BOUNDARIES OF THE UNIVERSE

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This one is for John, Anne Marie, Morag, and Raymond,
for whom this will one day be past history

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Preface

For more than 2,000 years after the time of Hipparchus and Plato, astronomy was beset by myth and superstition and at best was merely a descriptive science. Inevitably, it failed to provide any real understanding of the nature of the universe. Even as recently as the mid-sixteenth century, the basic belief that the Earth was the centre of all creation, with the Sun, Moon, planets and stars revolving around it at various distances, remained unchallenged and to have suggested otherwise would have branded one as a heretic. Not until Man's true place in the universe was recognized and accepted did astronomy begin to advance out of the Dark Ages and take its rightful place among the other sciences.

Most astronomers would argue that it is only during the present century that we have gained an insight into the much wider problems of the cosmos as opposed to our more parochial view of the stellar system – the Galaxy – in which our Sun is but one inconspicuous speck among 100,000 million others. It is certainly true that in the past fifty years or so the boundaries of the universe have been pushed back at an ever-increasing rate, so much so that many astronomers alive today could scarcely have foreseen the tremendous changes which have taken place during their lifetimes.

The age of merely looking at the heavens, of mapping and cataloguing the positions of the stars down to fainter and fainter limits, is past. Throughout this long period the pace of astronomical discovery was necessarily very slow and for centuries it remained virtually static. The invention of the telescope and then the spectroscope brought about an acceleration in the rate of progress which has continued unabated to the present day. Scarcely a year now passes without some spectacular advance being made so that today, with the cooperation of modern techniques in physics, chemistry, rocket technology and biology, many of the older notions have been completely overthrown and new ideas set up in their place.

It is difficult, if not impossible, to draw any precise boundaries but it is probably true to say that chronologically the science of astronomy may be divided into three phases. First, there is descriptive astronomy, which seeks to provide us with a picture of the dimensions and masses, of the various planetary and stellar bodies, together with accurate measurements of their positions and movements. From these, the basic laws have been derived.

More recently, that branch of astronomy known as astrophysics was developed, enabling us to determine the chemical and physical compositions of the stars and planets, their origins, mode of evolution, temperatures and eventual demise. Already astrophysics has made discoveries that could have resulted neither from naked-eye nor from purely telescopic investigation.

Finally, we enter the realm of cosmology which may be said to have begun with the classical researches of Edwin Hubble during the second and third decades of the present century. With the recognition that our Galaxy is but one of many millions which reach out to the very limits of the observable universe, the true position of Man in the overall concept of things became apparent.

We may feel humbled by our utter insignificance but there is no denying that we may also justifiably derive some comfort from the knowledge that, first by the use of our unfettered imagination and later by our growing scientific technology, we can range over distances which are utterly incomprehensible to the layman and back into time to the point where all of creation itself may conceivably have originated.

Coming nearer home, the rapidly developing technique of rocket research has made it possible not only for Man to go beyond the confines of this planet and set foot upon another world, but also to carry astronomical instruments beyond the atmosphere, which effectively confines our visual and photographic observations to an extremely narrow band of the electromagnetic spectrum. Now we are able to view the universe in ultraviolet light, infra-red light, X-rays, and radio emissions which are almost completely absorbed by the atmosphere that surrounds the Earth. Each problem that is solved, however, only serves to present us with a host of others of increasing complexity. The boundaries are being pushed back steadily, it is true, but the realm of the partially understood and the totally unknown is still as great as ever and it is with this vast no-man's-land of astronomy that this book is concerned.

The reader will soon appreciate that after the quiescence of the Middle Ages astronomy is now the most changing of all the sciences. This is the reason why astronomers always seem to be changing their minds over what may appear to be fundamental concepts. So many new discoveries are being made that even recent theories have to be modified, often to an appreciable extent. The arguments for and against the Big-Bang theory and the steady-state concept of the universe are an excellent example of this, while the idea of an oscillating universe has gained ground in recent years. Observational evidence in favour of all three may be put forward and it seems unlikely that a clear-cut decision will be made in the near future.

However, even in the midst of so much apparent uncertainty, the reader will undoubtedly experience some of the tremendous fascination of present-day astronomy – and without the unknown to provide the basic challenge of exploration, Mankind must surely stagnate.

Stevenston, Scotland J. S. G.
January 1970

1. Astronomical Instruments and their Applications

The art of astronomy had its beginnings in the ages of prehistory, long before there were any written records, when men measured the lengths of the day, seasons, and the year by the movements of the Sun, Moon and stars without any knowledge of the true nature of these bodies. It mattered little to the early observers whether these various bodies revolved around a stationary Earth or whether the Earth rotated upon its axis, although the latter idea would have appeared almost incomprehensible to the early astronomers. It is perhaps inevitable that myth and superstition should have entered into astronomy and lingered for countless centuries; and it was not until the invention of the telescope that astronomy relinquished the title of an art and became a true science, subject to physical laws. Once this stage was reached and the stifling shackles of superstition were thrown off, progress was rapid, culminating in Man leaving his own planet and venturing forth to the Moon.

The main theme of the present book lies in the description of the major discoveries which have been made in recent years, covering most aspects of astronomical research; in particular, an attempt will be made to combine these into an overall and comprehensive picture of the universe as seen through the eyes of present-day astronomers. The universe is, by definition, the sum total of all things: atoms, planets, stars, galaxies, and the seemingly empty space that exists between them. It also includes Man himself and all living things, and this inevitably raises the important question whether life has come into being elsewhere than on our own planet.

First, however, we must consider the instruments used by astronomers and the techniques that have provided us with this vital information and, since certain terms will be used throughout the book with which the layman will be unfamiliar, these too must be explained in detail.

Astronomical Telescopes

Without the telescope, astronomy could never have emerged from the purely descriptive art of the ancients. The true nature of the Milky Way could never have been proved, and the existence of other vast star systems beyond our own would have been hidden from us. The ancient belief in a geocentric universe, with the Earth holding a privileged place at the centre of all things, would still have prevailed.

Astronomical telescopes are of two basic types, refractors and reflectors, the former employing two sets of lenses known as the objective and the eyepiece, and the latter a series of reflecting mirrors. The first instruments were all refractors and suffered from several defects, chiefly that of chromatic aberration. An ordinary objective does not bring the rays of light of different colours to the same focus, with the result that the image of a star appears surrounded by a coloured halo. Since chromatic aberration may be reduced, although not entirely eliminated, by increasing the focal length of the telescope, the seventeenth century saw the construction of many large and unwieldy instruments. Not until the discovery of the achromatic objective by Dolland in the middle of the eighteenth century was it possible to make refracting telescopes of more reasonable proportions. The achromatic lens consists simply of a converging lens of crown glass in combination with a diverging lens of flint glass, the opposing chromatic aberrations of the two lenses being adjusted to make the chromatic aberration of the combination negligible.

The reflecting telescope, on the other hand, using a spherical or parabolic mirror as the objective, does not suffer from chromatic aberration since in this case all of the rays are brought to the same focus irrespective of colour. One further advantage the reflector has over the refractor is that the largest lens that can be produced is far smaller than the largest mirror. There are two main reasons for this: firstly, the internal stresses set up within a large lens are much greater than in a mirror of comparable size; second, a lens must be supported by its edges which are its weakest part, this alone seriously limiting the diameter of lens that can be satisfactorily used. One further important point is that the thicker the lens, the more light it absorbs, whereas the reflective coating of silver or aluminium on a mirror absorbs very little. For these reasons, the largest telescopes are all reflectors.

The largest telescope in operation at present is the 200-inch Hale reflector at Mount Palomar Observatory, although a 238-inch reflector will shortly be commissioned at a site in Georgia, U.S.S.R. It is extremely unlikely that any larger instruments of high optical quality will be built as the terrestrial atmosphere makes it impractical to use them satisfactorily, but large flux collectors giving less sharp

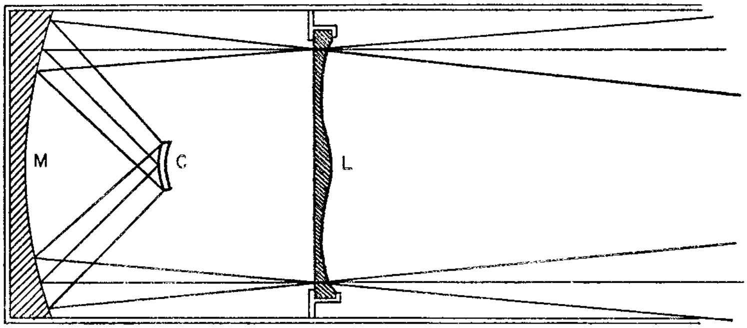

Fig. 1 Diagram of the Schmidt camera. The aspherical correcting plate *L* has a spherical aberration opposite and equal to that of the spherical concave mirror *M*. The curved plateholder *C* provides a sharp image over a wide field.

images are possible for specialized purposes such as optical interferometers. If any more powerful instruments of high quality are brought into operation, it appears probable that they will be erected upon the lunar surface, where atmospheric turbulence presents no problem and the lower gravity will, to a certain extent, reduce the mechanical problems of their erection.

From what has just been said, it might seem that the ordinary reflector has no serious disadvantages. This, unfortunately, is not strictly true. A parabolic mirror such as is used in the large reflectors suffers from what is termed coma, which has the effect of distorting star images in the field if they are situated some distance from the optical axis of the telescope, that is, around the edges of the field of view. This seriously reduces the size of field that is usable by the astronomer, particularly since the coma-free area decreases with increase in the size of the objective. Not until 1930, with the invention of the Schmidt camera, was this difficulty successfully overcome. The optical system of this instrument produces a coma-free field by means of a spherical mirror and an aspherical correcting plate which has a spherical aberration equal and opposite to that of the mirror (Fig. 1).

One may ask why this instrument is termed a Schmidt camera rather than a Schmidt telescope. As will be seen from Fig. 1, the image of the field is formed inside the instrument and consequently, without very drastic modifications, it can only be used as a camera and not visually. A further modification was made to this instrument in 1940 by Maksutov in Russia and Bouwers in Holland, and this is generally known as the Maksutov telescope. Since, in both types of instrument, the plateholders have curved surfaces, the plates or films have to be bent to the correct curvature before use. Nevertheless, these instruments have found an extremely important application in the photographing of large areas of the heavens down to very faint objects. Large reflectors, however, are still necessary for the purpose of flux collecting and obtaining large-scale images in an area of half a degree or less.

With very few exceptions, all of the instruments in the large observatories are mounted equatorially – that is, the telescope can be rotated about two mutually perpendicular axes, one of which points exactly to the north (or south) celestial pole. By rotation about this polar axis alone, the telescope can be made to follow a particular star with only one motion as the rotation of the Earth moves the star across the sky; for long photographic exposures, electric driving clocks are employed to keep the star centrally upon the optical axis.

Those telescopes which are employed for the measurement of stellar positions and motions are usually refractors since the quality of the stellar image is not affected by small changes in temperature as it is with a reflecting telescope. The most accurate of these instruments, known as meridian circles, are mounted between two very massive pillars supporting the horizontal axis, the telescope being able to swing in a vertical plane with very great precision. The proper motions of the stars, that is, the components of their random motions through space which are at right angles to our line of sight, are usually measured by means of photographs taken with Schmidt cameras some years apart. The photographs are compared by means of an instrument known as a blink miscroscope, a device in which the two photographs, placed side by side, are illuminated alternately. Any star that has changed its position during the intervening years will seem to jump back and forth, thereby betraying its presence. The change in position may then be measured extremely accurately with the aid of a micrometer. Micrometers are also used extensively to measure the relative positions of the components of double stars, particularly those which are physical doubles, or binaries, in order to determine the period of rotation of the components about their common centre of gravity.

Telescopes perform two main functions for the astronomer. To the layman, the chief function would seem to be that of magnifying an image, but in general this is of secondary importance as far as astronomical work is concerned. The magnifying power – of a telescope is a function of the focal lengths of the objective and the eyepiece, given by the simple formula:

$$M = \frac{F}{f},$$

where F is the focal length of the objective and f is that of the eyepiece. For any given instrument, therefore, we may change the magnification quite simply by merely changing the eyepiece. Of much greater importance to the astronomer are the resolving power and the light grasp of the instrument, both of which depend only upon the diameter of the objective.

Owing to the wave nature of light, whenever it passes through an aperture that limits its amount, for example the objective of a telescope, the light becomes spread out, or diffracted, resulting in an overlapping of very close images such as those of a very close double star. Since this effect is inversely proportional to the diameter of the objective, small apertures will reveal only a single image, the components being separated into discrete points of light only when the aperture is sufficiently increased. Very large apertures will therefore, not only resolve two very close stars but will also reveal finer detail upon the lunar and planetary surfaces.

The light grasp of a telescope, on the other hand, is directly proportional to the square of the radius of the objective and a large value of it enables us to see fainter stars. As a result, the aperture of a telescope is of prime importance both for resolving fine detail and for penetrating to the faintest possible limits.

Spectroscopic Analysis

By the middle of the nineteenth century, telescopes had improved to such an extent that the Milky Way had been resolved into myriads of very faint stars and the general outline of the Galaxy, the huge system of thousands of millions of stars of which our Sun is one, had been defined as a vast lens-shaped disc of incredible size. Yet in spite of this advance in our knowledge, astronomers knew nothing of the chemical and physical constitution of the stars, or of the faint nebulous objects which had been discovered in large numbers during surveys of the heavens. Indeed, it seemed impossible at the time that anything further could ever be discovered about them. The large telescopes revealed stars many times fainter than those which could be observed with the naked eye, but nothing of their composition.

As long ago as 1666, however, Newton had carried out the fundamental experiment which proved to be the basis for astronomical spectroscopy, namely, that of passing a beam of sunlight through a glass prism, whereupon a band of colours – red, orange, yellow, green, blue, indigo, and violet – is formed, this band of colour being named by him the solar spectrum. Until 1802 this spectrum was considered to be continuous, with each colour blending imperceptibly into the next, but in that year Wollaston allowed the sunlight to pass through a very narrow slit rather than through a circular hole as had been done previously and found that the spectrum produced was crossed by seven dark lines. As it happened, five of these lines appeared to separate the component colours and he considered them to be merely dividing lines between one colour and the next. It remained for Fraunhofer, in 1815, to show that if a small telescope is used in conjunction with a prism mounted on a goniometer the solar spectrum contains not seven but several hundred narrow dark lines.

Over the next half century or so, several chemists and physicists studied the different spectra produced by several incandescent solids and gases, and these experiments eventually showed that three different kinds of spectra can be differentiated. The spectrum produced by an incandescent solid or liquid (in certain cases also by gases, as in the Sun) is a continuous spectrum and shows only the familiar band of rainbow colours.

An incandescent gas at lower pressures, however, gives an emission spectrum consisting of a series of bright, coloured lines on a dark background. If, on the other hand, the light from an incandescent solid or a gas at high temperature passes through a gas at a lower temperature, an absorption spectrum is formed, consisting of a series of dark lines upon a continuous background. This is the type of spectrum normally given by the stars and, significantly, the dark lines occupy the same positions as those which the coller gas would produce in emission if it were acting solely as the source of the radiation, being due to the absorption of light of these particular wavelengths from the continuous spectrum.

In 1862, Bunsen and Kirchhoff established that every chemical element produces its own unique spectrum and that every element is also able to absorb the same radiations that it emits. This not only led to the recognition of a 'reversing layer' within the solar atmosphere which gives rise to the dark lines in the spectrum but also paved the way for the identification of many of the chemical elements present in the Sun from their characteristic absorption lines.

The wavelengths of the lines produced by the various elements having been catalogued, the next phase in astronomical spectroscopy came with the application of photography. Ten years after Bunsen and Kirchhoff's pioneering work, Draper obtained the first photograph of a stellar spectrum, that of the first-magnitude star Vega, using a quartz-prism spectrograph in conjunction with a 28-inch telescope. On the observational side, three types of spectrograph have been used for the study of stellar spectra.

The objective prism consists essentially of a large prism having a small angle at the apex, which is placed in front of the telescope objective. By means of this instrument, the spectra of a very large number of stars are produced on a single photographic plate. Normally, each spectrum would be merely a point of light, but if the objective prism is placed so that its edges are horizontal when the telescope is in the meridian, the spectra are then extended north and south. The drive may then be adjusted so as to lose or gain a few seconds per hour in order to widen the spectra sufficiently for observation of the spectral lines. This method was first used by Pickering in the compilation of the Harvard Sequence of stellar spectra and is extremely useful when large numbers of spectra require to be examined in a short time but, as may be realized, both the resolution and dispersion are necessarily low. In addition, the objective-prism method is satisfactory only for the brighter stars.

For recording low-dispersion spectrograms of very faint stars a slitless spectrograph is used in conjunction with the largest telescopes, the spectrograph being mounted at the focus of the instrument. Since the sky background must be minimized, there is a limit to the faintness of the object which can be satisfactorily observed. When, however, high-dispersion spectrograms of moderately bright stars are required, a slit spectrograph is employed in which the light from the telescope is first focused on a narrow slit at the end of a collimator before passing into the prism.

Another way by which a spectrum can be formed is by means of a grating. This is simply an aluminized glass plate on which a large number of parallel lines have been engraved. The grating has two distinct advantages over the prism for stellar spectroscopy. First, the same dispersion can be achieved with a faster camera (i.e. one having a smaller focal length using a practically achievable aperture). Second, the grating provides a uniform dispersion of the different wavelengths. With a prism we find that the blue end is spread out much more than the red end, whereas with a grating all of the wavelengths are spread equally.

Classification of Stellar Spectra

As the amount of spectroscopic data increased, it became possible to classify the stars according to their spectra, a technique which has had far-reaching effects in astrophysics. The first attempt at classification was made between 1866 and 1869 by Secchi, who distinguished four main classes: Type I consists of hot, white stars and Type II of cooler, yellow stars; those of Types III and IV are all red stars but show recognizable differences in their spectra to justify placing them in two distinct classes.

This system has now been generally superseded by the Harvard classification of stellar spectra, which is a continuous series with the intensities of the lines changing smoothly from the hottest to the coolest stars. At first, the sequence was labelled with letters in alphabetical order, but changes and omissions were made as more detailed information was obtained and the sequence is now W, O, B, A, F, G, K, M, N, R, S, with a special class Q which is reserved for the novae. The major characteristics of the individual classes of spectra are as follows.

Class W stars are known as Wolf–Rayet after the two French astronomers who first described them. They are extremely hot, with surface temperatures as high as 40,000°K; their spectra consist of a continuous background crossed by a large number of bright emission lines mainly of neutral and singly ionized helium in conjunction with either nitrogen (Class WN) or carbon (Class WC). Only a few Wolf–Rayet stars are known and, as we shall see later, they are very short-lived in comparison with other stars and evolve extremely rapidly.

Class O stars, like those of the preceding class, have high surface temperatures, of the order of 32,000°K, and are white in colour. At this very high temperature, the spectral lines of any metals that may be present in their atmospheres appear in the ultra-violet region of the spectrum and, since our atmosphere effectively absorbs ultra-violet light, these lines are unobservable from the surface of the Earth although they could be observed from orbiting satellites. Lines due to hydrogen are present, but the dominant lines are still those of neutral and ionized helium and of nitrogen and oxygen in which two or three electrons have been stripped from the atoms by collisions within the stellar atmosphere.

Class B stars have somewhat lower surface temperatures, around 25,000°K. Since the temperature is lower, we find that the lines of helium are those of the element in its neutral state (the lower the temperature, the more difficult it is to knock electrons out of their orbits) and even nitrogen and oxygen have only one electron removed. Stars of this spectral class are found in very large numbers within the Orion nebula and elsewhere in this constellation, and for this reason they are often termed Orion stars. Very blue in colour, they are giant stars with mean densities about one-tenth that of the Sun.

Class A stars show very intense hydrogen lines in their spectra, and lines due to helium are either absent or extremely faint. Their surface temperatures are about 11,000°K and since Sirius, the brightest star, is typical of this class they are often known as the Sirian stars. They appear to predominate in low galactic latitudes, along the galactic equator. Apart from stars of Class K, they are the most numerous of all the stars. Although the surface temperature is still too high for absorption lines of neutral metals to appear, those of ionized metals are found in emission.

Class F stars are intermediate between those of the preceding class and Class G. With a surface temperature of only 7,500°K, there is a marked decrease in the strength of the hydrogen lines accompanied by a corresponding increase in the intensity of the metallic lines, those of ionized calcium being exceptionally prominent.

Class G stars, which include the Sun, show very narrow lines of hydrogen with stronger lines of ionized calcium. The surface temperature about 6,000°K, is now sufficiently low for numerous lines of neutral metals to appear in absorption. The majority are dwarf stars with a mean density about twice that of water. Such stars show little galactic concentration until one includes the very faint members of this class.

Class K stars form the largest group and are orange-yellow in colour, the brightest example being Arcturus. By now, the hydrogen lines in the spectrum have been considerably weakened, although those due to neutral metals are still prominent. The surface temperature of about 4,000°K is low enough for absorption bands of certain chemical compounds, particularly hydrocarbons, to appear. These compounds are those which are relatively stable to heat and are therefore able to survive undegraded within the atmosphere of the star.

Class M stars have surface temperatures in the range 2,000 to 3,000°K, their spectra being dominated by the fluted bands of titanium oxide which, since this molecule absorbs strongly in the blue end of the spectrum, means that they are all red stars. Both giant and dwarf stars of Class M are known, the former being nearly all variable in brightness to a certain extent. The mean density of the giant stars is only about one ten-thousandth that of the Sun; the density of the red dwarfs is somewhat greater than that of the Sun. Generally, the red giants are very distant stars. Several of the red dwarfs, on the other hand, are very close. Proxima Centauri, the nearest star of all, belongs to this class.

Class N stars are among the reddest of all the stars with surface temperatures of about 2,600°K. Like the Class M stars, they are nearly all variable and their spectra possess a similar fluted appearance, although in this case the absorption bands are due to carbon compounds and the fluting goes in the opposite direction to that in stars of the preceding class. The majority of these stars lie in, or close to, the Milky Way.

Class R stars visually resemble those of the preceding class but photographically they are quite different. The violet end of the spectrum is brighter than in Classes M or N and as a result these stars are not quite so red, although they have somewhat lower temperatures, between 1,700 and 2,300°K. The characteristic bands in the spectrum are those due to compounds of carbon.

Class S stars have extremely complicated spectra, consisting of bright hydrogen lines, many absorption and emission lines, and broad absorption bands due to zirconium oxide. Almost all of these stars are long-period variables and so far no dwarf stars belonging to this class have been discovered. Prior to 1922, these stars were included in Class N.

When the various types of spectra are arranged in a sequence such as that just outlined, it is easy to see how the spectrum of a star tells us at once a great deal about its temperature since the two are so closely related. Since the sequence represents such a gradual change from very high to very low surface temperatures, we may subdivide each spectral class still further and this is generally done by using a number from 0 to 9 as a suffix. A star of type A5, for example, lies midway in its spectroscopic characteristics between types A0 and F0. In a similar manner, astronomers use other prefixes and suffixes to denote certain peculiarities found in stellar spectra. The letter 'c' denotes that all the lines are very sharp and narrow, which is characteristic of supergiant stars. The letter 'g' has a similar connotation for giant stars, indicating that the lines due to ionized atoms are fairly strong. Conversely, the prefix 'd' indicates a dwarf star, the lines of ionized atoms being relatively weak.

To understand the reason for these differences we must examine the conditions prevailing within the atmospheres of giant and dwarf stars. As one might expect, the major difference is one of density, the atmospheres of the giants being extremely tenuous and extensive compared with those of the dwarf stars of the same spectral class and therefore of the same surface temperature. Since the intensity of radiation is virtually the same in both types of stellar atmosphere, the number of ionized atoms produced due to absorption of radiation will be similar in the two cases. In the very tenuous giant stars, however, the distances between the atoms is far greater than in the corresponding dwarf stars, and the lifetime of an ionized atom (before it can capture an electron and thereby become neutral) is much longer. As a result, the lines due to such atoms are more intense in the spectra of the giants than in those of the dwarfs.

The suffixes that are in most common use are 'e', indicating that bright emission lines are present in the spectrum; 'k', that the spectrum shows stationary lines of ionized calcium, these arising in interstellar matter lying between us and the star in question; 'n', that the lines are abnormally wide and diffuse; 'v', that the spectral characteristics are themselves variable; and 'p', that other peculiarities are present apart from those already mentioned.

Monochromatic Filters

Once the technique of stellar photography became established, it was soon recognized that there is a distinction between the visual and the photographic magnitude of a star. For some stars this difference is quite small, whereas for others it is of the order of one or two magnitudes. This difference between the visual and the photographic magnitude is known as the colour index of the star; it arises from the fact that, whereas the eye is more sensitive to the red and yellow end of the visible spectrum, ordinary photographic emulsions are more sensitive to the blue and the ultra-violet. A positive colour index is therefore indicative of a red star and a negative one of a blue star. The importance of the colour index is that, even if a star is too faint for its spectroscopic class to be determined, the colour index enables it to be placed somewhere along the Harvard Sequence.

Naturally, purely visual estimates are subjective to a certain degree and more accurate results are obtained from photovisual plates, which have been sensitized to the red and yellow wavelengths and are used with a yellow filter which reduces the intensity of the blue and ultra-violet. In order to standardize this procedure still further, Stebbins and Whitford have introduced two-colour photometry, in which the magnitude of a star is measured at about 5,000

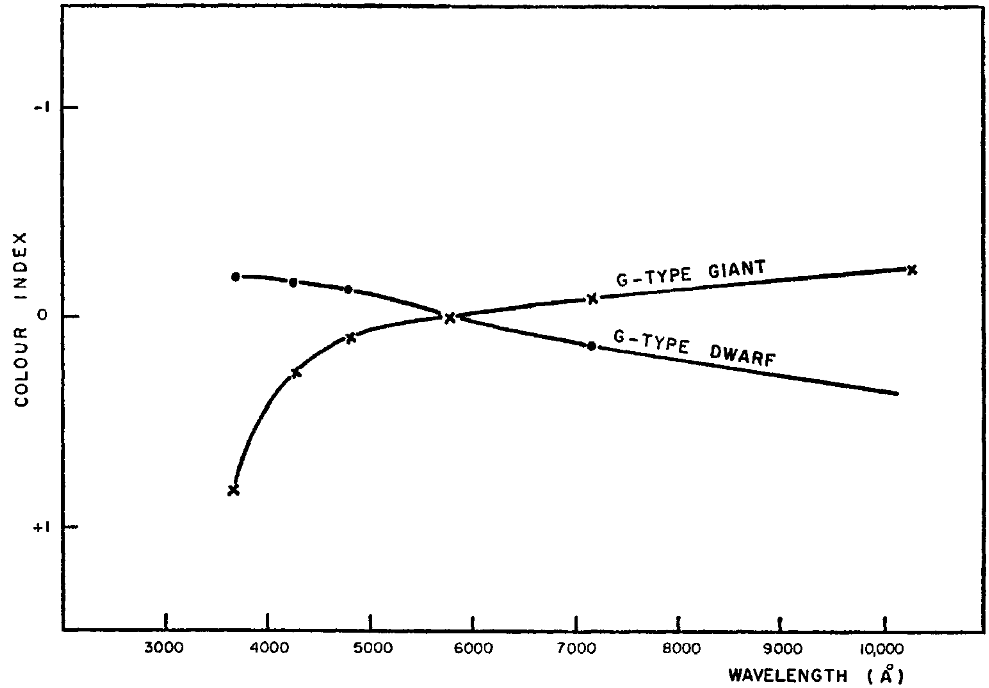

Fig. 2 Typical six-colour curves of giant and dwarf stars of the same spectral type.

Å and also at 4,300 Å, a yellow and a violet filter respectively being used. Such a method is, of course, capable of even further extension, and in the more recent technique of six-colour photometry the brightness of a star is measured in the ultra-violet, violet, blue, green, red, and infra-red regions of the spectrum. This not only provides us with an energy-distribution curve relative to wavelength, as shown in Fig. 2, but also enables us to differentiate quite readily between giants and dwarfs of the same spectral class, since giant stars are brighter in the infra-red and dwarf stars more brilliant toward the ultra-violet end of the spectrum.

When this technique is applied to the galaxies, more especially those which are sufficiently close for their internal structure to be discerned, some very interesting results have been obtained, particularly by Zwicky. The central regions of these galaxies (here we are speaking only of the spirals), are very rich in red stars and show maximum intensity in the red of the spectrum. Integration of the light over the whole galaxy, however, results in a shift of intensity towards the blue and ultra-violet, owing to the much greater abundance of blue stars in the outer regions. Zwicky has employed a very ingenious technique which allows the stars of different spectral types to be identified in these spiral galaxies. Here two different prints are made; in one a blue negative is combined with a red positive, and in the other a red negative is combined with a blue positive. In the former, hot blue stars appear as black images while the cool, red stars are white; the reverse is found in the second case.

Six-colour photometry is, of course, somewhat tedious and for more routine work the U, B, V system is employed in which the brightness of the star is measured in the ultra-violet, blue and yellow regions of the spectrum. The excess blueness of the star is then given by $V-B$ and the ultra-violet flux by $U-B$.

2. The Lunar Landscape

For some thousands of years our knowledge of the universe was based solely upon what could be seen and measured by the naked eye. Unfortunately, although this yields excellent results in certain cases, it can also lead us into serious error and the early centuries of astronomy were filled with erroneous beliefs which persisted until the invention of the telescope and later of the spectroscope and other pieces of ancillary equipment now commonplace in the large observatories. The fundamental notion that the Earth was the centre of the universe died hard; many other theories have not stood the test of time and have long since been discarded.

It is important to realize, however, that it is not only the ancient beliefs which have been challenged, proved wrong, and relegated to past history. Our present concepts of the universe as a whole have altered dramatically in recent years and many ideas held only a decade or so ago have been either abandoned entirely or radically changed in the light of more recent discoveries. Astronomy, perhaps more than any other branch of science, exists in a state of continual change. Each problem that is solved, or appears to have been solved, presents in its turn a bewildering array of further puzzles awaiting solution.

To the layman, the astronomer would seem to be labouring under the most difficult and frustrating of conditions. Unlike workers in other scientific fields, he must be content merely to observe and theorize since he cannot, with rare exceptions, handle any of the objects he studies. His laboratory is the heavens, where he plays the role of a bystander unable to move far, as yet, from his native planet, witnessing a grand sequence of cosmic events beyond all imagining, striving to find the key to the secrets it contains. Where the stars and galaxies are concerned, the vast edifice of astronomical knowledge which has been built up over the centuries, is based solely upon the feeble rays of light that reach us across the tremendous vastnesses of space.

However, the universe is so vast, the time scale concerned so long, that rather than suffering from a dearth of observational data we have, more often than not, a surfeit of it. The problem then resolves itself into one of systematic analysis, of breaking down the complex information presented by the radiation we receive from the Sun, stars, and galaxies. It is with the deciphering of this bewildering mass of data that astronomers have been concerned for the past three centuries.

This book is designed to give an overall outline of our present knowledge of the universe and especially of those twilight areas which lie on the very boundaries of astronomy, out at the furthermost limits of the largest instruments. Speculation will necessarily enter into many of the arguments, for here we are often groping blindly in an attempt to understand the observations made on the very fringes of the unknown. We shall begin, however, much nearer home, with our own satellite, the Moon. For countless centuries the Moon has been an object of special attention; it is the only body on which the surface features may be examined in minute detail. It is probably true to say that, at least as far as the earthward side is concerned, we know more about the topography of the Moon than we do of our own planet.

The Composition of the Moon

Being the closest of our celestial neighbours, the Moon in all probability was formed either from the primal Earth or at some point in space very close to it. The average density of the Moon has been accurately determined; as Table 1 shows, it occupies an intermediate position within the range of densities found for the other planetary satellites of comparable size.

Table 1
Mean Densities of Satellites
(water = 1)

Planet	*Satellite*	*Density*
Earth	Moon	3·33
Jupiter	Io	4·02
	Europa	3·78
	Ganymede	2·35
	Callisto	2·05
Saturn	Titan	2·41
Neptune	Triton	2·0 (?)

Here, two facts are of particular importance. Both Io and Europa have mean densities that are consistent with the presence of iron in their cores (about 20 per cent), suggesting that they are similar in composition to Mars. All of the others, with the exception of the

Moon, have mean densities that are too low for there to be any iron at all in their physical make-up. The Moon is, unfortunately, a borderline case. A lot depends upon the type of rock of which it is mainly composed. If this is similar to that found in the mantle of the Earth, then we may be reasonably certain there is no iron present. If, on the other hand, it is mainly of a very light kind, like that found in the Earth's crust, with a density between 2·5 and 2·8, then the Moon could perhaps contain up to 25 per cent of iron.

Here we may be tempted to ask: Why is it so important to assume that the Moon's core contains a fairly high percentage of iron? The answer lies in what has already been said, namely that the Earth and the Moon were formed very close together, at about the same time and, if they have been distinct bodies since their formation, their general composition should be similar. It seems scarcely conceivable that the Earth should have taken all of the dense elements at the time of formation and the Moon none at all.

Fortunately, there is some fairly convincing evidence that the Moon may be composed mainly of very light rock, possibly basaltic in nature. One characteristic of the Moon is that, in spite of its obviously mountainous terrain, volcanic activity is virtually absent. Geological evidence based upon the internal structure of the Earth suggests that volcanic eruptions are due to the exudation of light rock in a molten condition that is forced to the surface along pressure channels by the action of the denser material of the Earth's mantle. It may be, of course, that the temperature inside the Moon is not sufficiently high to allow of the formation of molten rock of any kind, with the result that the central regions are completely solid.

Now although we have said that there appears to be virtually no evidence for volcanic activity on the lunar surface, this statement needs some qualification. Certainly there is no positive evidence for any violent outbursts such as are commonly witnessed during volcanic eruptions on Earth, but over the years there have been many instances of changes on the lunar surface that require some comment here.

In 1903, Pickering catalogued the various descriptions of the small crater Linné that had been made by Riccioli in 1651, Schröter in 1788, Lohrmann about 1810, Mädler around 1830 and Schmidt in 1843 and 1866. This crater had been variously described as a small but extremely brilliant spot and as a deep crater, the bottom of which is totally dark. In 1866, Schmidt even found that it was not visible in his telescope although it had been readily observable with the same instrument some time before and was again visible a little while later. We could, of course, dismiss these conflicting observations on the grounds that there may have been misidentification by some of the observers, probably owing to the use of inadequate apertures, or that they did not allow for the effect of varying inclination of the sunlight, which could certainly alter the appearance of so small an object.

In 1956, however, Alter photographed Linné in violet and infra-red light, using the 60-inch reflector at Mount Wilson, with some very interesting results. Whereas in violet light Linné appears as an elevated crest on the lunar surface, in infra-red light it seems to be made up of a cluster of small craterlets. These observations would tend to confirm the earlier descriptions of this region and indicate that it may well be the centre of small, but definite, changes on the Moon.

Perhaps the most celebrated instance of activity on the lunar surface is that of the distinctive crater Alphonsus, which was also photographed by Alter in 1956. He found that in infra-red light there are small clefts around the periphery of the crater and also within the central regions, these showing up very clearly on the photographs. In violet light, however, these clefts are extremely indistinct, almost as though they were, at that time, covered by a misty obscuration indicative of some sort of vapour emission from this area. Two years later, in 1958, Kozyrev studied Alphonsus spectroscopically and announced the presence of carbon vapour rising during a thirty-minute period from some point close to the summit of the central peak within the crater. Subsequent visual studies of this region have revealed the presence of a darkish patch very close to this particular spot near the mountain crest, the colour being described variously as orange or red. It must be emphasized here that, although the spectroscopic evidence appears to be beyond doubt, certain observers have failed utterly to see the coloured patch on the side of the mountain peak. A lot, of course, depends upon the angle of the incident sunlight, and this may be a major problem in detecting minute differences in colour.

It had been hoped that more direct evidence concerning the internal structure of the Moon could be obtained from a seismometer left on the lunar surface in the Mare Tranquillitatis by the members of the Apollo 11 mission. Signals transmitted back to Earth by this instrument have recently been analysed. They have shown the presence of horizontal waves travelling through the lunar surface but, significantly, no body waves moving radially towards the surface from the interior have been detected. The possibility that these vibrations may have been due to the fall of a meteorite on to the lunar surface had been considered but virtually ruled out for several reasons. The amplitude of the vibrations shows that such a meteorite must have weighed at least a ton and such bodies are extremely rare. The fact that three such waves were recorded makes it much more likely that these moonquakes were due to internal causes.

The dispersion of the signals – a progressive lengthening of the wave forms – and the absence of any vertical waves are indicative of a layer structure of the Moon. Preliminary examination of the signals indicates that they are consistent with this picture, but a more recent report has shown that no further signals have been received from the seismometer and some doubts have been expressed concerning the validity of the inferences drawn from analysis of the original signals. However, a further instrument was landed upon the Moon by the Apollo 12 mission and three more, designed to act simultaneously, are scheduled to be landed by the next three Apollo flights. If all function satisfactorily, we may confidently expect to obtain a much more detailed picture of the internal constitution of the Moon.

We cannot leave this question of the seismological records obtained from the Moon, however, without mentioning the very important experiment carried out by the members of Apollo 12. During the ascent stage from the lunar surface, the Intrepid section of the lunar landing vehicle was ejected back on to the Moon to to simulate a meteoritic impact. The results were completely unexpected. Reverberations continued for almost an hour, the effect being similar to that produced when a bell is struck. So far, only a preliminary analysis has been made of the signals but, from what has been done, it would appear as though the Moon has a peculiar layered structure.

The Lunar Craters

We now come to a very important and much-debated problem – that of the origin of the lunar craters. That these are not distributed evenly over the lunar surface is immediately obvious even in a small telescope, and observation shows that there are far more of them towards the region of the south pole than in the northern hemisphere. One further obvious feature is that they cover a very wide range of sizes, from only a few metres across, as shown in the early television pictures transmitted back to Earth in the few seconds before the unmanned rocket probes crashed and on the more recently obtained photographs taken by the manned flights around the Moon, to giant craters hundreds of kilometres in diameter.

The maria, too, are noticeably devoid of large craters, and any explanation of their formation must clearly take this heterogeneous distribution into account. We also have to explain the appearance of the craters themselves. Some, for example, have well-defined central peaks; in others these are conspicuously absent. The walls of certain craters exhibit a markedly terraced structure; others have walls that have been broken in places by smaller craters and in almost every case it is the small crater which is intact, strongly suggesting that this smaller crater was produced later than the large one. Finally, there are the large ray systems associated with certain craters which, in the telescope, give the appearance of powdered material ejected from the main crater by some form of impact, although an explosive origin of the rays cannot be ruled out.

There are two main theories concerning the origin of the lunar craters: one is that they were formed by the impact of meteoritic bodies crashing on to the surface, the other that they are due to some form of vulcanism. The first theory was advanced in 1892 by Gilbert and subsequently enlarged and modified by Baldwin. The large majority of the craters are, according to this theory, believed to have been formed during the early stages of the Moon's career when, as seems possible, the number of such meteoritic bodies moving in orbits similar to that of the Earth-Moon system was quite large. Whether the maria, the very large plains, were also formed by impact, but in this case by bodies similar in size to the asteroids, is problematical. That large numbers of such bodies would be present in the newly-formed planetary system seems very likely and, since the Moon possesses no atmosphere, such bodies would reach the lunar surface, not only with high velocities, but also would suffer no frictional burning such as they undergo when plunging through the terrestrial atmosphere.

Now what will happen when a large body strikes the lunar surface? Since it will be travelling with a speed of several kilometres per second, it will not be stopped at the moment of impact but will penetrate to a depth dependent upon its mass and impact velocity. With the larger meteorites, this may be some kilometres below the surface. The impact theory has to face several criticisms. For example, if we are to explain the very large craters on the assumption that several meteorites fell close together (in space, although not necessarily in time), this would imply that such craters should have uneven floors, not only indented to varying degrees by the several impacts but strewn with boulders and debris from the breakup of the meteorites themselves. Observation, however, suggests that the floors of large craters are smoother than can be accounted for by this theory unless there is some other mechanism whereby the floor becomes appreciably smoother following the impact.