$ where a and b are constants and t is the variable, usually time. Such a case occurs in calculating the longitude of the central meridian of Jupiter for a series of observations, and a simple summation check will be

found suitable. The answers are added together and compared with the result obtained from the sums of the separate parts of the formula (see Example 1 below).

In the case of trigonometrical formulæ, it is always wise to use those which are self-checking (e.g. use all three formulæ for a spherical triangle), but if these are not available, then at least some common-sense checks can be applied. Thus, values of the answer are often obtainable on sight when the variable is 0°, 30°, 45°, 60° and 90°, and from these values a rough graph may be drawn, which will provide some sort of check on the answer. But this kind of check is only useful if many calculations of the same kind are to be done.

Mistakes. The commonest mistakes are nearly always those due to carelessness, particularly in copying figures. It is not unknown for a computer to be unable to read his own figures, and this particularly when working in pencil. It is always best to make an extra effort, writing well-formed figures in ink, with a systematic lay-out of the work, especially if it is to be kept for future reference. Even in the best work it is very easy to make an unconscious interchange of digits, e.g. to copy 57682 as 56782, while the doubling of a digit may give trouble, as in writing 55706 instead of 57706. Other fruitful sources of mistakes arise in simple mental arithmetic, as in division by 60 (or even by 2!) or in relying too much on one's memory in the use of a constant, such as log π, or log root 2. It is never safe to trust to one's memory; every figure should be verified. It is also particularly important to check the initial data, especially those involving trigonometrical functions, because the omission of a sign at this stage would place the angle in the wrong quadrant, and give an erroneous result. The inexperienced computer sometimes finds the signs of the functions in the four quadrants a source of confusion, perhaps because he is trying to remember too many facts. All that is necessary is to remember the *positive* function in each quadrant. The facts may be summarized in a very simple way: the calculation gives the angle A (less than 90°) and to assign this to its correct quadrant we must know the sign of at least two of its functions, sine, cosine or tangent. If we have only one of these, then some other information must be given (e.g. A is less than 180°) or the answer remains ambiguous. The positive functions in the four quadrants are given in the following scheme:

	Quadrant	*Angle to use*	*Positive*
I	0° – 90°	A	ALL
II	90° – 180°	180 – A	SINE
III	180° – 270°	180 + A	TANGENT
IV	270° – 360°	360 – A	COSINE

The sequence of positive functions in the four quadrants—**A**ll — **S**ine — **T**angent — **C**osine — is easily remembered by means of the mnemonic: **A**ll — **S**ing — **T**he — **C**horus.

Signs are a constant source of trouble, and in computing it is always wise to insert all of them. There is an exception to this rule when using logarithms, where only the negative signs are inserted, by writing the letter *n* after the logarithm. In this case the addition or subtraction of the logarithms follows the old rule that "two minuses make a plus". But it is surprising how often one forgets to insert that *n*!

In taking figures from tables, mistakes are quite easy to make, e.g. using log tables instead of antilogs, or sine instead of cosine; or forgetting that the differences in a table of cosines must be subtracted, not added. Tables of antilogs are a nuisance, and it is a wise policy not to use them. In any case they are generally available only for four-figure work, and no such tables are possible in trigonometrical work. Furthermore, they are decidedly inaccurate in the early part of the table, and it is no trouble to use the log tables to find a number inversely from its logarithm, just as one finds an angle from its log sine.

Errors. Even if no mistakes are made, the result of a calculation will inevitably contain errors. These are of two kinds, *rounding errors* and *truncation errors*.

Rounding errors are due to the fact that only a certain number of significant figures is used in the calculation. Thus if four-figure tables are employed, only the first four figures of every number are considered, the rest being discarded. One may actually round off the numbers in this way before beginning the calculation, and it may be as well to quote the rules generally adopted. When a figure less than 5 is omitted, the preceding figure is left unaltered; this is "rounding down".

When the omitted figure is greater than 5, the preceding figure is increased by 1; this is "rounding up". The case of rounding a number ending in 5 is a matter of personal choice, but it is the usual practice in computing to round such a number so that the preceding figure is made even. Thus successive roundings of the number 4·55037 will lead to 4·5504, 4·550, 4·55 and 4·6. It is to be noticed that in 4·550 the last zero is significant; it indicates that the number is accurate to 3 decimal places, and it must not be omitted.

It is clear that any number that has been rounded must contain an error, which may be as large as half a unit of the last decimal, and may be of either sign. It follows that the sum of several such numbers will contain the sum of the roundings, while the errors increase even more rapidly in multiplication. An entry from a table always contains two roundings—one from the main body of the table, and the other from the small table of proportional parts (or any other method of interpolation). Hence any entry from a table is liable to an error of a whole unit in the last decimal and, in a lengthy piece of work, these errors may accumulate.

Truncation errors arise when a formula (usually an infinite series) has been cut down to include only a few terms. Such errors are of importance in machine work, where expressions in the form of a series of terms are of common use, but they are less likely to arise in amateur work in astronomy. One example occurs in the use of a few terms of the series for calculating the true anomaly v of a planet from the mean anomaly M, given the eccentricity e:

$$v = M + 2e \sin M + \dots$$

These two terms alone would be sufficient to give a rough answer, but if any real accuracy is required, then more terms must be included, depending, of course, on the magnitude of e. Even more drastic approximations are used in dealing with small angles, but if the limitations of this device are realized, it can be extremely useful. The common approximations are

$$\sin A = \tan A = A \qquad \text{and} \qquad \cos A = 1$$

when A is expressed in radians. If A is expressed in seconds of arc, it must be divided by 206265 to convert it to radians, and this is usually expressed in the form

$$\sin A = A.\ \sin 1''$$

It will be realized that these expressions are obtained by using only the first term of an infinite series, and that they therefore involve truncation errors. These are quite negligible in the case of very small angles, but the range is limited. The upper limits to the angle A may be calculated from the second term of the series in each case, and are as follows:

No. of	*Upper limit*	
decimals	sin & tan	cos
7	1000″	60″
6	2000	200
5	5000	600
4	10000	2000

These values have been rounded down to give safe limits; we see from this that for four-figure working, we may take $\sin A = \tan A = A$ quite safely for angles less than about 3°, but the approximation $\cos A = 1$ is only true to about half a degree.

How many figures? It is never possible to attain full four-figure accuracy by the use of four-figure tables, because of the accumulation of errors. If full accuracy is necessary, then an extra figure should always be used, and if the work is lengthy or complicated, it is advisable to use two extra figures. The requirements for calculating angles must also include a similar factor of safety. Thus in four-figure sine tables the difference between two entries 1′ apart is a maximum of 3 in units of the fourth decimal. Even if it were possible to obtain an answer with an error of only one unit in the fourth place, the angle could not be obtained to better than 0′·3, and this only in the small angles. Similar arguments may be used with respect to other tables, and the facts may be summarized as follows:

4 figures suffice for work to	0°·01	or to 1′
5 figures „ „ „ „	0°·001	0′·1 or 10″
6 figures „ „ „ „	0°·0001	0′·01 or 1″

These limits are applicable only in the most favourable circumstances.

There is always a temptation, especially when using a calculating machine, to do the work with far too many figures, and to give the answer to an impossible degree of accuracy. There is nothing wrong in using too many figures in the work, except that it makes the work harder, and wastes a great deal of time; but the answer must always be given in realistic terms. Suppose, for example, that we have measured the dimensions of a small box with an ordinary ruler, and obtained the figures 8·6 cms by 6·9 cms by 4·3 cms. Multiplying these together we find the volume to be 255·162 cc. Now this answer is absurd, because it suggests that we can obtain the volume to 0·001 cc. Yet the original dimensions are known only to 0·1 cm, so that there is a possible error in the smallest dimension of one part in 43. The volume cannot possibly be more accurate than this, and in fact is likely to be less accurate, since there are also errors in the other measurements. It is therefore safer to assume an error in the answer of at least one part in 40, and it is accordingly rounded off to 260 cc. This sort of analysis often comes as an unpleasant shock to the inexperienced computer, who is inclined to delude himself by using too many figures. A very rough working rule is to give the answer to the same number of significant figures as the *least accurate* quantity in the original data.

The total error present in a numerical result (called the absolute error) may be of importance, but usually it is the relative error that matters—this is the ratio of the absolute error to the true result. An absolute error of 100 miles in measuring a distance on the Earth's surface is a serious matter, but the same error in the distance of the Sun is quite negligible. It is important to note that in addition and subtraction the absolute errors (which may be of either sign) are added or subtracted; in multiplication or division, it is the relative errors that accumulate in this way. It does not follow that the answer to a problem can always be obtained with an accuracy governed by such simple rules. In astronomy there are many cases in which the result is indeterminate—for example, the calculation of the hour angle and azimuth of a star low down on the horizon in the north or south. Here the slightest error in the declination of the star will have very large effects on the values of the bearings.

Interpolation. In all work involving tables (including astronomical ephemerides) interpolation is essential. This is the commonest and most important of all numerical processes, and it must be mastered right from the start. It is true that in most cases interpolation is a simple matter of simple proportion, and even this is made easy in four-figure tables by the provision of tables of proportional parts. But it sometimes happens that this simple process is not good enough, and the resulting errors may be quite serious. Suppose, for example, that we are dealing with the motion of a planet. In the case of a slow-moving planet like Jupiter, we are perfectly justified in assuming that for at least a short period of time its motion is almost exactly in a straight line; but it would not be safe to make this assumption in the case of a rapidly moving body like Mercury, or a comet. Consider the following values for the right ascension of Mercury and Jupiter for five dates in 1963:

Mercury				*Jupiter*			
	h	m			h	m	
Sept. 28	11	25·0		Sept. 16	1	06·2	
			+5·7				−3·5
Oct. 3	11	30·7		24	1	02·7	
			18·7				3·8
8	11	49·4		Oct. 2	0	58·9	
			26·4				4·0
13	12	15·8		10	0	54·9	
			+30.0				−3·9
18	12	45·8		18	0	51·0	

If these values are plotted against time the resulting graph for Jupiter will be found to be almost a straight line, but that for Mercury is decidedly curved. It is therefore clear that in the case of Jupiter we can interpolate between any two points A and B by assuming that AB is a straight line, so that a point between them is found by simple proportion. This is a case of linear interpolation. If, however, we take two such points on the Mercury curve, then it would certainly not be safe to assume linearity, and in such a case we must take the curvature of the line into account. There is no need to have any knowledge of the actual curve, since we can always fit a curve through a given number of points. Many suitable formulæ for this purpose have been derived, and of these, the formula of Bessel is perhaps best suited for amateur use. It is explained here in simple terms, but the reader seeking further information will find full details (but with a different notation) and special tables, in the

Astronomical Ephemeris, or in that invaluable booklet *Interpolation and Allied Tables* (H.M.S.O., 1956, 5s. net).

Suppose we have a series of values of a function f, at equal intervals of time, t_0, t_1, t_2, etc., and we difference these values as in the following scheme:

Time	*Function*	*Diff.*
t_{-1}	f_{-1}	
		a
t_0	f_0	
		b
t_1	f_1	
		c
t_2	f_2	

(Note that the differences are always taken in the same sense, e.g., $b = f_1 - f_0$. Similarly the second differences will be $b - a, c - b$ and so on.)

The problem is then to find the value f_p of the function at some time t_p between t_0 and t_1. Let p be the fraction $(t_p - t_0)/(t_1 - t_0)$ i.e., p is the proportion of the interval through which we have to interpolate. Without going into detail, we may express Bessel's formula of interpolation as

$$f_p = f_0 + p.b + B(c - a)$$

where B is given by $B = \frac{1}{4}p\,(p - 1)$. It should be noticed that B is always negative. (Extensive tables of the values of B, and of the contribution made by the last term in this formula, are given in the books already mentioned.) The formula given here takes account only of second differences, and is not accurate if the third differences are greater than 60 in units of the last figure.

The maximum value of B occurs at $p = \frac{1}{2}$, when $B = 1/16$; it follows that second differences may only be neglected if they are less than 4 (because $c - a$ is the sum of *two* second differences). It may now be seen that in the table of positions of Mercury and Jupiter given above, interpolation of the Mercury values requires the use of second differences, but these are negligible in the case of Jupiter, and linear interpolation is therefore sufficient. The values for October 5 will therefore be found as follows:

Mercury	*Jupiter*
Interval 5 days; $p = \frac{2}{5} = 0{\cdot}4$	Interval 8 days; $p=\frac{3}{8}=0{\cdot}375$
$B = \frac{1}{4}(0{\cdot}4)\,(-0{\cdot}6) = -0{\cdot}06$	

	h m		h m
R.A. Oct. 3 =	11 30·7	R.A. Oct. 2 =	0 58·9
$p \times (+18{\cdot}7)$	+ 7·48	$p \times (-4{\cdot}0)$	− 1·5
$B \times (+20{\cdot}7)$	− 1·24		
R.A. Oct. 5	11 36·9	R.A. Oct. 5	0 57·4

Formulæ to avoid. It is sometimes found that an answer cannot be obtained with any real precision, and this is often due to the use of an unsuitable formula. The two types of formulæ to avoid at all costs are those which express the answer as the difference between two nearly equal quantities, or as the ratio of two small quantities. In both cases one loses several significant figures, and the answer is indeterminate. For the same reason, angles should be obtained (if possible) from their tangents, for these are always well defined; on the other hand, an angle near 90° cannot be determined from its sine, or a small angle from its cosine. Thus, in the log sin tables, the value $\bar{1}{\cdot}9998$ may represent any angle between 88° 04′ and 88° 29′. (Note: these figures are from the best four-figure tables; the reader may like to compare with his own tables, which may not be so reliable.)

Logarithms are not suitable for formulæ which involve much addition and subtraction, and, although special addition and subtraction logarithms are available, it is best to find an alternative formula. The standard example of this occurs in finding the angles of a plane triangle, given the three sides. Here the formula

$$\cos A = \frac{b^2 + c^2 - a^2}{2bc}$$

is entirely suitable for use with a calculating machine, but the alternative

$$\tan \tfrac{1}{2}A = \sqrt{\frac{(s-b)\,(s-c)}{s(s-a)}} \quad \text{where } s = \tfrac{1}{2}(a+b+c)$$

is better for logarithmic working. Similar formulæ are available for the calculation of spherical triangles (see Example 5 below).

EXAMPLES

The following examples illustrate some of the more important points raised in this chapter.

Example 1: to find the longitude of the Central Meridian of Jupiter (System II) on 1963 November 19 at $18^h\,42^m$, $18^h\,55^m$, $19^h\,07^m$, $19^h\,14^m$, $19^h\,36^m$.

(The 1963 *B.A.A. Handbook* gives the longitude for this date at 16^h, and provides tables of the motion for integral numbers of hours and minutes.)

Time		*Interval*		*Long. at 16ʰ*	*Motion in*		*Long.*
h	m	h	m	*at 16ʰ* °	*hours* °	*minutes* °	°
18	42	2	42	133·2	72·5	25·4	231·1
18	55	2	55	133·2	72·5	33·2	238·9
19	07	3	07	133·2	108·8	4·2	246·2
19	14	3	14	133·2	108·8	8·4	250·4
19	36	3	36	133·2	108·8	21·7	263·7
Check sums:		15	34	666·0	471·4	92·9	1230·3

The longitudes in the last column will contain an accumulation of rounding errors; they should be rounded to the nearest degree, but the checks are applied to the calculated values. The sums are merely checks on the addition—they do not verify the table entries; a further check should be made by showing that the motion in $15^h\,34^m$ is equal to the sums of columns 4 and 5.

Example 2: Find the mean daily motion of Venus from the formula $n = k\,a^{-3/2}$ when $a = 0^\circ{\cdot}7233$ and $k = 0^\circ{\cdot}9856$.

(Two methods are shown, using

$$\log n = \log k - \tfrac{1}{2}(3 \log a) = \log k - (\log a + \tfrac{1}{2} \log a)$$

In the first method, always multiply by 3 before dividing by 2).

(1)	log k	$\bar{1}{\cdot}9937$	(1)	log k	$\bar{1}{\cdot}9937$
(2)	log a	$\bar{1}.8593$	(2)	log a	$\bar{1}.8593$
(3)	3 times (2)	$\bar{1}{\cdot}5779$	(3)	½ of (2)	$\bar{1}{\cdot}9296$
(4)	½ of (3)	$\bar{1}{\cdot}7890$	(4)	(2) + (3)	$\bar{1}{\cdot}7889$
(5)	(1) − (4)	0·2047	(5)	(1) − (4)	0·2048
(6)	antilog	$1^\circ{\cdot}602$	(6)	antilog	$1^\circ{\cdot}602$

Example 3: The three sides of a plane triangle are 15·27, 12·61, and 2·84. Find the angle opposite the smallest side.

We use the tangent formula:

$$\tan A/2 = \sqrt{\frac{(s-b)\,(s-c)}{s(s-a)}}$$

where s is half the sum of the sides. We have $s = 15{\cdot}36$, so that $s - a = 12{\cdot}52$, $s - b = 2{\cdot}75$, $s - c = 0{\cdot}09$, and as a check, the sum of these three $= 15{\cdot}36 = s$. Then

(1)	log s	1·1864	(5) = (3) + (4)	$\bar{1}$·3935
(2)	log (s − a)	1·0976	(6) = (1) + (2)	2·2840
(3)	log (s − b)	0·4393	(7) = (5) − (6)	$\bar{3}$·1095
(4)	log (s − c)	$\bar{2}$·9542	(8) = ½ of (7)	$\bar{2}$·5548

Line (8) gives log tan $A/2$, and we see from the tables that $A/2$ must lie between 2° 03′ and 2° 04′; if a more accurate answer is required, we use the fact that tan $A/2 = A/2$ radians. Since 1 radian = 3438′, we have

log tan $A/2$	$\bar{2}$·5548	
log 3438	3·5363	
sum	2·0911	antilog = 123′·3 = 2° 03′·3
		$A = 4°\ 06'{\cdot}6$

Example 4: A spherical triangle, right-angled at C, has $A = 82°\ 29'$ and $c = 96°\ 11'$. Find a and b.

(Most problems in spherical trigonometry can be reduced to the solution of right-angled triangles. The formulæ are

$$\cos a \cos b = \cos c \qquad \text{(P)}$$
$$\cos a \sin b = \sin c \cos A \qquad \text{(Q)}$$
$$\sin a = \sin c \sin A \qquad \text{(R)}$$

and it is the convention to take all sides and angles as less than 180°. This implies that all sines are positive, but cosine and tangent are negative in the second quadrant. It is not advisable to find a solely from the third equation; the standard method is to find b first, from $\tan b = \frac{\mathrm{Q}}{\mathrm{P}}$, and then use sin b or cos b, *whichever is the larger,* to calculate cos a from $\cos a = \frac{\mathrm{Q}}{\sin b}$ or $\frac{\mathrm{P}}{\cos b}$. In this way there is a check on the value of a, and hence on that of b.)

(1) log sin c	$\bar{1}$·9975	(5) log P	= (2)	$\bar{1}$·0323 n
(2) log cos c	$\bar{1}$·0323 n	(6) log Q	= (1) + (4)	$\bar{1}$·1142
(3) log sin A	$\bar{1}$·9963	(7) log R	= (1) + (3)	$\bar{1}$·9938
(4) log cos A	$\bar{1}$·1167			

(8) log tan b	= (6) − (5)	0·0819 n
(9) log sin b		$\bar{1}$·8866
(10) log cos a	= (6) − (9)	$\bar{1}$·2276

From the sign of line (8), b is in the second quadrant; from line (10), a is in the first quadrant.

$$a = 80°\ 17' \qquad b = 129°\ 38'$$

(Note: in line (9), sin b must agree with tan b, and must not be found from the rounded value of b.)

Notes on Contributors

HOLE, G. A., F.R.A.S., Director of the Instruments and Observing Methods Section of the British Astronomical Association (*Selection of Telescopic Equipment*). Born 1912, in Canterbury. Amateur optical worker between 1928 and 1948, when he joined the firm of Cox, Hargreaves & Thompson. He has an international reputation as a maker of telescopic mirrors and other astronomical equipment. As an observer, he concentrates upon the Moon, together with planetary work; the 24-inch reflector which he constructed for this purpose is one of the largest instruments to be devoted to observation of such objects.

DALL, H. E. has made many original contributions with regard to astronomical equipment, and his work is known all over the world. For many years he has been an active member of the British Astronomical Association, and carries out his observing work, visual and photographic, from his home at Luton, using equipment constructed by himself. (*Astronomical Photography*).

BRINTON, HENRY, F.R.A.S., has a private observatory at his home at Selsey, equipped with a 12-inch reflector; he pays particular attention to the planet Venus. He is the author of many political and social works, and during the war held a senior post in the Ministry of Labour. He has also written several books dealing with astronomical subjects, and has broadcast frequently on sound radio and television. (*Observatories and Observatory Equipment*).

BALL, LESLIE F., is primarily a lunar and planetary observer, and has long been celebrated for his beautiful drawings of these objects, made from his personal observations—largely with the aid of his 10-inch reflector. He has for many years been a member of the British Astronomical Association, and has made many contributions to its publications. (*Astronomical Recording*).

The late **W. M. BAXTER**, former Director of the B.A.A. Solar Section, had an observatory in Acton. His solar work was internationally known, and some of the photographs which he took were among the best of their kind. His book *The Sun and the Amateur Astronomer* was re-issued in 1973. (*Solar Observation*)

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MOORE, PATRICK, O.B.E., D.SC., F.R.A.S., former Director of the Mercury and Venus Section of the British Astronomical Association (1954–63) and of the Lunar Section (1963–66); former Director of the Armagh Planetarium (1965–68). Amateur astronomer. Lorimer Gold Medallist of the Edinburgh Astronomical Society (1962); Goodacre Gold Medallist of the British Astronomical Association (1969).

The late **M. B. B. HEATH**, former Director of the Saturn Section of the British Astronomical Association, had made extensive observations of the planets, particularly Mercury, Venus, Mars and Saturn. Among the posts he held at various times were Works Inspector at a large engineering works in Birmingham; Experimental Investigator at a scientific instrument and optical works in London, and as a Local Government Officer in Devon, from which he retired in 1954. He was elected a member of the British Astronomical Association in 1926, and became Director of the Saturn Section in 1951. He was elected a Fellow of the Royal Astronomical Society in 1937. He was elected a member of the International Astronomical Union at the Rome Congress in 1952, and appointed a Member of Committee 16, for the physical observation of planets and satellites. At the Dublin Congress, in 1955, he was appointed a member of the I.A.U. Sub-committee to deal with Martian nomenclature. He died in 1965. (*Mars*).

The late **B. M. PEEK, F.R.A.S.**, was formerly Director of the Jupiter Section of the British Astronomical Association, and had made a lifelong study of the planet. He was recognized as one of the leading authorities on the subject, and his book *The Planet Jupiter* is accepted as the standard work. He died in 1966. (*Observation of Jupiter*).

The late **A. F. O'D. ALEXANDER** was Director of the Saturn Section of the British Astronomical Association from 1946 to 1951, and of the Jupiter Section from 1951 to 1957. He graduated with first class honours B.A., M.A., and Ph.D. of London University, in History, and taught for a few years in England and Japan. For 38 years, until his retirement in 1962, he was an Education Officer, first in Londonderry and afterwards in Dorset. He conducted adult education courses on astronomy between 1947–57 and 1962–63, and is the author of the standard book *The Planet Saturn*. In 1962 he was awarded the Walter Goodacre Gold Medal of the British Astronomical Association. (*Observation of Saturn*).

WHITE, J. L., F.R.A.S., is Librarian of the British Astronomical Association. He is Tutor in Astronomy for adult classes of London and Southampton Universities and London, Middlesex and Surrey County Councils. He is also Lecturer in Astronomy for the British Association for the Advancement of Science. (*Observation of Minor Planets*).

HENDRIE, J., F.R.A.S., is with the British Petroleum Company, engaged on the planning of refineries and supply facilities. He has been observing comets, both visually and photographically, for the Comet Section of the B.A.A. since June 1951, and is evaluating the use of small-scale photography for comet-seeking at his observatory near Colchester. His other astronomical interests include occultations and meteors.

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PATON, JAMES, was the late Reader in Meteorology at the University of Edinburgh, and Director of the Aurora Section of the British Astronomical Association. He was the British National Reporter for Aurora and Airglow in the International Geophysical Year, and a Member of Council and International Reporter for Aurora for the International Year of the Quiet Sun (I.Q.S.Y.) 1963–64. (*The Aurora*).

CANDY, M. P., F.R.A.S., former Director of the Comet Section of the British Astronomical Association, joined H.M. Nautical Almanac Office in 1947, and transferred to the Astrometry Department of the Royal Greenwich Observatory, starting observing double stars with the 28-inch refractor in 1958. He has discovered a comet, and is an assiduous computer of cometary orbits. In 1969 he accepted an astronomical post in South Africa. (*Observation of Double Stars*).

ROBINSON, J. HEDLEY, F.R.A.S., has for many years been an active observer of variable stars, and uses the 10½-inch reflector at his private observatory at Teignmouth, Devon. His variable star determinations amount to several thousands. He is also an energetic observer of the Moon and of the planets, particularly Venus. (*Observation of Variable Stars*).

FEA, K., F.R.A.S., has been working since January, 1961, at University College, London, in the Physics Department, Space Research Group; the subject of his research is optical satellite tracking, especially by photoelectric techniques. He is also interested in visual tracking by amateurs, and has recently obtained Royal Society backing for a net of six advanced amateur tracking stations to be equipped with 4-inch reflectors. He has written several books, and lectures for the Extra-Mural Department of London University on astronomy, astrophysics and space research. (*Earth Satellite Observation for Amateurs*).

MILES, HOWARD, F.R.A.S., Director of the Artificial Satellite Section of the British Astronomical Association, is a lecturer at the Lanchester College of Technology, Coventry, and has undertaken considerable research into the orbits of artifical satellites. (*Appendix to Chapter 19*).

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PORTER, DR. J. G., F.R.A.S., was for many years associated with the production of the *Nautical Almanac* (now the *Astronomical Ephemeris*), and retired from the Royal Greenwich Observatory in 1961. He specializes in mathematical astronomy, but also writes and broadcasts frequently on astronomical matters. A Past-President of the British Astronomical Association, he was for over twenty years Director of its Computing Section. (*Elementary Astronomical Calculations*).

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