THE UNIVERSE

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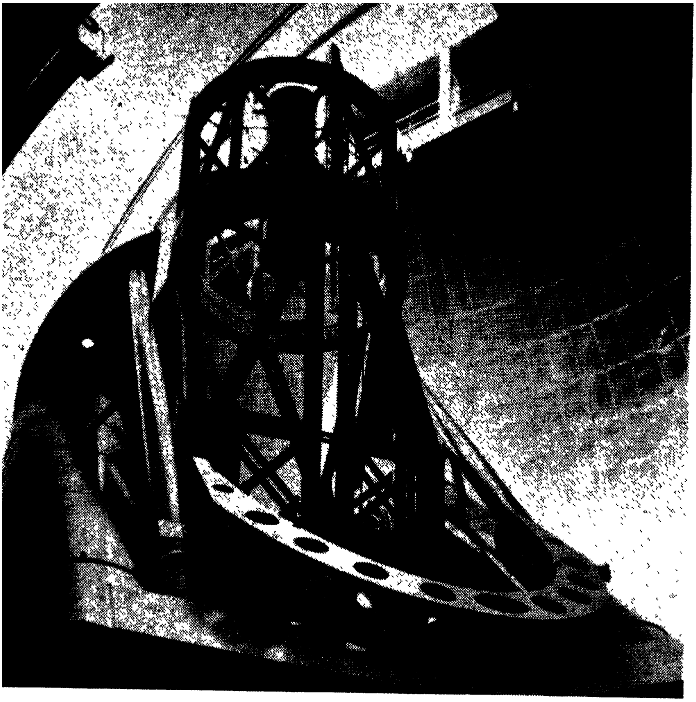
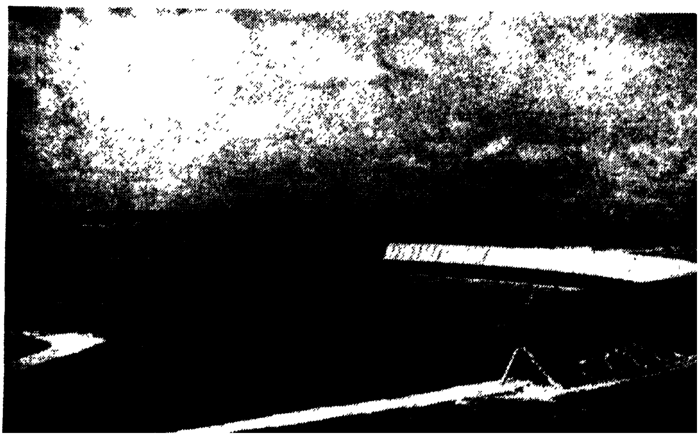
CONTENTS



THE 200 INCH HALE TELESCOPE AT PALOMAR OBSERVATORY, CALIFORNIA.

WITH THEIR FAR-SEEING EYES THESE RADIO TELESCOPES HAVE ENABLED ASTRONOMERS TO SEE REMOTE GALAXIES, AND HAVE MORE THAN DOUBLED FOR MAN THE KNOWN DIMENSIONS OF THE UNIVERSE.



THE RADIO TELES-COPE AT PULKOVA OBSERVATORY, U. S. S. R.

PREFACE

THE splendour of the starlit sky has always fascinated man and will continue to do so. But will his joy not increase immensely if he acquires some scientific knowledge about the heavenly bodies?

Primitive man regarded the heavenly bodies, like the sun, moon and stars, as gods, and the sky as their abode. He believed that his very existence depended on these gods. Consequently, he not only bestowed his most careful attention on these heavenly bodies, but also worshipped them. Even this superstitious worship added to our knowledge of astronomy. The continued observation over centuries of the (apparent) motion of the sun by the priests gave us our first calendars, sun-dials, and definite knowledge about the seasons which helped the farmer. In the middle ages the intimate knowledge of the stars and stellar constellations helped in marine navigation.

The invention of the astronomical telescope by Galileo Galilei in 1609 marks the beginning of modern observational astronomy. Since then, scientists have uncovered many of the mysteries of the universe. Understanding the true nature of astronomical phenomena has helped to remove many a deep-rooted superstition and has delivered man from his feeling of helpless dependence on a destiny shaped by supernatural powers.

Astronomical studies have led to outstanding advances in other branches of knowledge. Mathematics, for example, and astronomy have always gone hand in hand. In the earlier days, geometry and trigonometry were very largely used in describing the grouping of the stars, in studying the paths of the planets and in solving problems about the rising and setting of the sun and other heavenly bodies. In 1665, in an attempt to understand the motion of the planets, Sir Isaac Newton invented the theory of fluxions, the forerunner of modern differential calculus, and in 1666, he enunciated his universal law of gravitation. Astronomy has also inspired great advances in various branches of modern physics and chemistry, for example, spectroscopy, properties of matter under extreme conditions of temperature and pressure, the theory of relativity, quantum mechanics, and atomic energy. In the applied sciences, too, work of astronomers has led to remarkable advances in such fields as photography, the development of sensitive instruments to measure minute quantities of energy, photoelectric devices and so on. Sir John Herschel (1792-1871) introduced the technique of taking photographs on glass plates using sodium thiosulphate as a fixing agent. Similarly the need to photograph the feeble light from the distant stars and galaxies resulted in the development of extra-sensitive photographic plates. The development of modern balloon and rocket techniques to explore the space round the earth, and finally space vehicles, got considerable impetus from the intense desire to know about the universe.

In this book an attempt has been made to present some elementary information about the structure of the universe and its inhabitants: the galaxies, the nebulæ, the stars, and the planets. As the book is intended for the young reader, care has been taken to keep the explanations non-technical as far as possible. However, in discussing a scientific topic like the present one, certain basic technical terms are unavoidable.

Readers not interested in the technical aspects of optical and radio telescopes may leave out Chapters III and IV at the first reading. The stellar charts are placed at the end of the book. For more detailed information on the subject, the reader is advised to consult the following excellent books:

Our Sun by D. H. Menzel (Harvard University Press, Cambridge, Mass., 1963)

Galaxies by H. Shapley (The Blakiston Company, Philadelphia, 1944)

The Astronomical Universe by W. S. Krogdahl (The MacMillan Company. New York, 1962)

Astronomy by R. H. Baker (Van Nostrand, 1964)

Earth, Moon, and Planets by F. Whipple (The Blakiston Company, Philadelphia, 1947)

Radio Astronomy by F. Graham Smith. (Penguin Book)

Frontiers of Astronomy by Fred Hoyle (Harper, New York, 1955)

Astronomy by Fred Hoyle (Rathbone Books, London, 1962)

The Flammarion Book Astronomy by G. C. Flammarion and A. Danjon; translated by Annabel and B. Pagel (George Allen and Unwin, London, 1964)

Larousse Encyclopedia of Astronomy by L. Rudaux and G. De Vaucouleurs (Batchworth Press, London, 1959)

ACKNOWLEDGEMENTS

THIS book is based on a series of lectures given by the author under the scheme 'Popularizing Science' sponsored by the University Grants Commission. The suggestion that these lectures could be published as a book is due to Dr. R. N. Rai of the National Council of Educational Research and Training. The author is grateful to Dr. R. N. Rai for his valuable suggestions which have improved the original draft considerably and wishes to thank the above organizations for the opportunities given to him.

The photographs of the various heavenly bodies have been taken from a large number of sources: Mt. Wilson Observatory, Mt. Palomar Observatory, Yerkes Observatory, Lick Observatory, Kitt Peak National Observatory, Sacramento Peak Observatory, Harvard College Observatory, Meudon Observatory, Jodrell Bank Observatory, Pulkova Observatory, and Radio Physics Laboratory, Sydney. It is needless to say that without these pictures it would have been impossible to bring out this book. The author wishes to record here his indebtedness to these Observatories.

CHAPTER I

Introduction

Scope of the Book

THE title of this book is so general that it could cover any topic that we can think of. Consequently, we start by clearly defining its scope. We shall try to present in this book the picture of the physical universe that emerges as a result of scientific enquiry. We shall not, therefore, even touch upon questions such as 'What is the purpose behind the creation of the universe? Who is its Creator ?' The reason is evident. Even today science is unable to throw any light on these questions. But one thing is certain that so far no observed natural phenomenon has required the hypothesis of *'the creator'* for its explanation. Moreover, the answers of the philosophers, no doubt consistent with their theological beliefs and the contemporary patterns of civilization, are no more than speculative—speculative in the sense that they involve tremendous extrapolation of an experience based on extremely limited evidence. Another matter that deserves mentioning is that with the exception of the sun and its tiny neighbourhood, the universe has little or no influence on human affairs. Then why all the effort that is being made to explore space ? Perhaps it is because the unknown has always been and will continue to be a challenge to the human mind. Perhaps this challenge is the prime mover behind this quest. Moreover, the study of cosmic phenomena has given clues for an understanding of the true nature of matter and energy. To illustrate this we record below some outstanding advances brought about by the study of astronomy.

1 *The Rapid Development of Atomic Physics.* As stated by Dalton's atomic theory, it was believed that an atom is the smallest particle of matter and hence indivisible. Astronomers and physicists came in direct clash with this idea when they tried to interpret the messages that the light from distant stars brought to them. We shall discuss in greater detail the new concept of the atom which emerged from these studies in Chapter II. Here, it is enough to say that the new

concept gave a death blow to Dalton's atomic theory by attributing a structure to the atom—a positively charged nucleus carrying almost all the mass of the atom surrounded by electrons each bearing the smallest possible negative charge, a normal atom being electrically neutral.

2 *Thermonuclear Sources of Energy.* The stars are huge masses of matter which pour into space enormous energy in the form of light and heat. It was conjectured that this energy comes from the contraction of these bodies. But when numerical estimates were made, it was discovered that this source is inadequate to supply heat to a star throughout its life. It was only in 1938 that physicists discovered the true source of stellar energy. According to these newer ideas, at the high temperatures of the order of tens and hundreds of million degrees which prevail in the interiors of stars, the atoms of hydrogen, helium and other light elements can synthesize heavier atoms. In this process, called the thermonuclear reaction, some matter is destroyed and reappears in the form of energy according to the principle of mass-energy equivalence propounded by Albert Einstein, the author of the theory of relativity. This process is the basis of the atomic bomb.

3 *Highly Dense Matter.* From the known mass and radius of a star, we can calculate its mean density. When mean densities were calculated for a special class of stars, called the white dwarfs, it was found that on an average the matter which formed them possessed densities millions of times greater than those found on the earth. This observation led to considerable theoretical discussion on the equation of the state of gases. These discussions suggested that, under extremely high pressures prevailing in the interiors of white dwarfs, atoms can be completely deprived of all their encircling electrons and the bare nuclei can be pressed together to produce such inordinately dense matter (degenerate state of matter). This phenomenon is called *pressure ionization.*

It is evident that any description of a phenomenon depends on our means of observing it. How perfect or imperfect our picture is, depends on the fact how perfect or imperfect our tools are. Consequently, during the entire course of the development of science, the major concern of scientists has been to invent increasingly more efficient instruments to assist them. Therefore, we shall devote this chapter to a brief description of the sources of our information and of the instruments that have helped us in constructing the present-day picture of the universe.

Important Visual Observations

To start with, we mention some astronomical phenomena which man could not fail to observe even without the aid of any instrument.

1 *The phenomenon of day and night.*
2 *The phases of the moon.*
3 *The recurrent motion of the sun in the heavens through well-recognized constellations of the stars.* The average time taken by the sun in completing one round was estimated to be 365¼ days (2300 B.C.).
4 *The cycle of the seasons.* A season is repeated whenever the sun is again in the same constellation.
5 *The eclipses of the sun and the moon.*
6 *The Saros.* The ancient Chaldeans discovered by simply tabulating the character of the solar eclipse over a large number of years that the eclipses separated by an interval of about 18 years and 11¼ days, were more or less identical in character. This time-interval is known as *Saros* (3800 B.C.).
7 *Exploding Stars called Novae and Super-novae.* As early as 1054 A.D. the Chinese recorded the appearance of an extremely bright object in the sky. This is now known as the Crab nebula and is the remnant of a star that exploded long ago. In 1572 the famous Dutch astronomer, (Swedish by birth), Tycho Brahe, has recorded a supernova. Similarly, the great German astronomer Johann Kepler recorded another supernova in 1604.
8 *The comets.* Comets are the bodies which revolve round the sun, just as our earth and other planets do, but their orbits are very much elongated ellipses. When they come near the sun they become very highly luminous and develop a long luminous tail always directed away from the sun.

Invention of the Optical Telescope

The year 1609 brought about one of the most revolutionary events in the history of science. That year, an Italian astronomer, Galileo Galilei invented the optical telescope with the help of which he proved that the planet Jupiter possesses several moons in the same way as our earth possesses one moon. He was also able to show that the surface of the sun is not uniformly bright. At places it has dark patches, which he called sunspots. Since then increasingly more efficient and versatile telescopes have been invented and used in the task of discovering the universe. The initial success brought by the telescope was so spectacular and rewarding that people did not grudge any investment in the form of effort, time and money in the construction of telescopes. As a result of this keenness, a large number of observatories, some small and some big, came into existence. The year 1917 saw the installation of a giant telescope with a reflecting mirror of 100-inch diameter at Mount Wilson in California in the United States of America at the suggestion of astronomer George Ellery Hale. This event was followed by the installation of a still bigger telescope of 200-inch diameter at Mount Palomar, also in California, in 1947. This telescope brought the universe up to the distance of a few thousand trillion miles under observation. In astronomical studies we have to deal with such enormous distances that it is convenient to take the distance of six million million (10^{12}) miles travelled by light in one year as the unit for measuring distances. This unit of length is called a light year (l.y.). On this scale we have the following important distances:

One light second (l.s.)	= 1,86,000 miles
One light minute (l.m.)	= 11,160,000 miles
One light hour (l.h.)	= 669,600,000 miles
Distance of the moon from the earth	= 1.1/3 l.s.
Distance of the sun from the earth	= 8 l.m.
Distance of the outermost planet, Pluto from the earth	= 5 l.h.
Distance of the nearest star, Proxima Centauri from the earth	= 4 l.y.

In terms of light years, we can describe the power of the 200-inch telescope by saying that it can 'see' heavenly bodies situated even at a distance of three thousand million light years.

It is gratifying to note that today every country possesses one or more good observatories. For example, our country has three:

Kodaikanal Observatory, in Madras State.

Nizamia Observatory, Hyderabad, and
Uttar Pradesh Observatory, Nainital.

In these observatories hundreds of astronomers stay night after night, away from the glamour of the cities, struggling to construct bit by bit the picture of the universe around us.

The telescopes, in association with certain specialized instruments, can perform a wide variety of functions. They can photograph the heavenly bodies like the sun, moon, planets, nebula and galaxies, which produce extended images. They can measure the very minute quantities of energy reaching them from the stars and can produce sufficiently accurate spectra. From the study of these spectra we can not only know the elements present in abundance at the source or in the intervening space but also know roughly the physical conditions prevailing there. The modern telescopes can take motion pictures of the fast changing cosmic events like eclipses, solar prominences, and so on. Finally, very recently colour photography has been introduced in astronomical investigations through the efforts of Miller, a research photographer at Mount Palomar Observatory. Thus our telescopes can record faithfully the brilliant and fascinating hues of the heavens.

Birth of the Radio Telescope

Resuming the story of the development of instruments for the exploration of the universe, we come to the radio telescope (Chapter IV). Radio astronomy is hardly two decades old and the story of its birth is both interesting and inspiring. Karl G. Jansky, a radio engineer with the Bell Telephone Company in the U.S.A., was interested in measuring the general noise level for the construction of short-wave radio receivers for long distance communication. He discovered (1932) that the noise of greatest intensity always came from a certain fixed direction relative to the stars. Later it was found that this direction pointed towards the centre of the Milky Way (Chapter VIII). Thus Jansky had the good fortune of being the first to listen to the cosmic radio signals. This discovery inspired Gorte Reber, a radio amateur in the U.S.A., to make further investigations. In his spare time, with his own modest means, he built a 30-foot parabolic reflector which could be steered in any direction. He used this radio telescope with sensitive receivers to make some remarkable recordings of cosmic radio signals. Reber even today is a radio astronomer exploring the heavens. The moral from Reber's story is evident: 'Where there is a will, there is a way'.

Another outstanding discovery which gave a great impetus to radio astronomy was made accidentally in England during World War II. The radars mounted on the eastern shore of England recorded the arrival of strong radio waves. Thinking that they indicated the arrival of German bombers the authorities alerted the anti-aircraft guns, but no invasion took place. It was then discovered that the source of the waves recorded by the radars was none other than our own sun. This discovery established that the sun gives out energy not only in the form of heat and light waves but also in the form of radio waves.

These events show that the birth of radio astronomy is rather accidental, like certain other scientific discoveries. In conjunction with the optical telescope the radio telescope is a very powerful tool of observation. The optical telescope is still needed to recognize the object which is the source of radio waves. During the last decade and a half, some very large and spectacular radio telescopes have been built and employed on the task of exploring the universe. We may mention in particular the following radio telescopes (Chapter IV) which have already gathered very valuable information about the universe:

Cambridge, England—Mullard Interferometer with a 3,300-foot-long fixed antenna.

Jodrell Bank Observatory, Manchester, England—250-foot parabolic reflector.

Green Bank, West Virginia, U.S.A.—140-foot parabolic reflector.

Sydney, Australia—(*a*) Interferometer with one antenna mounted on a 300-foot high cliff in Sydney and the other mounted in New Zealand; (*b*) 210-foot parabolic reflector.

Pulkova Observatory, near Leningrad, U.S.S.R.—Reflecting telescope with adjustable surface extending over an arc which is 500 feet long.

That it is possible to explore space with the help of the radio telescope is indeed very fortunate. The atmosphere of the earth acts like a veil between us and the glory of the heavens. Prior to the birth of radio astronomy, we could peep at the heavens only through an extremely narrow gap extending from 3.9×10^{-5} cm to 7.5×10^{-5} cm in the wave length range which extends

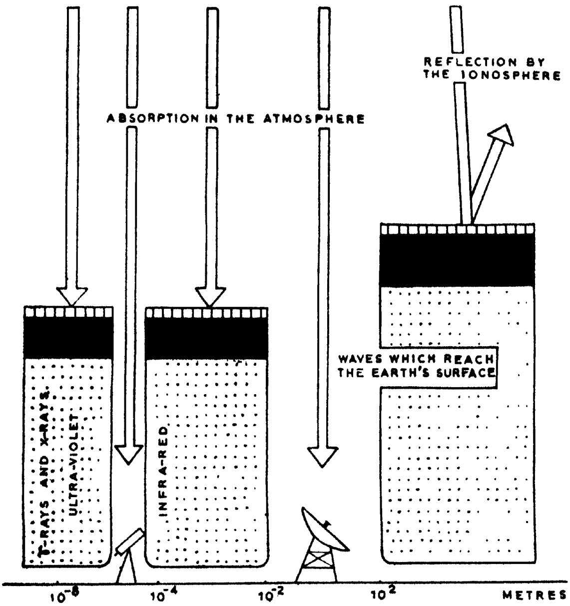


FIG. 1.1 *Windows in the earth's atmosphere for optical and radio observations*

from almost zero to infinity. This range marks a region slightly bigger than visible light and extends from the ultra-violet to the infra-red (Chapter II). The radiation outside this gap suffers either heavy absorption by the water drops and other gases present in the atmosphere or gets scattered by the heavier molecules and dust particles. Radio astronomy provides an additional window for exploring the universe in the long wave length range extending from a few centimetres to about ten metres. For radio waves, too, there exists a very powerful source of disturbance in the atmosphere, called the ionosphere.

It consists of clouds of electrically charged particles. It is situated near the outer fringe of the atmosphere and its thickness and the number of charged particles present in it go on constantly changing. For radio transmission on earth, these changes affect the quality of the radio reception. In the records of the cosmical radio signals, they produce random fluctuations. Moreover, the ionosphere reflects more or less completely waves of lengths greater than 10 metres. Thus the terrestrial atmosphere is a big obstacle in the way of our observation. However, it is a boon too, as it provides us with the life-sustaining oxygen and rain and shields us from the harmful effects of ultra-violet, X-ray and other radiations from the cosmos.

Meteors, the Direct Samples of Extra-Terrestrial Matter

Meteors, the so-called shooting stars, and meteoric showers form another very important source of knowledge about our close neighbourhood. They represent direct samples of the matter that exists outside the earth. On the basis of their chemical composition, they can be divided into two distinct classes: (*i*) stone type meteors containing some iron, with a composition corresponding closely to the outer rocky crust of the earth, and (*ii*) iron type meteors containing about 99 per cent of nickel-iron alloy, with a composition corresponding to the inner part of the earth. It is interesting to note that about 10 tons of meteoric matter is being added every day to the earth !

Due to the similarity of their composition with that of the earth, it was thought at one time that meteors are nothing but the terrestrial matter blown off by violent volcanic activity. Careful observations on comets, like Biela with a period of six and a half years, have shown that meteoric showers are the debris of a comet and that the earth receives them when it crosses the comet's tail in its journey round the sun. However, in 1945, Hey and Stewart proved beyond doubt, with the aid of their radars, that sporadic meteors come from remote spaces between the stars. A word of caution ! We must be careful in extrapolating the chemical composition of these meteors to that of the space from where they come, as they are bound to lose the volatile matter during their passage through earth's atmosphere when they are heated to luminiscence by the friction of the air.

Cosmic Rays

Cosmic rays are the nuclear particles, i.e., nuclei of atoms (Chapter II), which have been stripped of their electrons and other elementary particles like mesons. These particles keep on bombarding the earth at all times and from all directions. Most of them are protons, i.e., the nuclei of hydrogen atoms, and only a tiny fraction consists of the nuclei of heavier atoms. Most of them possess enormously high energy and move with speeds comparable even with the speed of light, which marks the maximum speed that a material particle can ever attain. To give an idea about the magnitude of their energy, we may mention that some of them (hard cosmic rays) can even possess an energy as high as a few thousand million electron volts.

Cosmic rays have tremendous penetrating power. For example, about 50 per cent of the cosmic rays which arrive at the surface of the earth after crossing its atmosphere still possess enough energy to penetrate another six feet of water. We recall that the earth's atmosphere is equivalent to 34 feet of water. The hard component has enough energy on reaching the earth's surface to enable it to penetrate several hundred feet below the surface of a lake.

The origin of cosmic rays is still an open question. However, astronomers believe that comparatively low energy cosmic rays are certainly produced by the sun, probably during solar flares (i.e., outbursts of very hot gases). They also believe that stars like the sun, which are in a steady state, cannot be the main source of cosmic rays, but that the physical conditions prevailing in the exploding stars, called super-novae, are favourable for their production. Some astronomers feel that the origin of these particles may be a still larger system, namely, the galaxy itself (Chapter VIII).

The study of these particles is certainly bound to give considerable information about the space outside the earth. Moreover, to confine these particles, which possess tremendously high energies and velocities, within the galaxy, we require some very effective mechanism. The general feeling is that the widespread magnetic fields do this job. We may explain the interaction of a magnetic field with these charged particles briefly as follows: if a moving particle carrying a charge is subjected to a magnetic field, its motion is considerably modified.

If the magnetic field is strong, it is compelled to move along the magnetic line of force whirling round it all the time. It appears as if the particle is glued to a line of force. Naturally then, a detailed study of cosmic rays is bound to reveal considerable information about the magnetic field that pervades the entire space.

Rockets and Artificial Satellites

At the end of the section on the radio telescope we have pointed out the difficulties created by the earth's atmosphere in our observation of the universe. As far as optical observation is concerned, these difficulties have been overcome in part by locating the observatories high above the sea level. But no matter how high a ground-based observatory is placed, it is always below the outer layers of the atmosphere which contain clouds of ice crystals—each one acting as a miniature lens to distract the radiation passing through it. Some astronomers have employed the very clever device of sending up small telescope in balloons to great heights in the atmosphere to photograph the cosmic events. As far as radio telescopes are concerned, the ionosphere will always be there above them, to confuse their view. Naturally therefore, astronomers were craving to go above the atmosphere and observe the universe more completely. This has now been partly achieved through the artificial satellites (packages of instruments revolving round the earth just like the moon) and the space probes. Without going into details, we would like to mention the following outstanding achievements of these recent modes of space exploration:

1 The Soviet Luniks have taken photographs of the side of the moon which is always directed away from the earth.
2 Satellite observations have provided information about the shape and internal constitution of the earth.
3 As a regular service, American TIROS (television and infra-red observation satellite) satellites relay television pictures of the cloud cover over the earth. The study of these pictures helps in forecasting the weather.
4 Mariner II has provided us with novel facts about Venus. Temperatures higher than those previously suspected exist in its atmosphere.

Cosmic Rays

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CHAPTER II

Matter And Radiation

THE stars, like our sun, give out light and we see them by their own light. Planets, like our earth, do not glow, but become visible in the light of the sun. Thus light is fundamental to astronomy. It is a matter of common experience that it is hotter in sunshine than under shade. Consequently, the sun radiates heat along with light. We shall learn shortly that the sun radiates besides heat and light rays, other rays also. We call all the rays that a heavenly body pours into space as its radiation. We shall devote this chapter to radiation as it is the basic agency through which we learn all that we know about the universe.

We start our story with the famous experiment of Sir Issac Newton in 1666 which proved beyond doubt that a beam of white light is composed of colours ranging from red to violet. Figure 2.1a gives schematically the set-up of his experiment. A beam of white light coming from a pin-hole A in a piece of cardboard passes through a glass prism B and the emergent beam is received on a ground glass screen C. The screen shows a patch of different colours. Starting from the bottom they are arranged in the following order: violet, indigo, blue, green, yellow, orange and red (the first letters form the meaningless word VIBGYOR). To make sure that these colours were not caused by the material

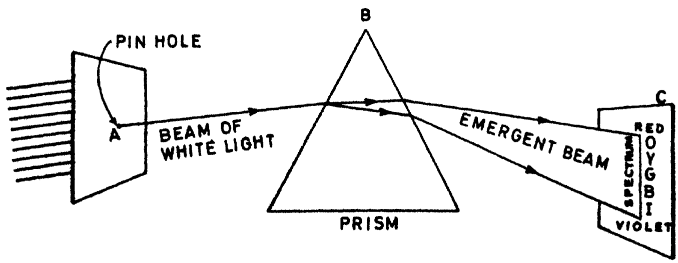

FIG. 2.1*a* *Dispersion of light into its colours Violet, Indigo, Blue, Green, Yellow, Orange and Red*

of the prism, Newton interposed another prism B′, identical with B, between the prism B and the screen C with the apex set opposite to that of B and with their nearer faces parallel (Figure 2.1b). The emergent ray now produced a white patch

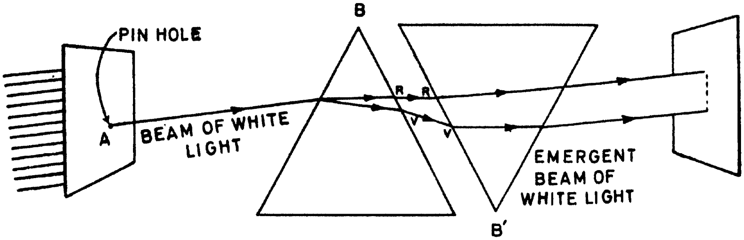

FIG. 2.1*b* *Recombination of colours into white light*

on C. If the colours had been caused by the material of the prism, the effect of B should have been doubled by introducing B′ rather than nullified! The band of colours into which the incoming beam of light is decomposed on passing through a prism is called the spectrum. Figure 2.2 gives the schematic diagram

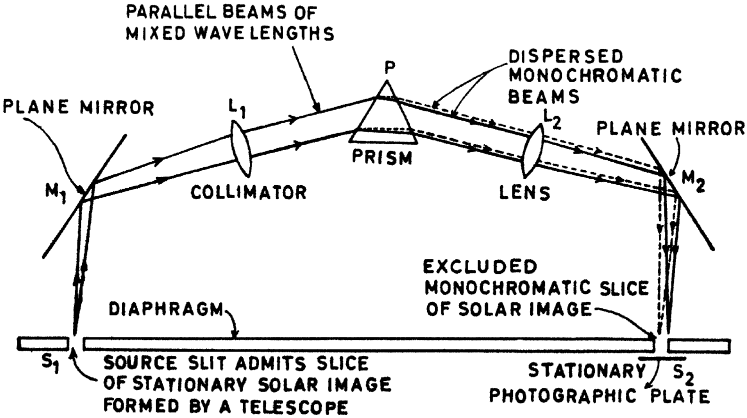

FIG. 2.2 *Schematic diagram of a prism spectroscope*

of a prism spectroscope, an instrument which is used in astronomy for resolving radiation into its colours. S_1 is the slit through which the radiation from a source is allowed to pass. A plane mirror M_1 deflects the incoming radiation in a convenient direction. The lens L_1, called the collimator, renders the incoming rays of light parallel. The light is then passed through a small glass prism P which forms the image of the slit in various colours present in the incident light at different places like fine lines which the physicist calls the lines of spectrum. L_2 is another convex lens which focusses these images sharply. M_2 is a plane mirror which deflects the emergent light without changing its character. Now the spectrum is received on a ground glass screen for visual observation or photographed on a photographic plate. When we wish to study the source in a particular colour, we may select that colour with the help of another adjustable slit S_2.

Infra-red Radiation

The spectrum represents only the small fraction of radiation that the eye can see. The curiosity to know if there exists some form of radiation beyond the visible spectrum was natural. In 1800, Sir William Herschel, a British astronomer, produced the spectrum of sunlight in the usual manner and tried to study the effect of the various colours of the spectrum on the thermometer. He discovered that the heating effect increased as the thermometer was moved from the violet end to the red end of the spectrum. When he placed the thermometer beyond the red end, it registered an even higher temperature. This established beyond doubt that in the sun's radiation invisible heat rays are also present and that they lie beyond the red end of the spectrum. He called these rays infra-red radiation (*infra* meaning *below*). He performed a large number of experiments on infra-red radiation and found among other things that it can be reflected by a mirror and focussed by a lens just like the visible radiation.

The heat radiated by the sun is measured with the help of an electrical instrument called the pyroheliometer. The pyroheliometer makes use of a thermocouple which consists of two wires of dissimilar metals, like iron and copper or bismuth and antimony, joined together at one end while the other ends are connected to a milliammeter to measure the current flowing in the circuit. When heat is supplied to the junction, a current results, the magnitude of which depends on the quantity of heat falling on the junction. To increase the surface area receiving heat from the source we attach to the junction a metal disc with a layer of lampblack on its outer side, as pure black absorbs radiation in all the colours with equal efficiency. Astronomers have built compound thermocouples of very high precision and sensitivity. With the help of these instruments we can measure, for example, the radiation from a candle placed 100 miles away from the instrument. Figure 2.3 represents schematically a simple pyroheliometer.

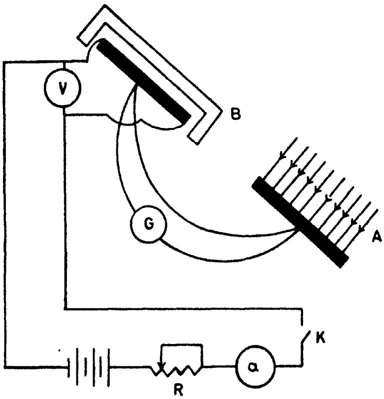

FIG. 2.3 *Schematic representation of a pyroheliometer*

A and B are two thin, exactly similar blackened strips of platinum or manganese suitably mounted so that one can be exposed to the radiation from the source falling on it normally and the other can be shielded. A pair of copper-constantan thermojunctions are attached to the backs of A and B. The thermocouples are electrically insulated from the strips to avoid leakage of current. G is the galvanometer placed in the thermocouple circuit. The strip B is connected with a battery by a circuit containing an ammeter a, a variable resistance R, and a contact key K. V is the voltmeter to measure the potential difference across the strip B. When A is exposed to the heat source, the strip A is heated and this in turn heats the junction of the thermocouple attached to it, resulting in a current in the thermocouple circuit. This current produces deflection in G. Now the current is passed through B; this heats B. With the help of R, the current is so adjusted that G does not show any deflection. At this stage the current I registered by a and the potential difference E registered by V are recorded. It is clear that, when this condition is attained, the temperatures of A and B are the same and hence the rate at which the heat is supplied to both is the same. Now the heat supplied to B $= \frac{IE}{4.2}$ calories per second; hence this is also the rate of heat supplied to A. From this it is possible to calculate the energy radiated by a unit area of the sun's surface per minute, which is called the solar constant. If A square cenimetres is the area of strip A and d cm its distance from the sun, r cm the radius of the sun and S calories the energy radiated by the sun per square cm per minute, then

$$4\pi r^2 S = 4\pi d^2 . 60.\frac{E I}{4{\cdot}2} \frac{1}{A}$$

$$\text{or} \quad S = 60 \left(\frac{d}{r}\right)^2 \frac{1}{A} \frac{E I}{4{\cdot}2} \text{ cal. cm}^{-2} \text{ min}^{-1}$$

It must be noted that in calculating the value of S, we have to take into account the absorption of heat energy by the earth's atmosphere. It is found that $S \simeq 88080$ calories cm^{-2} min^{-1}. It is easy to calculate from this value of S, the solar constant, i.e., the amount of heat received by one square centimetre of the earth's surface per minute is approximately equal to 2 calories.

Ultra-violet Radiation

The credit of discovering radiation beyond the violet end of the spectrum goes to Johann Wilhelm Ritter, a German physicist. Knowing that if we spread silver chloride along the visible spectrum, it gets blackened and that the intensity of blackening increases as we move from the red end to the violet end, he concluded that the radiation beyond the violet end, if it existed, could perhaps be discovered through this property of radiation. Accordingly, in 1801, he spread silver chloride along a straight line in the visible spectrum and beyond it. Surprisingly, he found that the substance got blackened more rapidly in the region beyond the violet end than in the visible part of the spectrum. This simple experiment established the presence of radiation beyond the violet colour and Ritter called it ultra-violet radiation ('ultra' meaning 'beyond'). It was found that ultra-violet rays can also be reflected by mirrors and focussed by lenses, but they do not penetrate glass very well. Later on, Sir George Stokes, a British physicist, discovered that these rays produce fluorescence in certain chemicals, i.e., these chemicals, when exposed to ultra-violet rays, shine with visible light.

A laboratory study of these rays can be made by photographing them on sensitive plates. However, air and glass strongly absorb ultra-violet rays so that when these rays pass through air or glass their intensity reduces considerably. Consequently, for studying ultra-violet radiation we use a special type of spectrograph from which air has been evacuated and in which a quartz prism is used instead of a glass prism. Our atmosphere is a great boon to us inasmuch as it does not allow the harmful ultra-violet rays of the sun to reach us; it is also a curse in the sense that it debars us from studying the sun through ultra-violet radiation.

Wave Nature of Light

Before we discuss the radiation beyond the infra-red and ultra-violet range, we shall say a few words about the nature of light. Since the time of Newton, considerable effort has been put in to understand the nature of light. In fact, even in his day, two significantly different theories, namely the corpuscular theory and the wave theory were in vogue. Newton himself showed preference for the corpuscular theory according to which light consisted of myriads of minute particles, called corpuscles, and some intrinsic property of these corpuscles, such as their size or mass, determined the colour. However, he did not totally discard the wave theory according to which light was a wave motion, and some intrinsic property of the wave, such as the spacing between its successive crests, called the wave length, determined the colour. Newton vaguely believed that waves were either always associated with corpuscles or were produced by them when they entered a material medium.

Till the beginning of the nineteenth century, not much progress was made towards understanding the true nature of light, in spite of the fact that in 1690, Christian Huygens, a Dutch physicist, published a well thought out wave theory. As Newton's influence dominated science, this theory could not be accepted at that time, but later it won general acceptance. Early in the nineteenth century, Thomas Young made the first decisive experiment which appeared to establish beyond doubt the wave character of light. He showed that two identical beams of light, when superimposed, cancelled each other under certain conditions. This phenomenon is known as *interference*. Evidently, interference of light could not be explained on the corpuscular theory, for how could two identical light

2

particles nullify each other ? On the contrary it was to be expected that their effects would add up. The wave theory, on the other hand, offered a satisfactory explanation for this phenomenon. Let us consider two waves (dotted and continuous curves in Figure 2.4) of equal amplitude, displaced in phase by half a wave length so that the crests and troughs of one wave fall respectively over the troughs and crests of the other. On addition the entire wave motion will be destroyed.

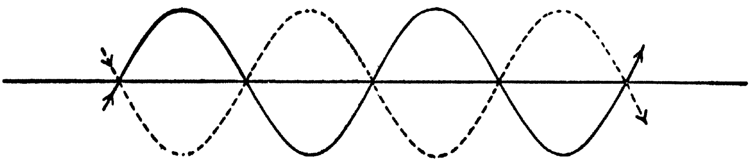

FIG. 2.4 *Interference phenomena according to wave theory*

We denote the wave length by the Greek letter λ (lambda) and the wave velocity by C. Another important parameter (and more fundamental than λ) associated with wave motion is the frequency denoted by the Greek letter

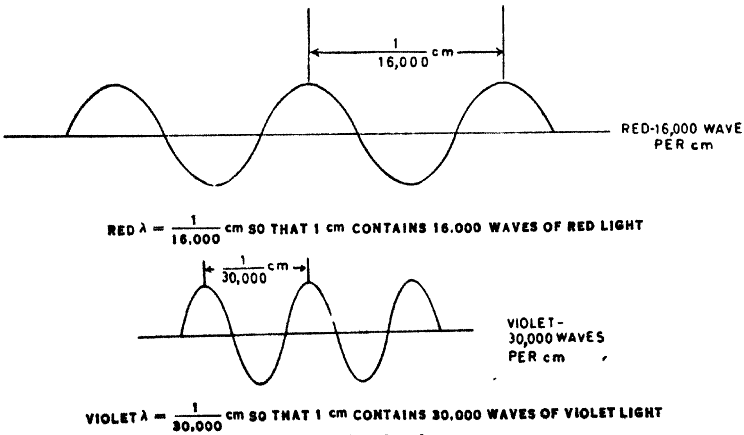

FIG. 2.5 *Red and violet waves*

ν (nu). This frequency specifies the number of times the amplitude at a point in a wave vibrates in unit time. λ, C and ν are connected by the following relation: $\lambda \nu = C$. The velocity C of the wave depends on the nature of the medium in which the wave propagates and hence the wave length for a given frequency also varies from material to material. In figure 2.5 we draw, for the sake of comparison, the wave profiles for the extreme colours, red and violet.

Light as Electromagnetic Waves : Radio waves

In 1864, James Clerk Maxwell, a Scottish physicist, published a series of theoretical papers which showed that light waves are electromagnetic in character. The importance of Maxwell's findings can be understood as follows. The forms of wave motion that had been discussed till then, like water waves, sound waves, etc., all needed a material medium for their propagation. Consequently, for the propagation of light waves the scientists had, by analogy, to postulate a medium, called ether. However, if light waves are merely the propagation of the state of electric and magnetic fields, they require no material medium.

One of the most brilliant suggestions of Maxwell deserves mention. He suggested that electromagnetic waves could extend far beyond the infra-red and that a vibrating charge could set up such waves. The first confirmation of Maxwell's theoretical ideas came from the experimental work of a school teacher, Elihu Thompson, in 1871. He was experimenting on high voltage electric sparks between two terminals separated by several inches. He connected one of the terminals with a water pipe and the other with the metal top of a table. He found that while the sparks were jumping from one terminal to the other, he could go to distant parts of the building and draw a spark on the blade of a knife by holding it near a metallic object. However, these findings of Thompson remained unnoticed. In 1887, Heinrich Hertz, a German scientist, working with equipment basically similar to that of Thompson, proved beyond doubt the existence of electromagnetic waves, as predicted by Maxwell. These waves came to be known as Hertzian Waves after Hertz, and are now popularly known as *radio waves*, as they are responsible for carrying radio transmissions. We shall later learn that many heavenly bodies also emit radio waves, the study of which provides us with valuable information about these cosmic radio sources.

X-rays, Gamma rays and Cosmic rays

Are there waves of frequencies higher than (or wave lengths, lower than) those of ultra-violet rays ? The answer to this question was provided in 1895 by Wilhelm Konrad Roentgen, a German physicist who showed that an electric discharge produced in an evacuated glass bulb produced rays which lay beyond the ultra-violet. These rays could produce fluorescence, blacken photographic plates, could pass through many solid materials, like paper, wood, human flesh, and one could photograph the bones in the human body with their help. Roentgen gave these mysterious rays the name X-rays, as in science X stands for the unkown. Later, it was discovered that the frequency of these rays depends on the voltage of the electric current used to produce them. The higher the voltage, the greater the frequency and the lower the wave length; for example, when the voltage is 100,000 volts, the wave length $\lambda = \frac{1}{800,000,000}$ cm, i.e., it is $\frac{1}{40,000}$ times shorter than that of visible light. In some of the modern devices for breaking the nuclei of atoms, it is possible to generate voltages as high as hundreds of millions of volts. The frequencies of the radiation produced in these devices are still higher. The radiations of frequencies even higher than these are associated with cosmic rays that come from all sides of the earth from extra-terrestrial sources.

From the above discussion it is clear that electromagnetic radiations of all frequencies are possible, and perhaps exist in nature, but at the present stage in

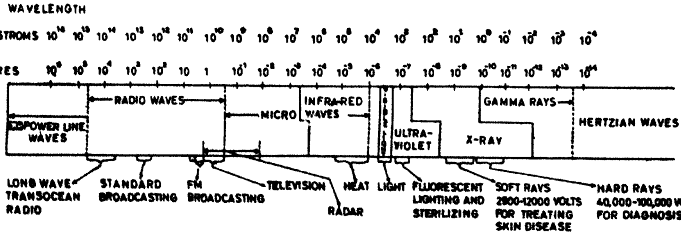

FIG. 2.6 *Electromagnetic radiation and its uses*

our knowledge, we are unable to detect them beyond a certain range on account of the limitations of our instruments of observation. Figure 2.6 gives the wave lengths in metres and Angstrom units (1 A=Angstrom unit=10^{-8} cm) and the uses of the various types of waves that we have discussed so far.

Corpuscular Theory of Light

After the work of Huygens and Maxwell on the wave theory of light, it was thought that the corpuscular theory of light had been completely done away with. However, around the year 1900, Max Planck in Germany and Niels Bohr in Denmark showed that there were certain effects that could not be explained by the wave theory. For example, radiations coming from excited atoms exhibited a particle-like behaviour inasmuch as they consisted of streams of tiny corpuscles of energy called photons, a photon being defined as the smallest amount of light energy possible. Similarly, when atoms were exposed to radiation, they absorbed from it energy in separate particle-like units called *quanta*. Here was now a difficult situation to explain: how could light behave like corpuscles in one instance and like a wave in another. Around 1925, Louis de Broglie, a French physicist and Erwin Schrödinger, an Austrian physicist, hit upon a brilliant idea to resolve this riddle. They propounded a theory of wave mechanics according to which all forms of matter and energy have both wave-like and particle-like properties, but these two types of properties never show up simultaneously. All particles have waves associated with them, the wave lengths of which depend on the masses and velocities of the particles. A bullet fired from a gun has a relatively huge mass and small velocity and hence the wave associated with it is too small to be detected; but an electron has an infinitesimal mass (9.1×10^{-28} grammes) and moves with a velocity close to the speed of light (3×10^{10} cm sec or 186000 miles/sec) and consequently the wave length associated with it is large enough to be measured. Thus, in solving one puzzle, de Broglie and Schrödinger introduced a new puzzle, namely, that matter, so far considered entirely as corpuscular, could also behave like a wave. However, these apparently puzzling ideas have been generally accepted in science. It is interesting to compare these ideas with those of Newton. Was Newton not ahead of the rest of the scientists by two centuries and a half?

Atomic Structure

It will be recalled that the ancients regarded atoms as tiny geometrical figures: spheres, cubes, pyramids, and so on. They regarded atoms as indivisible and it never occurred to them that these atoms could possess any internal structure (the Greek word *atom* meaning *indivisible*). Even the early chemists, who were mainly concerned with explaining the differences between chemical elements, like iron and copper, were also satisfied with the explanation that their atoms were different in shape. But, in 1871, when Dmitri Mendeleev, an eminent Russian chemist, gave his periodic table in which elements having similar chemical properties were grouped together, a very difficult situation arose: how could atoms, having nothing in common, possess such striking similarities ? These ideas of Mendeleev gave birth to the idea of atomic structure. Again, the ideas of Planck and Bohr and those of de Broglie and Schrödinger could only be substantiated if one could associate a structure with an atom; otherwise how could an atom generate a wave without undergoing some sort of internal change ? To cut the story short, we may simply mention the modern concept of an atom. An atom consists of a positively charged nucleus, around which are moving negative electrons. In the case of an atom of hydrogen, the lightest known element, there is only one electron moving round the nucleus which bears a positive charge equal in magnitude to that of an electron (1.602×10^{-19} coulombs, which is also the smallest possible charge). An atom of the heaviest known element, lawrencium (Lw) has 103 electrons moving around its nucleus. Normally, these electrons move in certain regions called orbits and each of these orbits is associated with a definite amount of energy which increases as we go to orbits farther and farther from the nucleus. When the atom absorbs energy these electrons jump from their normal orbits to higher orbits. The atom is then said to be in an *excited state* and the electrons are described as having shifted to *higher energy levels.* When the absorbed energy is sufficiently large, the electrons may even be removed completely from the atom. In this state the atom is said to be *ionized* and the residual atom which as a whole possesses a positive charge is called an *ion.* This process of removing one or more electrons from an atom is said to be *ionization.* The excited atom is in an unstable state, and the electrons tend to return to their normal orbits. In this process each electron gives out energy equal to the difference of energies associated with the initial orbit and the final orbit. This energy comes out in the form of radiation consisting of quanta of definite amounts of energy. The outer electrons give rise to visible and almost infra-red and ultra-violet radiation, while the inner electrons give rise to radiation varying from very short ultra-violet rays to x-rays.

The nucleus itself consists of protons and neutrons. Sometimes the nucleus can also undergo changes as in the case of radioactivity which is the spontaneous disintegration of heavy elements like uranium, thorium, polonium, radium, etc., with the release of an alpha particle (the nucleus of the helium atom) or a beta particle (a fast moving electron) or gamma rays (electromagnetic waves of very short wave length). Radiation of shorter wave lengths, like the gamma rays, comes out from radioactive elements, as a result of changes of the energy state in the nucleus itself. The longer infra-red rays are not associated with the atomic configuration. They are associated with the coarser units of matter, namely the molecules, which consist of a number of atoms. The changes in their rotational and vibrational energies give rise to these radiations.

Spectrum

As early as 1752, Thomas Melvill, a Scottish divinity student, had discovered that when the light from an incandescent gas passes through a prism, it does not give a complete spectrum but only certain bright lines with definite wave lengths. These spectrum lines are characteristic of the gas which gives rise to them; in fact, they act as *finger prints* for the identification of the gas. In 1802, William Wollaston, a British physician, found certain dark lines in an otherwise continuous coloured band of spectrum. These dark lines were later rediscovered in 1814 by Joseph Fraunhofer, a self-educated Bavarian instrument maker, and are now known as Fraunhofer lines. Fraunhofer did not know what these lines represented. Their significance was pointed out in 1859 by Gustav Kirchhoff, a German physicist, and Robert Bunsen, the inventor of the Bunsen burner, who worked together in close collaboration. Their findings are represented in the following three laws of spectrum analysis:

1 Any incandescent solid, liquid or gas *under high pressure* gives rise to a continuous spectrum ranging from red to violet;

2 Any incandescent gas *under low pressure* gives rise to a spectrum consisting of isolated bright lines of very definite wave lengths;

3 When light producing a continuous spectrum passes through a gas under low pressure, the spectrum consists of a continuous band of colour crossed by dark lines. These lines occur at exactly the same positions that the bright lines would occupy if the intervening low pressure gas were the only source of radiation.

We note the following important points:

1 We can employ these dark Fraunhofer lines also to identify the gas.

2 In the light of the atomic structure, which we have described above, we can easily understand these laws. For example, when an electron in an atom shifts from an energy level E_1 to a higher energy level E_2, the energy quantum of magnitude $E_2—E_1$ is absorbed; this results in subtracting from the incoming radiation, the radiation of frequency $\nu = \frac{E_2—E_1}{h}$ according to the quantum theory, where h is the celebrated Planck's constant (6.625×10^{-27} erg second). This results in the production of the Fraunhofer line of corresponding wave length. Conversely, if the electron falls from the level E_2 to E_1, it gives out radiation of the same wave length, which produces the bright line at the same position as the dark absorption line in the spectrum.

The invention of the spectroscope and the discovery of these three laws of spectrum analysis made a tremendous impact on the study of astronomy. Astronomers, with the help of these, could interpret the spectrum of the radiations emanating from the stars and of those reflected from the planets and could thus obtain some idea about the chemical composition of these heavenly bodies. Spectroscopy not only helped in identifying the elements present in these heavenly bodies but also led to the discovery of the new elements like neptunium, plutonium (in the manufacture of atomic bombs), californium, etc.

Wien's Law

In figure 2.7 we plot the intensity of radiation from sources at various temperatures. These curves differ mainly in the position of the maxima of intensity. The lower the temperature, the larger is the wave length at which the maximum of intensity occurs. These results are embodied in the theoretical

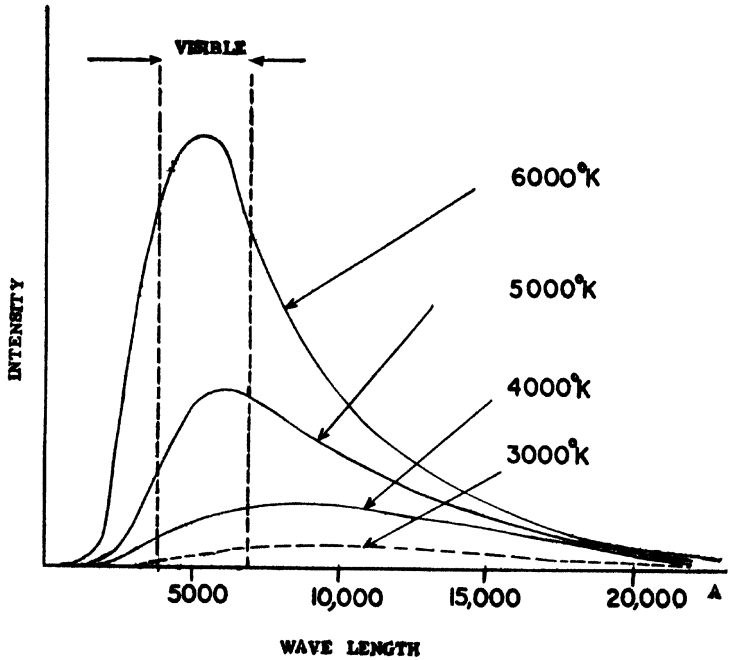

FIG. 2.7 *Variation in the intensity of radiation with wave length, at various temperatures*

law called Wien's law: The effective temperature of the source in degrees Kelvin $=\left(\frac{b}{\lambda_{max}}\right)$, $b=28.9\times10^6$ and the wave length λ_{max} of maximum intensity is expressed in Angstrom units. (K denotes the absolute scale of temperautre on which the melting point of ice is 273°K.) We have already mentioned that the wave length λ characterizes the colour of the radiation so that each temperature will show the predominance of a definite colour. This colour of the radiation, therefore, enables us to determine the effective temperature of the source of radiation. Wien's law predicts the effective temperature of the sun to be about 6000°K.

Stefan's Law

In Wien's law we have considered the quality of light. We shall now discuss the quantity of radiation. To be able to do so, we first define a black body. A perfectly black body absorbs radiations of all wave lengths which fall on it, and hence, according to Kirchhoff's laws, it will emit all wave lengths when rendered incandescent by heating to an appropriate temperature. Thus, a perfectly black body is a perfect absorber and also a perfect radiator. No known substance behaves as a black body; even carbon, which is one of the blackest substances known, shows some departure from this theoretical perfection. This necessitates a correction in the estimates made on the basis of the black body assumption. However, this assumption introduces considerable simplification in all discussions and we shall adopt it.

The total energy radiated by a black body depends entirely on its absolute temperature. This fact is embodied in Stefan's law. The amount of radiant energy E in ergs emitted by each square centimetre of its surface is directly proportional to the fourth power of its absolute temperature T, i.e., $E = \sigma T^4$ where $\sigma = 5.669 \times 10^{-5}$ erg cm^{-2} deg^{-4} sec^{-1} is a constant. From this it follows that a black body at 1000°K radiates 6×10^7 ergs per square centimetre per second or 6 watts per square centimetre. Now, if we double the temperature, the emission increases by a factor 2^4 i.e., sixteenfold, etc. The sun emits roughly 7500 watts per square centimetre; if the sun were perfectly black (of course, while cool) its temperature would be roughly 5800°K. The agreement between this value and that obtained on the basis of Wien's law is quite satisfactory.

Doppler Effect

It is a matter of common experience that, if a railway engine travelling at high speed approaches an observer with its whistle blowing, the pitch of the note appears to rise, and just as the engine passes the observer the pitch of the intensity. The lower the temperature, the larger is the wave length at which the maximum of intensity occurs. These results are embodied in the theoretical

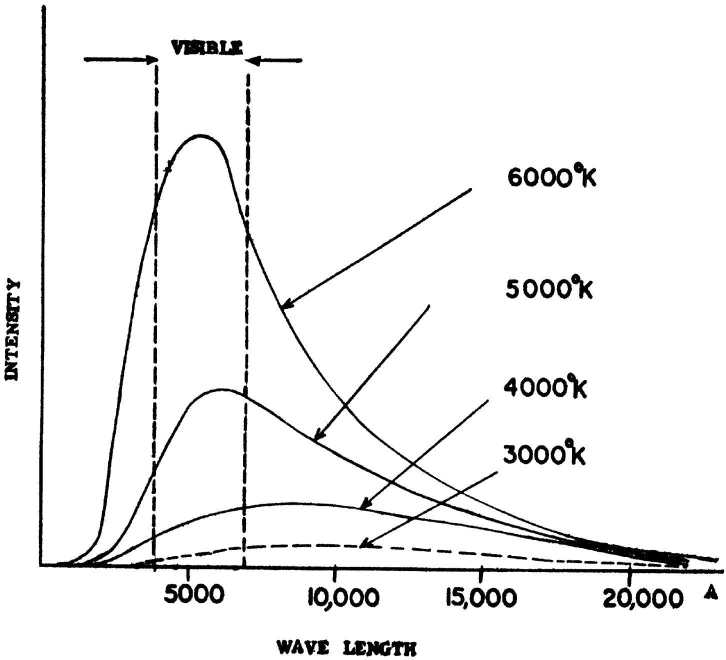

FIG. 2.7 *Variation in the intensity of radiation with wave length, at various temperatures*

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We know that an oscillating charge can produce an electromagnetic wave. Consequently, a vibrating electron sends out radiation in all directions, though the vibrations are most intense in the direction perpendicular to the electron's motion. Let an electron O (Figure 2.8) appear to vibrate along AB from the position P. Then the wave is propagating in the direction of OP, and the electric field at P will fluctuate parallel to AB and the magnetic field along the direction perpendicular to both AB and OP. The radiation as received at P is linearly polarized and the plane of AB and OP is the plane of polarization. Similarly, the radiation at a point will be circularly or elliptically polarized if the electron appears to describe a circle or an ellipse from that point.

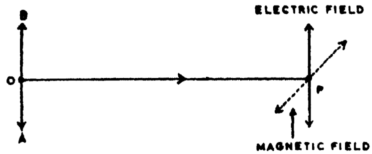


FIG. 2.8 *Plane polarized wave. The dotted arrow shows magnetic field.*

The study of the state of polarization of radiation from a source is extremely important as it gives us information about the dynamical state of the source electrons with respect to the position of the observer.

Zeeman Effect

In the presence of a strong magnetic field, electrons can execute a linear motion along the magnetic field and a circular motion in a plane perpendicular to the magnetic field. They cannot vibrate randomly. This restriction on the motion of an electron due to the presence of the magnetic field has a profound effect on the radiation produced by it. A spectral line produced in the presence of a magnetic field splits up, in the simplest case, into three components. The central component comes from the electrons vibrating parallel to the field, while the two outer components arise from electrons gyrating about the field, clockwise and anti-clockwise respectively. This splitting of a spectral line into its components due to the presence of the magnetic field is called the Zeeman effect, after the Dutch physicist who discovered this phenomenon in 1896.

The polarization and the pattern of the spectral lines depend on the direction from which one views the radiating atoms. If we look in the direction of the magnetic field, the electrons will appear to be performing circular motion in the clockwise and anti-clockwise directions and hence we shall see only the outer components of the spectral line and they will appear to be circularly polarized, but the central component will be missing because the electron is vibrating in the direction of the line of sight. If, on the other hand, we observe the emitting electrons from a direction perpendicular to the imposed magnetic field, all the three components will appear to be plane polarized, the central one parallel to the field and the two outer components perpendicular to the field (Figure 2.9).

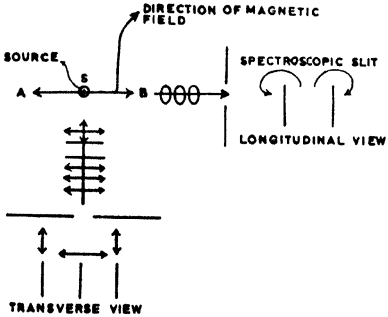


FIG. 2.9 *The Zeeman effect*

Some spectral lines do undergo this simple splitting into a triplet. However, the majority of spectral lines undergo a more complex type of splitting as each of these three main components further splits into symmetrically spaced sub-components.

The simultaneous splitting and polarization of a spectral line can only take place in the presence of a magnetic field. Thus if the spectral lines produced by a certain astronomical source exhibit both of these effects, the conclusion that the source is embedded in a magnetic field will be inescapable. Moreover, if ν is the frequency of the central component and $\nu \pm \nu_1$ be the frequencies of the two outer components, then

$$\nu_1 = \frac{e\,H}{4\,\pi\,m\,c},$$

where m,—e are the mass and charge of an electron, c the speed of light in vacuum and H the strength of the magnetic field. From the measurements of the wave lengths of the central and outer components, we calculate their frequencies. This gives us the difference ν_1 between the frequency of the central component and that of an outer component. Then, from the above formula, we can calculate the strength of the magnetic field H in which the source is embedded. We thus see how important the Zeeman effect is in the context of astronomy.

CHAPTER III

The Optical Telescope

THE telescope is the most important tool in astronomy. Without it astronomy would not have progressed much beyond what we could observe with the naked eye. It was the telescope that revealed the surface features of the sun, the planets and the moon, and the existence of the satellites of the major planets and the rings of Saturn; that gave us our idea of the structure of our galaxy; and that proved beyond doubt that space contains millions of systems like the Milky Way each one of which consists of billions of stars. It was the telescope together with the spectroscope that brought us whatever knowledge we possess today about the chemical composition of the stars and of the interstellar matter, i.e., the matter that exists between the stars. The telescope had a very significant impact in the other branches of knowledge also. For example, it was the telescope that provided the critical test to Newton's laws of motion through the observational study of the orbital motion of the planets and satellites. Later, in the beginning of the present century, it provided the critical test for Einstein's theory of relativity by detecting the deflection of light rays from a distant star by the gravitation of the sun and by measuring the advancement of the perihelion of the planet Mercury.

There are two types of telescopes in use: (*i*) optical telescopes and (*ii*) radio telescopes. In the present chapter we shall discuss the optical telescope and some other optical devices which form the inevitable tools of an astronomer.

Broadly speaking optical telescopes are of two types: (*a*) refractors, i.e., lens type, and (*b*) reflectors, i.e., mirror type.

Refracting Telescopes

In the barest outline, a refractor consists of two lenses (Figure 3.1), called the objective and the eye-piece, rigidly mounted at the two ends of an empty tube in proper alignment.

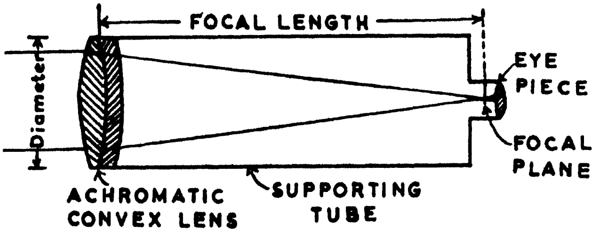


FIG. 3.1 *Refracting telescope*

The objective is a convex lens and its function is to form behind it an image of the object which we wish to study. The image of a very distant object formed by an ideal lens lies in a plane called the focal plane of the lens. The eye-piece is also a convex lens and its function is to magnify the image of the object for visual observations. However, if a permanent record is intended, as is always the case in observational astronomy, we can insert a photographic plate at the focal plane of the objective and photograph the image. In this respect, a refracting telescope is nothing more than an ordinary camera on a bigger scale.

Power of a Telescope. The capability of a refractor depends on its diameter and its focal length, i.e., the distance of the focal plane from its geometrical centre. The bigger the cross-sectional area of the objective, the more light rays from the object get focussed by it and the brighter is the image. Since the cross-section of the objective is proportional to the square of the diameter D, the light gathering power of the objective, and hence of the telescope, is proportional to the square of the diameter of the objective, i.e., proportional to D^2. Thus the relative light gathering powers of the telescopes of diameters 1 inch, 5 inch and 20 inch will be in the proportion $1^2:5^2:20^2$, i.e., 1:25:400.

The stars are very far from us and produce sensible point images. Thus as far as stars are concerned, the aim of an observer in using a telescope is to reach fainter and fainter stars. In contrast, the images of near objects like the sun, the moon, the planets and of the distant objects like nebulæ spread over definite areas. Consequently the brightness of the image will depend on the area over which the image is formed, in addition to the total amount of light which forms the image. The linear magnification of the lens is proportional to the focal length of the objective. To be more specific, an object which subtends an angle of one degree at the objective produces an image $\frac{f}{57.3}$ inches or centimetres in length according as f is measured in inches or centimetres. Thus the area of the image is proportional to the square of the focal length, i.e., proportional to f^2. Hence the aereal brightness of the image is proportional to $\frac{D^2}{f^2}$, and $\frac{D}{f}$ is called the index of the speed of the telescope for photographic purposes. Thus, the larger $\frac{D}{f}$ is, the smaller is the exposure time.

Resolving Power. We shall explain the meaning of the resolving power of a telescope by means of an example. Let us look at a page of a book. We can read it comfortably at a distance of about 20 inches. Let us now move further and further away from it. The letters subtend smaller and smaller angles at the eye and finally the angular separation of the upper and lower parts of a letter is so small that the eye ceases to recognize it. We then say that the angle subtended by the letter is less than the resolving power of the eye. We use the telescope to enable us to observe clearly the landscape of the heavenly bodies which cannot be seen by the unaided eye. Thus we can define the resolving power of a telescope as the smallest angular separation which can be appreciated by it. Thus, if θ (radians) is the smallest angle subtended at the objective by two point objects which can just be distinguished as separate, then $\frac{1}{\theta}$ is called the resolving power of the telescope. We can show theoretically that the resolving power of a telescope is $D/1.22\lambda$, where λ is the wave length of the light used and D is the diameter of the objective measured in the same unit in which λ is measured.

The theoretical limit of the resolution of a telescope is given by

$$L = \frac{4.56}{D} \text{ seconds of arc,}$$

where the diameter D of the objective is measured in inches. Thus a 10-inch telescope would just separate the two stars comprising a visual binary O″.456

apart, while the 200-inch telescope at Mt. Palomar would separate the components O″.0228 apart.

Main Defects of a Refractor. The most serious defects in a refractor are the following:

1 weakening of the intensity of light as it passes through the lens due to absorption.

2 the chromatic aberration. The blue light is refracted more than the red light during its passage through the lens so that the blue rays are more strongly convergent and the image formed in blue light falls short of the image formed in red light. This results in a fringe of rainbow colours round the image of each object. This defect is called the chromatic aberration and can be removed by using compound lenses.

3 it is not possible to make very large lenses of great homogeneity and the defects in the composition reflect in the deformation of the image.

4 the objective is at the far end of the tube so that the larger the lens the greater is the difficulty in balancing the telescope. These considerations limit the size of a refractor. However, a well-designed refractor gives an image of fine quality over most of the field.

Solar Telescope

As an example of a refractor, we describe a solar telescope employed, as the name implies, in the study of the sun. The sun gives plenty of light and if we can get a big image of it we can study any part of this image in detail. We have already mentioned that the larger the focal length of the objective, the bigger the image of the object. Consequently, in a solar telescope, an objective of large focal length is chosen. The biggest solar telescope is at Mt. Wilson Observatory (Figure 3.2), the objective of which is mounted at the top of a 170-foot high tower. The upper end of the solar telescope consists of two mirrors which reflect the sun's light to the objective. The mirror which turns to follow the sun as the earth rotates is called the coelostat. The objective focuses the

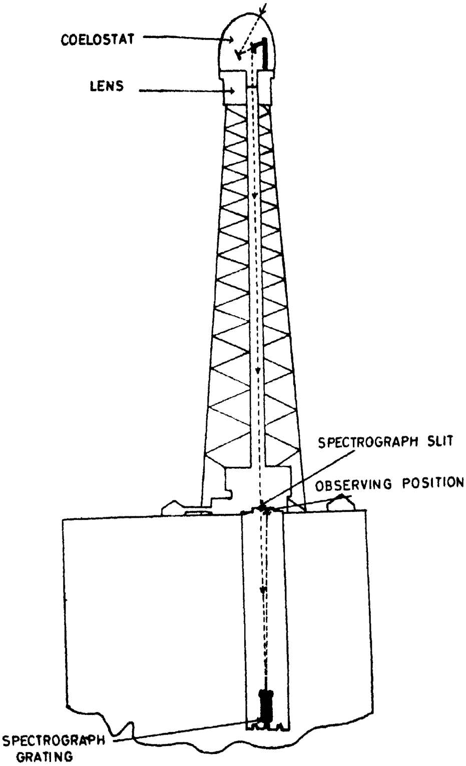


FIG. 3.2 *Solar tower*

light in a room at the ground level where the image is studied. If we wish to use the spectrograph, the light from the sun is allowed to go down to a grating mounted at the bottom of a pit, 75 feet below the ground level. The grating sends the component colours back to the spectrograph mounted at the observing position at ground level.

Reflecting Telescopes

Figure 3.3 represents the basic parts of a reflector. The main part of a reflector is a concave mirror, called the objective, mounted at the bottom of

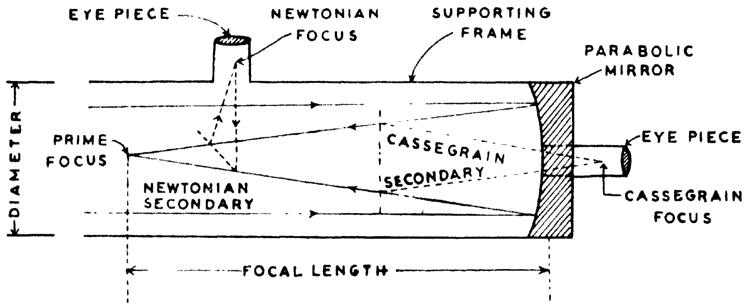


FIG. 3.3 *Reflecting telescope*

the telescope's tube. This concave mirror reflects back the light in the direction from which it came and forms an image in its focal plane, called the prime focus. A photographic plate placed here would record the image formed by the mirror. The observer in this position will see the objects situated behind him ! Evidently, unless the telescope is very big, visual observations are not possible in this position as the presence of the observer inside the tube will partially obstruct the light from the object from reaching the objective. To avoid this difficulty, an opaque plane mirror, called the secondary, is mounted at some convenient distance from the objective which simply turns the course of the reflected rays through 90° without affecting the image in any other way. By this device the image of the object is formed outside the tube of the telescope and it may be studied, without obscuring the view of the objective, with the help of an eye-piece or a photographic plate or a spectrograph. Such a mirror system constitutes a Newtonian reflector. In this arrangement, the observer will see in front of him, on the right, the objects which lie towards his left ! In a Cassegrain reflector the secondary reflects back the rays coming from the objective after reflection through a hole in the centre of the objective. In this arrangement the image is formed behind the primary and the observer looks in the direction of the object if he wishes to see it, as in the case of a refractor.

Power of a Reflector. As in the case of a refractor, the light gathering power of a reflector is proportional to the square of the diameter D of the objective and the aereal magnification proportional to the square of the focal length f. Thus the index of the speed of the telescope is once again D/f.

Advantages of a reflector:

1 mirrors do not show achromatic aberration.
2 the reflection weakens the intensity of light much less than the passage through a thick lens does.
3 moreover, mirrors are easier to make in much larger sizes than the lenses.
4 the mounting of a reflector is also easier than that of a refractor.

Thus a reflector possesses very important advantages over a refractor. This explains the existence of such big reflectors as the 100-inch Hooker telescope at Mt. Wilson and the 200-inch Hale telescope at Mt. Palomar.

Schmidt Telescopes

The reflecting telescopes suffer from one handicap, namely, the bigger the telescope, the smaller is its field of view. For example, the 200-inch Hale telescope is not able to photograph more than a small part of the moon's surface. Thus, the farther a telescope can 'see', the smaller is the piece of celestial sphere it can photograph. Schmidt, a German astronomer and optician, provided a simple device which, attached to a reflector, allows it to 'see far' as well as to 'see wide'.

Figure 3.4 represents the basic parts of a Schmidt telescope. The rays from the object pass through a thin lens, called the correcting plate, before reaching the objective which is a concave mirror of circular cross-section (spherical mirror). Thus a Schmidt telescope is a hybrid between a reflector and a refractor. The correcting plate bends the rays so that the area of space that appears in sharp focus on the photographic plate is much enlarged. For example, the 48-inch Schmidt telescope at Mt. Palomar can easily photograph an area equal to that of 200 moons at one time. The following statement provides a useful

Reflecting Telescopes

Figure 3.3 represents the basic parts of a reflector. The main part of a reflector is a concave mirror, called the objective, mounted at the bottom of

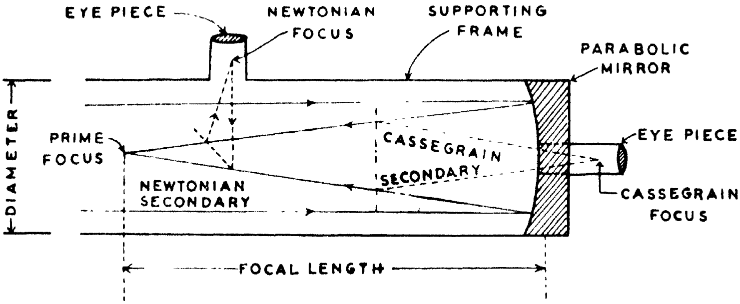


FIG. 3.3 *Reflecting telescope*

the telescope's tube. This concave mirror reflects back the light in the direction from which it came and forms an image in its focal plane, called the prime focus. A photographic plate placed here would record the image formed by the mirror. The observer in this position will see the objects situated behind him ! Evidently, unless the telescope is very big, visual observations are not possible in this position as the presence of the observer inside the tube will partially obstruct the light from the object from reaching the objective. To avoid this difficulty, an opaque plane mirror, called the secondary, is mounted at some convenient distance from the objective which simply turns the course of the reflected rays through 90° without affecting the image in any other way. By this device the image of the object is formed outside the tube of the telescope and it may be studied, without obscuring the view of the objective, with the help of an eye-piece or a photographic plate or a spectrograph. Such a mirror system constitutes a Newtonian reflector. In this arrangement, the observer will see in front of him, on the right, the objects which lie towards his left ! In a Cassegrain reflector the secondary reflects back the rays coming from the objective after reflection through a hole in the centre of the objective. In on its axis. Thus, by properly rotating the telescope about the polar axis, it may be given any desired hour angle. The angle through which the declination axis turns is measured on a graduated circular arc fixed perpendicular to the polar axis near the bottom. Similarly, by rotating the telescope about the declination axis, it can be made to trace an arc of a circle, i.e., along the hour circle. So, by properly rotating the telescope about the declination axis, it may be made to point at a star of a given declination. The angle through which the telescope rotates about the declination axis is measured on a graduated circular arc fixed rigidly at right angles to the declination axis. Thus, given the hour angle and the declination of the object, the telescope can be set on it by these two motions. Hence this mounting is called equatorial mounting.

However, if the telescope remained stationary after setting, the earth's west-to-east rotation would very soon sweep it past the object on which it is set. Therefore, if the telescope has to follow the object, it must rotate about the polar axis from east to west at a speed which compensates for the speed of earth's rotation. For this purpose, every large telescope is provided with an electric clockwork drive which may be engaged to rotate the polar axis east to west with the desired speed.

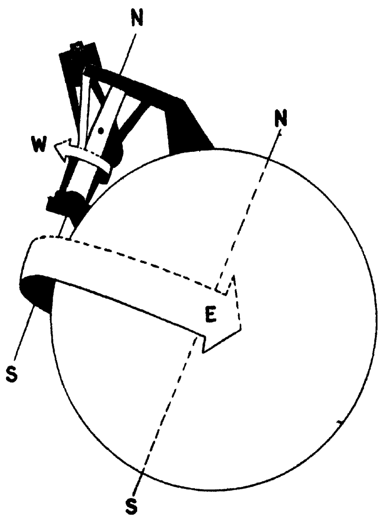


FIG. 3.5 *Equatorial mounting of a telescope*

Alt-azimuth Mounting: Transit Circle. When we wish to make the observations on a heavenly body only when it is on our meridian, the telescope is given an alt-azimuth mounting. In this mounting, the telescopic tube can rotate about a fixed horizontal axis with ends directed towards the east and the west. The telescope then traces the meridian circle of the observer. In the vertical position it points towards the zenith of the observer and can be made to point at any altitude. We can read the altitude of the star on a graduated circle attached firmly at right angles to the axis of rotation. The telescope having alt-azimuth mounting is called the transit circle.

CHAPTER IV

The Radio Telescope

WE have mentioned earlier that radio waves, like light waves, are electromagnetic in character. These waves therefore consist of mutually perpendicular electric and magnetic field vibrations in the direction transverse to the direction of wave propagation (Figure 4.1). However, radio waves differ from

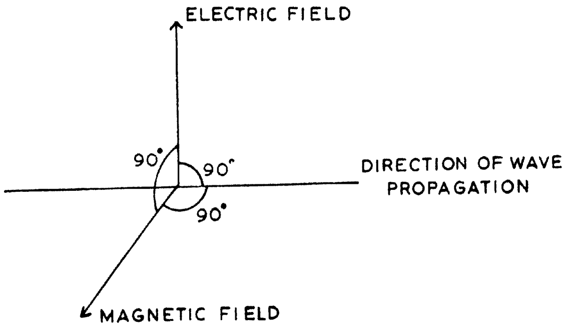


FIG. 4.1 *Electromagnetic fields associated with a radio wave*

light waves in frequency and wave length. This difference calls for techniques different from those used for light waves for detecting them and for measuring their characteristics. The instrument which is used for studying radio waves arriving from the heavenly bodies is called the radio telescope. There is a large variety of radio telescopes in use at present, but all of them essentially consist of the following three parts: (*i*) an antenna or aerial, (*ii*) a radio receiver, and (*iii*) a recorder. Thus a radio telescope in bare outline is nothing but a domestic radio receiver on an elaborate scale, in which the loud speaker is replaced by an automatic recorder.

Receiver and Recorder

We shall first briefly discuss some important points about the receivers used in radio telescopes. These receivers perform functions similar to those of the domestic radio receivers. However, these sets have to be extraordinarily sensitive to deal efficiently with cosmic radio signals which are generally very weak. The construction of these receivers follows closely the conventional radar design and employs a superheterodyne system in which the greater part (or all) of the amplification takes place at a lower frequency than the frequency of the incident signal.

The antenna receives the signal in the form of a noise, spread over a broad band of frequencies. The antenna does a certain amount of selection of the frequencies. The antenna is linked to an amplifier, usually by means of wave-guides for radiation with a wave length smaller than 20 cm and by coaxial cable for radiation with a longer wave length. The selection of the frequency is done by the amplifier which selectively amplifies frequencies in a narrow frequency band, say $\triangle \nu$, around a specific frequency, say ν, about a millionfold in typical cases. This signal is then rectified to produce a unidirectional current. The rectifier is a complex device and its output is not, in general, related in a linear manner with the input. Consequently, we have to rely on the calibration to establish the significance of a given output reading.

The resultant current even at this stage shows fluctuations and retains fixed phase and amplitude only over time intervals of the order of $\frac{1}{\triangle \nu}$. A recorder always records the average power received over a certain time interval which is called its time constant. Let τ (tau) be the over-all time constant of the recorder. If $\tau = \frac{1}{\triangle \nu}$, the recorded output will show the fluctuations of the current conspicuously. We can smoothen out these fluctuations by either increasing the frequency band width $\triangle \nu$ or the time constant τ of the recorder. Which device one should use out of these two depends on the nature of the problem under study. For example if we wish to study the variation of the intensity of the signal with frequency ν, evidently we should keep $\triangle \nu$ as small as we can. In this case then the smoothing of the current fluctuations can only be brought about by increasing τ. Figure 4.2 depicts the evolution of the radio signal in the receiver.

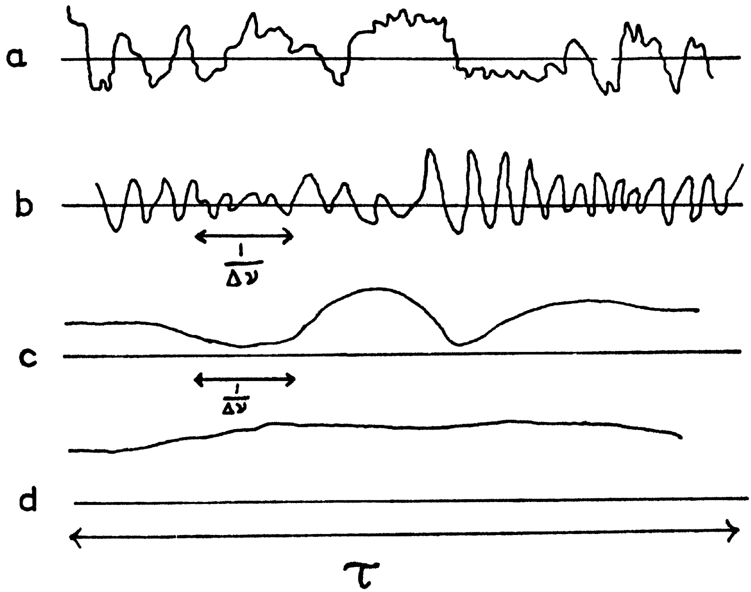


FIG. 4.2 *Evolution of a radio signal in a receiver*
a. *Original noise*
b. *After selective amplification*
c. *After quadratic detection*
d. *After smoothing by the recorder with time constant*

We shall later deal in greater detail with the internal noise produced by the receiver and the external noise captured by the antenna, arriving on it from the radio sources other than the one under study. These disturbances complicate our study as the recorder records the resultant effect of all these radiations and the desired signal is recognizable only through the increase in the mean level of output contributed by these internal and external noises. These disturbances severely limit the sensitivity of the radiotelescopic receivers.

The receiver output is ordinarily connected with a pen recorder which records the signal power in the form of deflections superimposed on the curve depicting the internal noise of the receiver. Sometimes cathode ray spot photography is used for recording the receiver output.

Antenna

The function of an antenna, like that of the aerial of a radio receiving set, is to capture the radiation that falls on it. The radiation from the heavenly bodies is so weak that we require very large and sensitive antennae for radio telescopes. Apart from the weak intensity of this radiation there are other important factors which put a heavy demand on the sensitivity of the antennae. We shall deal with these factors briefly in the following:

Noise Generated in the Receiving Set. The thermal motion of the electrons in the resistors and tubes results in rapid fluctuations of the electric current in the circuit elements. This rapidly fluctuating current gives rise to electromagnetic waves. Thus every receiving set generates its own radiation which is called the 'noise', i.e., the radiation over a large range of frequencies with rapidly fluctuating intensity. Therefore, if the intensity of the radio signal is less than this noise level of the apparatus, we shall not be able to detect the signal. Consequently, the antenna should capture as much radiation as possible. Just as in an optical telescope we can increase the quantity of light gathered by a telescope by increasing the size of its objective, we can increase the radiation-capture power of an antenna by increasing its effective size.

Galactic Noise. There are a large number of sources in the universe which are randomly distributed on the celestial sphere and give out radio signals of varying intensities and at all frequencies. The antenna catches these signals also. Thus along with the signal from the object under study, the telescope also records this background noise, called the *galactic noise.* Here is an impasse. If we increase the dimensions of the antenna to increase the intensity of the radiation from the object we also increase the intensity of the galactic noise ! This fact, along with other practical considerations, sets an upper limit to the size of the antenna.

Scintillation. The radiation from a radio source passes through the layers of charged particles in the earth's upper atmosphere, called the ionosphere. In doing so, it undergoes irregular refraction at the dense clouds of these charged particles moving randomly with high speeds. This gives rise to the phenomenon of scintillation which is analogous to the twinkling of stars. The charged particles in the ionosphere are produced by the ionization of the gases by the ultra-violet radiation from the sun. Consequently during the night, in the absence of ionizing source, the ions and electrons recombine to form neutral atoms, thereby decreasing the particle density of charges and increasing the transparency of the earth's atmosphere. This also reduces the scintillation considerably so that radio observations during night are preferable if the object under study is accessible to the telescope.

Resolving Power

As in the case of the optical telescope, the antenna of a radio telescope receives radiation over an angle $\frac{\lambda}{D}$ where D is the effective width of the antenna and λ is the wave length of the radiation from a point source. Consequently, two point radio sources whose angular separation is less than $\frac{\lambda}{D}$ would appear as one and it would be impossible to separate their contributions to the radiation recorded by the telescope. Here, again, we can decrease the minimum angle of resolution for a given wave length by increasing the size of the antenna. It is easy to verify that to ensure the same minimum angle of resolution for a radio telescope operating on a 100 cm wave length as for an optical telescope (wave length $\sim 10^{-5}$ cm), the linear dimension of the antenna should be ten million times bigger than the diameter of the objective. Remembering that the minimum angle of resolution for the 200-inch Palomar telescope is 10^{-5} degree, we find that the antenna of a radio telescope operating on 21 cm wave length should be about 5000 miles to ensure the same minimum angle of resolution. Such fantastic lengths of antennae are impossible to achieve and hence we have to be contented with a considerably smaller resolving power for a radio telescope. For example, for the 250-foot parabolic radio telescope at Jodrell Bank Radio

Observatory, Manchester (England) operating on the 21-centimetre wave length, the minimum angle of resolution is greater than $\frac{1}{10}$ of a degree.

Some Important Parameters of an Antenna

To explain the working of a radio telescope, we must know some important parameters associated with the antenna.

Directional Pattern. The radio wave is always associated with an electric and a magnetic field. Thus, if E gives the average magnitude of the electric field and c is the speed of light in vacuum, then $S = \frac{cE^2}{4\pi}$ units of energy are brought by the wave at this point, per unit area of the wave front, over the entire range of frequencies. The energy varies with frequency as in the case of light waves. Thus we may regard the power per unit area of the wave front and per unit frequency band width as a measure of the strength of a signal. When the antenna is at right angles to the direction of the signal, the power received by it is the maximum. Let us now rotate the antenna about an axis perpendicular to the direction of the signal and record the power received by it in various positions. If we plot power against the angle that the antenna makes with the direction of the signal, we get a plot of the type as shown in Figure 4.3. This plot is called the directional 'diagram of the antenna' or the 'antenna pattern'. It is clear that to specify the directional effect on

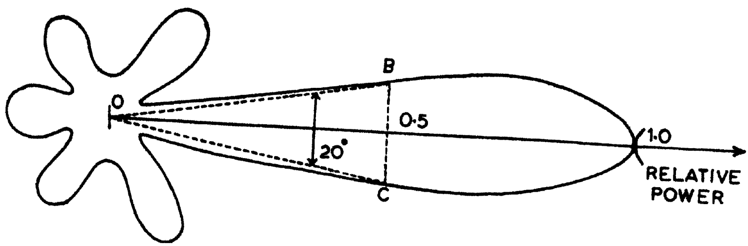


FIG. 4.3 *Directional diagram of an Antenna*

the antenna in three dimensions, we must draw another directional diagram of the antenna by rotating it about another axis perpendicular to the former axis of rotation and to the direction of the source.

The directional diagram usually consists of a main lobe and several secondary lobes symmetrically distributed about the main lobe. By properly designing the antenna, the secondary lobes can be made very small though they cannot be obliterated completely. The larger the size of the main lobe in comparison with the secondary lobes, the greater is the directional sensitivity of the antenna.

Beam Width. Let us draw a circle with centre at the centre O of the antenna and with radius equal to half the maximum extension of the main lobe, cutting it in the points B and C. The angle BOC is then called the beam width or more properly the half-power beam width (Figure 4.3). The beam width (in radians) in a given plane is of the order of $\frac{\lambda}{L}$ where L is the effective linear dimension of the antenna in that plane. The smaller the beam width, the greater is the directional sensitivity of the antenna.

Effective Area of an Antenna. The effective area of an antenna is the measure of the wave-front area from which it can extract energy. The effective area of an antenna is a function of the angle which it makes with the direction of the source, being maximum when it is at right angles to the direction of the incident radiation.

Gain. To explain the concept of gain we shall treat the antenna as a transmitting antenna rather than a receiving antenna and use the 'principle of reciprocity' according to which 'if an electromotive force E applied at a point P in an antenna A produces a current I at a point Q of antenna B, then the electromotive force E applied at Q will cause the same current I (both in magnitude and phase) to flow at the point P of antenna A'. It is interesting to note that this principle is an analogue of Helmholtz's reciprocity principle in sound which runs as follows: 'Let us consider a space filled with air which is partly bounded by fixed boundaries. If a sound wave excited at a point A makes the air at another point B to move with velocity V, then the sound wave excited at B will produce the same velocity V (both in magnitude and phase) at A.'

Let us supply a certain amount of power P to the antenna, and let S be the flux density produced at a given distance d in a given direction l. Also let Ś¹ be the flux at the same distance d when P is radiated equally in all directions. The ratio S/Ś¹ then measures the gain in the direction l at the distance d.

Band Width. The gain of an antenna varies with frequency and is usually the greatest at the resonance frequency. If we plot the gain against frequency we get the familiar resonance curve (Figure 4.4).

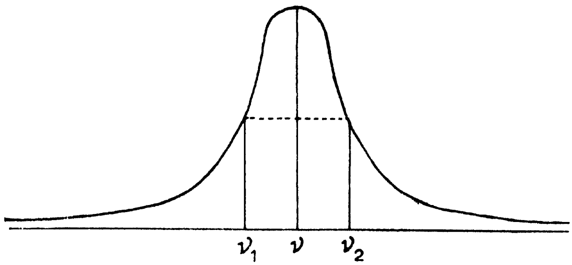


FIG. 4.4 *The Gain-Luminosity diagram*

If ν_1 and $\nu_2 > \nu_1$ be the frequencies at which half of the maximum gain is attained, then $\nu_2 - \nu_1$ is called the band width. The smaller the band width, the greater is the selectivity of the antenna in respect of the frequency.

Common Types of Antenna

A large variety of antennae is in use in radio astronomy. Among them the following three are commonly used: (i) dipole, (ii) horn, and (iii) parabolic.

Dipole. The most widely used is the dipole antenna. It consists of two conductors placed along a horizontal line with a small separation in between them (Figure 4.5).

The length of the dipole is so small that the phase variation along the conductors may be neglected. Moreover, the end capacity of the dipole is so large that it may be regarded as two oscillating point charges.

If the length a of the dipole is equal to the wave legnth λ or equal to half-wave length $\frac{\lambda}{2}$ of the incident radiation, it is resonant, i.e., it begins to oscillate with the frequency ν of the incoming radio wave [frequency of the wave remains the same in all materials; it is only the wave length that changes. They are connected by the following relation $\lambda\nu$=velocity of wave in that material. For vacuum we have the following relation: (λ in metres) (ν in megacycles/sec)=300, where a megacycle (Mc)=10^6 cycles]. These oscillations are recorded by the telescope.

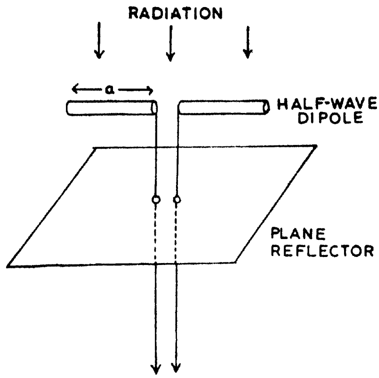


FIG. 4.5 *Dipole antenna*

For a dipole antenna the gain is maximum in directions perpendicular to its length and zero in the direction parallel to it. In general, if the direction of the incoming radiation makes an angle α with its length, then its effective length is a sin α. If the electric field associated with the incident wave lies in the plane of incidence, then the electromotive force induced in the dipole is E λ sin α and the power absorbed by it is proportional to $E^2 \lambda^2 \sin^2 \alpha$. It can be proved that for a dipole antenna, the effective cross-section is equal to $\frac{\lambda^2}{4\pi}$ and the maximum gain is 3/2. A linearly polarized dipole collects only half of the power arriving at it from a source.

In Figure 4.5, the dipole is mounted over a plane reflector. When the distance of the dipole from the reflector is equal to $\frac{\lambda}{4}$, the radiation reflected back by the plane to the dipole is in phase with the incident radiation, and they are added constructively. Thus the presence of the reflector increases the gain for the radiation coming from above and cuts the radiation coming from below by reflecting it back. The reflector may be a plane metallic sheet or may be made up of a wire mesh or of parallel metallic strips.

The gain may be further increased if instead of a plane reflector we use a corner reflector made up of two planes, with their line of intersection parallel to the dipole, or a parabolic reflector with the dipole at its focus.

We may increase the effective area of the antenna if we use several dipoles arranged in an appropriate manner. For example, in a linear array a number of dipoles are arranged along a horizontal line above a reflecting plane. In a broadside array the dipoles are arranged in rows and columns above a plane reflector and are connected with the receiver with transmission lines of such lengths that the signals sent by individual dipoles to the receiver add up in phase. The main disadvantage of these antennae is the difficulty involved in changing the wave length band.

Horn. A horn antenna consists of a waveguide* with a horn fitted at its open end as shown in Figure 4.6. The horn is so designed that it transfers maximum energy from the wave front to the waveguide. The waveguide in turn leads the captured radiation to a resonant cavity in the receiver. The horn is often used with parabolic reflectors. In this arrangement the horn is placed at the focus of the reflector in such a position that it can collect most of the radiation reflected by the mirror. The horn antennae are most useful at frequencies of several megacycles per second.

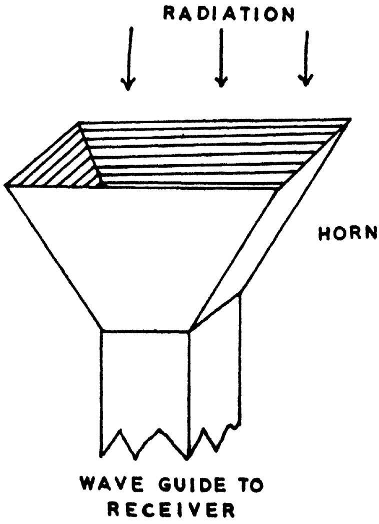


FIG. 4.6 *Horn antenna*

*The waveguide serves as a transmission line to guide high frequency signals of 1,000 mcs to 30,000 mcs from one point to another. Hollow metal pipes, usually rectangular or circular in cross-section, and cylinders of insulating materials are the most widely used forms

Paraboloidal Antenna. Paraboloidal antennae resemble the radar antennae but are several times bigger (Figure 4.7). These antennae are the most spectacular antennae used in radio astronomy. Their main advantage lies in the fact that they can be directed easily in any direction and can track an object on its diurnal path. They can be most effectively used in conjunction with a dipole or a horn placed at the focus, on the frequency range extending from 30 Mc/sec to 1000 Mc/sec, i.e., in the wave length range from 30 cm to 10 metres. The main disadvantage of paraboloids is that their effective areas are less than their actual areas by a factor of 0.3 to 0.7.

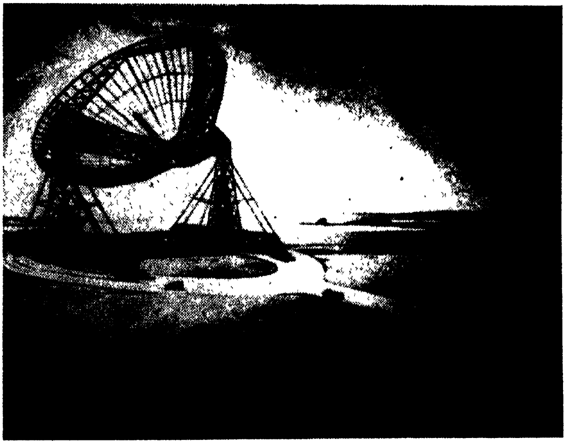


FIG. 4.7 *The 250-foot Paraboloidal Radio Telescope at Jodrell Bank, Manchester, England*

Yagi. The Yagi antenna consists of a half wave dipole with several directors ahead of it and a reflector behind it. The directors are simply metallic rods

of waveguides. The electromagnetic field is confined inside the hollow metal pipe so that there is no loss of energy due to radiation. There has evolved from the waveguide concept a wide range of useful circuit elements to be used at these very high frequencies or microwave frequencies as they are called. Some of the important examples are cavity resonators, filters and highly directive antennae.

mounted parallel to the dipole (Figure 4.8). The directors are also called the 'parasitic elements' as they are excited into forced oscillation. When radiation

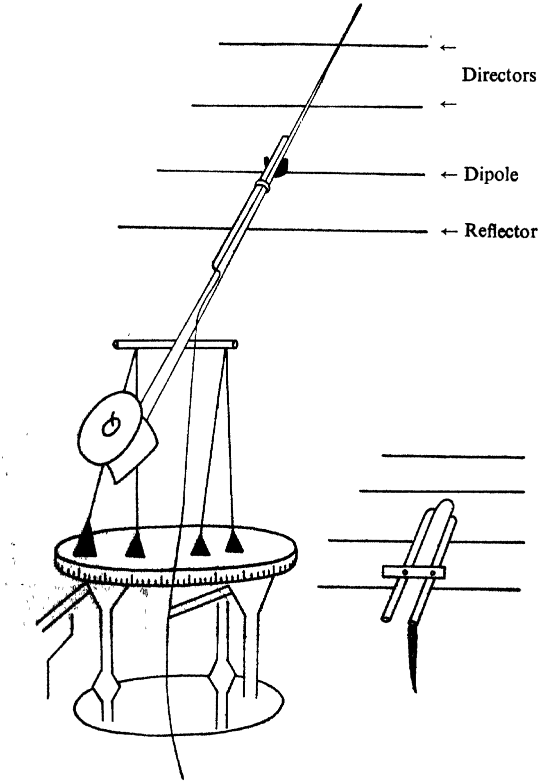


FIG. 4.8 *The Yagi*

passes a parasitic element, the induced current causes re-radiation of some of the power from the incident beam at the same frequency but in a different phase. The

Paraboloidal Antenna. Paraboloidal antennae resemble the radar antennae but are several times bigger (Figure 4.7). These antennae are the most spectacular antennae used in radio astronomy. Their main advantage lies in the fact that they can be directed easily in any direction and can track an object on its diurnal path. They can be most effectively used in conjunction with a dipole or a horn placed at the focus, on the frequency range extending from 30 Mc/sec to 1000 Mc/sec, i.e., in the wave length range from 30 cm to 10 metres. The main disadvantage of paraboloids is that their effective areas are less than their actual areas by a factor of 0.3 to 0.7.

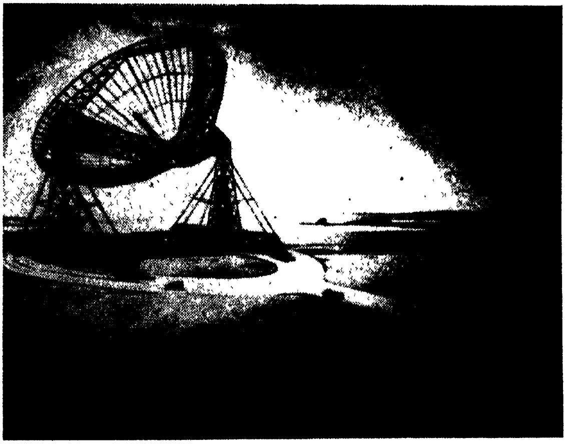


FIG. 4.7 *The 250-foot Paraboloidal Radio Telescope at Jodrell Bank, Manchester, England*

Yagi. The Yagi antenna consists of a half wave dipole with several directors ahead of it and a reflector behind it. The directors are simply metallic rods

of waveguides. The electromagnetic field is confined inside the hollow metal pipe so that there is no loss of energy due to radiation. There has evolved from the waveguide concept a wide range of useful circuit elements to be used at these very high frequencies or microwave frequencies as they are called. Some of the important examples are cavity resonators, filters and highly directive antennae.

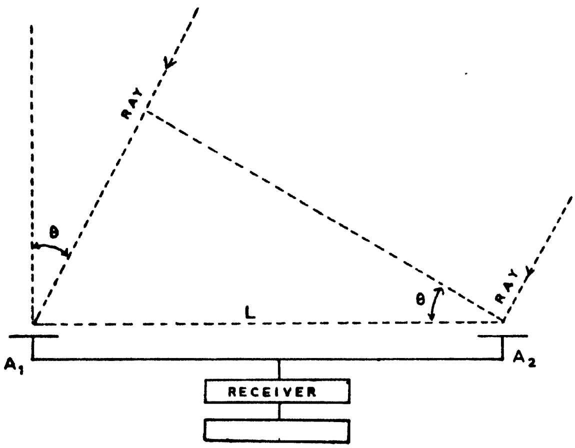


FIG. 4.9 *Schematic diagram of a Radio Interferometer*

Figure 4.9a shows the directional diagram of the interferometer when the radio source is overhead. Figure 4.9b also shows the directional diagram of the interferometer when the source is overhead, but now a half-wave length delay has been introduced in the feeder system of A_2. We find that the signals from A_1 and A_2 differ in phase by 180° so that they nullify each other with the result that the main lobe in the directional diagram is absent. Thus the radio interfero-

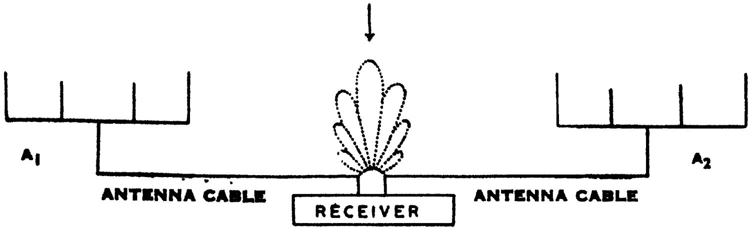


FIG. 4.9a

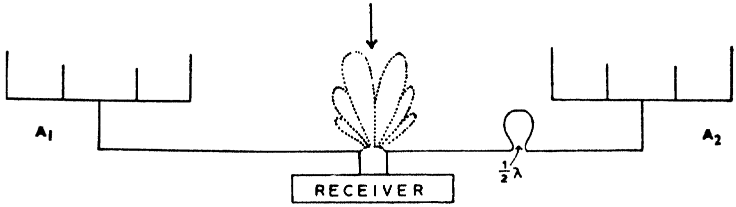


FIG. 4.9b

meter is the analogue of Michelson Interferometer and this explains the name of the instrument.

Let the incident radiation at any instant make an angle $\measuredangle$ with the meridian plane, i.e., the plane perpendicular to L. Each wave front has to travel a distance L sin $\measuredangle$ more, to reach A_1 than to reach A_2. Hence, if the transmission lines from A_1 and A_2 to the receiver have the same length, the signal from A_1 will lag behind the signal from A_2 in phase by ϵ (epsilon)$=\frac{360}{\lambda}$ L sin $\measuredangle$ degrees when they are added at the receiver.

Now, due to the rotation of the earth, the radio source rises at the eastern horizon and moves across the sky to set at the western horizon. Thus, due to the diurnal motion of the source, $\measuredangle$ changes from $-90°$ to $90°$ causing a continual change in the phase of the signals from A_1 and A_2. Whenever ϵ is an integral multiple of 360°, i.e., whenever L sin $\measuredangle$ is equal to an integral multiple of the wave length, i.e., when L sin $\measuredangle = n\lambda$, $n=0, 1, 2, \ldots\ldots$, the signals from A_1 and A_2 will be added up constructively and the input at the receiver will be the maximum. On the other hand, if L sin $\measuredangle$ is equal to a half-odd integral multiple of the wave length, i.e., if L sin $\measuredangle=(n+\frac{1}{2})\lambda$, the two signals will cancel each other. Thus, the input power graph against time will show alternately maxima and minima as in Figure 4.10.

We note the following important points: (i) The input power does not fall below a certain level which we have marked as the cosmic noise level. We shall presently see how we can get rid of the the cosmic noise and measure only the radiation from the source; (ii) The maximum amplitude of the fringe is proportional to the total power incident on the antennae, and consequently.

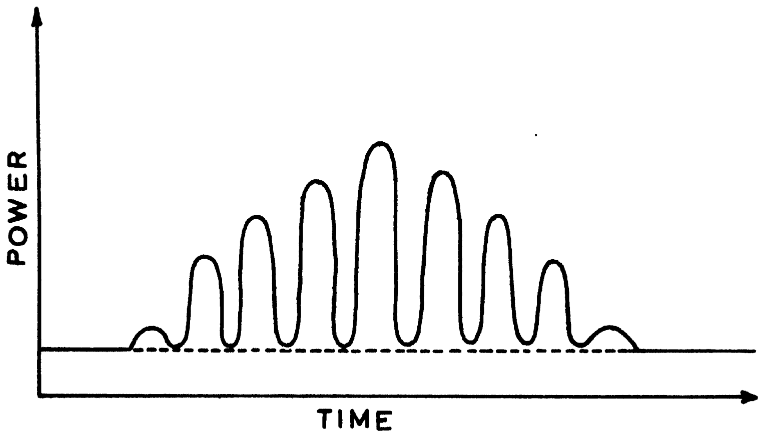


FIG. 4.10 *Interference pattern for a point source. The dotted line represents the background noise*

this simple type of interferometer is called the total power interferometer; (iii) the total gain of the interferometer is the geometric mean of the gains of the individual antennae A_1 and A_2; (iv) The interferometer converts a relatively broad antenna beam into a large number of narrow fan-shaped beams. This fact increases the resolution considerably.

We have seen in Figure 4.10 the type of record the interferometer gives for the power from a point source. If the angular width of the source is small compared with the width of one interferometer lobe, the recorded interference pattern is similar to that of a point source. For the sake of comparison we give the schematic interference pattern for a source, whose angular width is much broader than one lobe, in Figure 4.11, and for a source, whose width is comparable with a lobe, in Figure 4.12.

In the first case the interference patterns will hardly appear and there will be a single broad maximum. We can explain such a pattern as follows. We may regard a source with a large angular width as composed of a large number of point sources distributed over an angle which includes several lobes of the interferometer. At every instant some of the points will be in the direction of the lobe maxima and almost an equal number of them will lie in the direction of the lobe minima, so that the fringes are smoothed out.

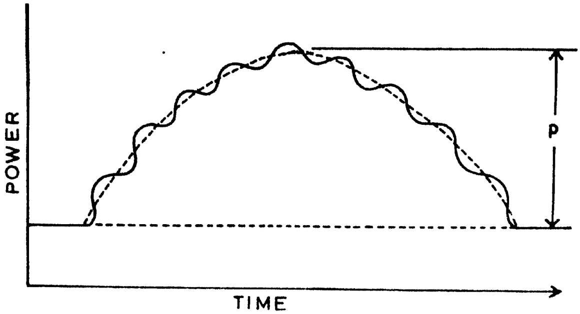


FIG. 4.11 *Interference pattern for a broad source with a width much larger than one Interferometer lobe. The dotted straight line represents the background noise. The dotted curve represents the mean power received by the antenna.*

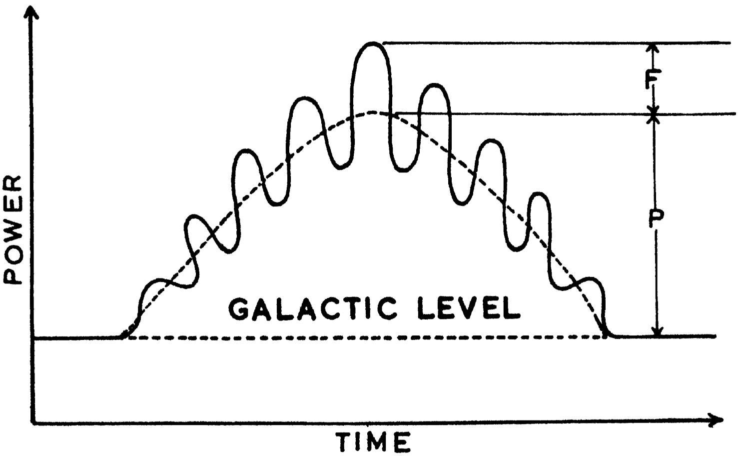


FIG. 4.12 ***Interference pattern for a broad source with width comparable to one Interferometer lobe***

In the second case, undoubtedly, the fringes will be present but they will be less pronounced than those for a point source. The dotted line passing through the mean of the fringes represents the total power component. P is proportional to the flux density. The fringe amplitude F depends on the size of the source relative to the lobe width. We now increase successively the length L of the base line of the interferometer and record F and P. We then prepare a plot of F/P against the base line L. We find that as L increases, the number of lobes also increases and that the lobes become narrower; also, the ratio F/P decreases. From this plot we can infer the angular width and the east-west shape of the source.

Phase-switching Interferometer

The cosmic radio sources may be regarded as randomly distributed on the celestial sphere and consequently we may regard the galactic source as very broad and hence it does not produce any interference fringes as shown in Figure 4.10. However, it interferes with the interference fringes produced by the source under study and we are unable to determine their positions and sizes with the desired accuracy. To eliminate the background noise, radio astronomers use the phase-switching interferometer which is much more complicated than the total power interferometer. However, the basic principle on which this instrument works is as follows. If the signals from one of the antennae of a total power interferometer are delayed in phase by 180°, for example, by inserting an extra transmission line of length equal to a half-wave length, the entire interference pattern alters in such a manner that the minima occur in the original directions of the maxima, and vice versa. Using electronic devices, this 180° phase shift is periodically introduced and removed several times during the course of a second. It is clear that this phase switching does not affect the cosmic radio noise, and the recorder now plots the difference between the receiver output signals for successive positions of the phase switch. If, at a given instant, a point source happens to lie in the direction of a lobe maximum for the zero phase shift, then it will be in a lobe minimum direction for the 180° phase shift. Thus the difference signal is maximum. When the source moves into the minimum of a lobe for the zero phase shift, it is in the maximum of the phase-shifted lobe, and the difference signal again approaches a maximum but in the negative sense. From this discussion it is clear that from the interference pattern given in Figure 4.10 for a simple interferometer, we can construct the interference pattern for a phase-shifted interferometer by subtracting from the ordinate at a point corresponding to time t, the ordinate at a point which is a half-wave length behind the first point, i.e., the ordinate at time $t+\frac{\lambda}{2v}$. The resulting interference pattern is as shown in Figure 4.13 on which the fringes are symmetri-

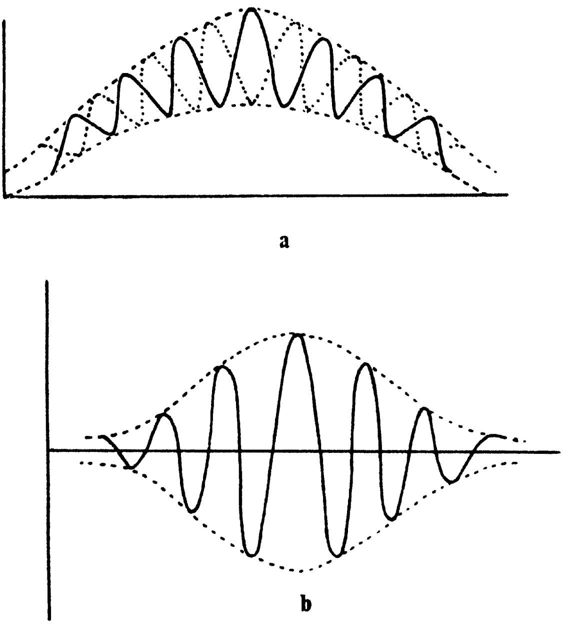


FIG. 4.13 *Interference pattern of a phase-switched Interferometer.*
(a) *The continuous curve represents the interference pattern when both the antennae are in phase; the dotted curve in the middle represents the pattern when they are phase-shifted by half a wave length.*
(b) *Resultant interference pattern for the phase-switched Interferometer*

cal about the zero power line and are devoid of the contribution of the cosmic radio noise.

Polarization

As we have pointed out earlier, the radio waves are electromagnetic in character and are consequently linearly or circularly or elliptically or randomly polarized. Hence the description of radiation from a source would be incomplete unless we specify its state of polarization. The polarization of radiation from a continuously emitting source can be determined with the help of a total

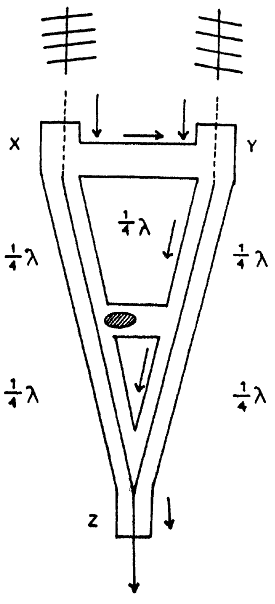


FIG. 4.14 *A simple Polarimeter*

power interferometer, provided its antenna is so mounted that we can rotate it about a central vertical axis giving the dipoles various orientations in the horizontal plane. We record the interference patterns in these various positions of the antenna. We can determine the polarization parameters from the relative positions and amplitudes of the interference patterns.

A simple device for measuring the polarization consists of two linearly polarized antennae, like the dipoles, mounted in a horizontal plane so as to be perpendicular to each other. These antennae are connected in parallel with an arrangement to insert a quarter-wave length delay in either. It is convenient to introduce delay in the transmission line, for example, by inserting a solenoid-operated plunger as shown in Figure 4.14. In essence this instrument measures the power output in two perpendicular directions. The power in any direction being proportional to the square of the electric field component in that direction, we measure, with the help of the polarimeter, electric field components in two mutually perpendicular directions. From these observations we can determine the state of polarization of the incoming radiation.

Mechanism for Radio Emission

We conclude this chapter by enumerating the mechanisms which give rise to radio waves in cosmic context.

(i) 21-*cm line of Neutral Hydrogen.* The hydrogen clouds surrounding very bright stars get ionized by the Ultra-voilet and X-ray radiations from the stars. These clouds consisting of ionized hydrogen are called the H-II clouds. They become optically visible by the continuous process of absorption of the stellar radiation and then emission according to the well known laws of atomic physics.

Neutral hydrogen clouds, which are situated far off from the bright stars, where utter cold prevails, cannot be optically detected. But nature has helped us in a curious manner ! We know that, in an unexited hydrogen atom, its solitary electron remains in the ground state, i.e., in the lowest orbit and as such it should not radiate. However, this ground state itself consists of two sub-states corresponding to two different orientations of the spins or the magnetic moments of the electron and the nucleus. The energy of the sub-state, in which the spins are parallel, is slightly greater than that of the sub-state in which the spins are anti-parallel. The transition from one sub-state to another is possible even at a low temperature of the order of 100°-125°K, i.e., about 175° to 148° centigrade below the freezing point of water. Moreover, this transition involves absorption or emission of a quantum of energy whose frequency is equal to 1420 megacycles per second or wave length 21.1 cm. Clearly, this emission, which is of non-thermal origin, lies in the range of radio waves and hence can be detected by a radio telescope.

(ii) *Thermal Emission of Radio Waves by Ionized Gases.* We can establish mathematically that an accelerated charged particle always emits radiation and the amount of energy thus radiated is proportional to the square of the acceleration. At very high temperatures, such as those prevail in stars, the matter is in ionized form and thus it contains both electrons and positively charged ions. Every electron performs an accelerated motion in the field of the ions and hence emits radiation. This emission is continuous and hence some portion of it falls in the range of radio waves.

(iii) *Plasma Oscillations.* An assembly of electrons, positive ions and neutral atoms is called a "Plasma". When a disturbance, mechanical or electromagnetic, is imposed on this assembly, longitudinal oscillations are set up of frequency which is proportional to the square root of the particle density of electrons. The plasmas can also radiate in the higher harmonics of this frequency. This mechanism is evidently non-thermal.

(iv) *Gyromagnetic Emission.* Another type of non-thermal emission is produced by what is called gyromagnetic mechansim. In the presence of a magnetic field, a charged particle acquires a motion of gyration about the magnetic lines of force. Since the charged particle is continually accelerated in this gyrating motion, it continually emits radiation in a frequency which is proportional to the magnetic field and inversely proportional to the mass of the particle.

(v) *Synchrotron Radiation.* The mechanism of synchrotron radiation is the same as for gyromagnetic radiation, but here we deal with electrons with velocities comparable with the speed of light in vacuum. Accordingly, the character of emission is quite different from that of gyromagnetic radiation as the electron does not radiate in the ground frequency and emits only in very high harmonics. As the frequencies of these harmonics are very close together, the emission gives an impression of a continuous band.

(vi) *Cerenkov Radiation.* When a very high energy charged particle penetrates into a medium in which the velocity of the electromagnetic waves is less than its velocity, it gets heavily decelerated and undergoes a loss of energy in the form of electromagnetic waves along a conical surface centred about its trajectory.

CHAPTER V

Stellar Constellation

Our walk in the woods becomes more interesting and enjoyable if we are able to recognize a few birds and their songs and name some of the flowers and trees. Similarly, our view of the night sky can be more thrilling, if we can recognize some of the stars and the patterns, they appear to form on account of their apparent nearness, along with the legends that are associated with them. We have used 'apparent' to indicate that the stars which appear to form a recognizable pattern called a constellation [like the Great Bear (Ursa Major) or the Big Dipper whose pointer stars locate the pole star on the tail of another stellar pattern called the Small Bear (Ursa Minor) or the Small Dipper] may not be neighbours at all. In fact, one star may be many many times farther away from us than the other. However, since the dawn of civilization, the stars and the fantastic imaginary patterns they form in the sky have always attracted man and excited his imagination. Later, men saw fanciful resemblances to animals or human beings in these constellations and wove legends around them. They named them after the legendary characters they were supposed to represent, such as Hercules or Orion. We shall later narrate some of these legends. The study of these constellations has been very rewarding to navigators. A man who knows stars can never be completely lost on land or sea or in the air so long as the sky is partly clear. The constellations act as 'signposts' of sky, as they help in locating the stars which a navigator uses as reference points in locating his position. The navigator measures the altitudes (i.e., the angles above the horizon) of two well separated stars, almost simultaneously. At the time of observation, these stars possess these altitudes in relation to just one point on the earth. Then, from the reference tables, the navigator reads his longitude and latitude.

Millions of stars appear to be shining in the sky and at first the task of learning their names and positions seems impossible. However, the reader would be comforted if we say that at any time on a clear night a person with good eyesight will not be able to see more than 4000 stars. Moreover, most of these stars are faint and, in any case, people would not be interested in learning their names. It appears that, since we are describing stars and stellar constellations in this chapter, we must start by defining what a star is. However, we shall only be concerned here with their relative brightness and with the fanciful geometrical patterns they weave in the sky; it is therefore not necessary to worry about their physical nature and properties right now.

Magnitudes and Names of Stars

Some stars appear brighter than the others. Does it mean that an apparently brighter star is really brighter than the fainter star ? If the two stars which we are comparing had been equally distant from us, the answer would have been yes. But the stars are situated so far off from each other that a really brighter star by its sheer distance may look fainter than a comparatively fainter star which is nearer to us. However, for practical purposes, we are concerned with their brightness as it appears to us, which is technically called the apparent brightness or apparent magnitude or, simply, magnitude. We define the magnitudes of the stars in the following manner. The faintest stars which can be seen by the unaided eye are arbitrarily allocated the sixth magnitude. The brighter the star, the smaller is its magnitude. The fifth magnitude stars are approximately 2½ times brighter than the sixth magnitude stars on the conventional scale. Similarly, a fourth magnitude star is approximately 2½ times brighter than the fifth magnitude star on this scale. Thus a decrease of magnitude by unity increases the brightness approximately by a factor of 2½. Clearly then, the first magnitude stars are about a hundredfold brighter than the faintest stars that we can see without any aid. The stars brighter than the first magnitude stars are given negative magnitudes. A knowledge of the first and second magnitude stars is sufficient for the purposes of navigation. Table I gives 22 air navigation stars along with their correct pronunciation and the constellation to which they belong.

We note that the brightest stars bear proper names which are mostly of Arabic, Greek or Latin origin. Bayer published a Star atlas in 1603 in which he introduced a new system of naming the stars, according to which the name

TABLE I

Air Navigation Stars

	Name	*Pronunciation*	*Meaning*	*Constellation*	*Magnitude*
1.	Achernar	ā'kĕr-när	the end of the river	Alpha Eridani	0.60
2.	Acruk	ā'krŭks	Alpha of the cross	Alpha Crucis	1.05
3.	Aldebaran (Rohini)	ăl-dĕb' å-răn	the hindmost or the follower	Alpha Tauri	1.06
4.	Alpheratz (Prathama Devayani)	ăl-fē' rătz	the horse	Alpha Andromedae	2.15
5.	Altair (Prathama Garuda)	ăl-tä'ir	the flying eagle	Alpha Aquilae	0.89
6.	Antares (Jyeshtha)	ăn-tā' rēz	river of Mars	Alpha Scorpii	1.22
7.	Arcturus (Svati)	ärk-tū' rŭs	the beer-keeper	Alpha Boötis	0.24
8.	Betelgeuse (Aridra)	bĕt″ ĕl-gûz'	the armpit	Alpha Orionis	0.92
9.	Canopus (Agastya)	Kå-nō' pus	named after a town in Egypt	Alpha Carinae	0.86
10.	Capella (Brahma Hridaya)	Kå-pel' la	a little goat	Alpha Aurigae	0.21
11.	Deneb (Prathama Hamsa)	dĕn' ĕb	the hen's tail	Alpha Cygni	1.33
12.	Dubhe (Rhritu)	dōŏb'hĕ	a bear	Alpha Ursae Majoris	1.95
13.	Fomalhaut (Prathama Dakshina Meena)	fō' măl-hôt″	the fish's mouth	Alpha Piscis Austrini	1.29
14.	Peacock (Mayura)			Alpha Pavonis	2.12
15.	Pollux (Dvitiya Mithuna)	Pol' u ks	the pugilist	Beta Geminorum	1.21
16.	Procyon (Prathama Laghu Swana)	Prŏ' si-ŏn	before the dog i.e., the star which rises before the dog star	Alpha Canis Minoris	0.48

	Name	*Pronunciation*	*Meaning*	*Constellation*	*Magnitude*
17.	Regulus (Magha)	reğ'ŭ-lŭs	the little king	Alpha Leonis	1.34
18.	Rigel (Dvitiya Mriga)	rī' jĕl	the leg of the giant	Beta Orionis	0.34
19.	Rigil Kentaurus (Prathama Kinnar)	rĭjĭ'lkentórŭs	the foot of centaur	Alpha Centauri	0.18
20.	Sirius (Lubdhak)	Sĭr'ĭ-ŭs	the sparkling star	Alpha Canis Majoris	1.58
21.	Spica (Chitra)	Spī' ka	the ear of wheat	Alpha Virginis	1.21
22.	Vega (Abhijit)	Vē' ga	falling	Alpha Lyrae	0.14

Key to Pronunciation

ā as in day	ē as in mēte	ī as in time	ŏ as in not
ȧ „ „ senate	ḗ „ „ event	ỉ „ „ idea	ô „ „ lord
ă „ „ add	ĕ „ „ end	ĭ „ „ ill	ū „ „ use
â „ „ care	ẽ „ „ term	ĩ „ „ firm	ủ „ „ unite
ä „ „ fär	g „ „ get	ō „ , old	ŭ „ „ us
å „ „ låst	ġ = j (gentile)	ŏ „ „ obey	û „ „ turn

indicates the constellation in which a star occurs and also its relative order among the stars of the constellation based on its apparent brightness or magnitude. This order is indicated by letters of the Greek alphabet recorded in Table II.

TABLE II

The Greek Alphabet

α alpha	ι iota	ρ rho
β beta	κ kappa	σ sigma
γ gamma	λ lambda	τ tau
δ delta	μ mu	υ upsilon
ε epsilon	ν nu	φ phi
ζ zeta	ξ xi	χ chi
η eta	ο omicron	ψ psi
θ theta	π pi	ω omega

Generally the brightest star in a constellation is named as α, next brightest as β, the next as γ, and so on down through Table II. Thus Sirius, the brightest star in the constellation Canis Major (in fact the brightest star in the sky) is known as α- Canis Majoris (genetive of Canis Major).

Coordinate Systems Used in Astronomy

In this section we shall introduce the coordinate systems that are used in locating the heavenly bodies. We can easily grasp the significance of these coordinate systems if we know that they are defined in the same manner as the longitude and latitude of a place on the surface of the earth. We recall that in defining the terrestrial longitude and latitude, the earth's equator and the Greenwich meridian are taken as the circles of reference. We draw the meridian passing through a place X on the earth (i.e., the great circle on the spherical earth passing through the north and south poles) cutting the equator in Y; the angle which the meridian of X makes with the Greenwich meridian is called the longitude of X, while the angle which X and Y subtend at the centre of the earth is called the latitude of X. In fact, in a map longitudes are marked on the equator starting with zero longitude for Greenwich and measured from 0° to 180° in the east and west directions. Similarly, latitudes are marked 0° to 90° north and south on the small circles called the latitude circles, drawn parallel to the equator starting from zero latitude for places lying on the equator. Thus both longitude and latitude coordinates are angles. Similarly, we shall presently see that celestial coordinates are also angles.

Celestial Sphere. The heavenly bodies appear to be situated on the surface of a vast (imaginary) sphere called the observer's celestial sphere. In fact, the size of the sphere is immaterial but is to be taken as being so large compared to the size of the earth that the stars viewed from any position on the earth's surface appear to be in the same direction. Comparatively, our sun and the planets are so close to the earth that they appear in different directions when viewed from different positions on the earth.

Horizontal and Equatorial Coordinates

Let us draw the vertical through the position of the observer both ways cutting the celestial sphere in the points Z and Z′. These points are called respectively the Zenith and Nadir. Similarly, if we extend the axis of rotation of the earth, then the points P and P′, in which it cuts the celestial sphere, are called respectively the 'north and south celestial poles'. Also let us extend the horizontal plane and a plane passing through the observer's position and at right angles to the polar axis to meet the celestial sphere in the great circles N W S E N and T W R E T. These great circles are respectively called the 'celestial horizon' and the 'celestial equator'. Evidently the angular measure of the great circular arc PZ is equal to the co-latitude of the observer. Moreover, the points N, W, S and E on the horizon mark the four fundamental directions, namely north, west, south and east for the Observer at 0.

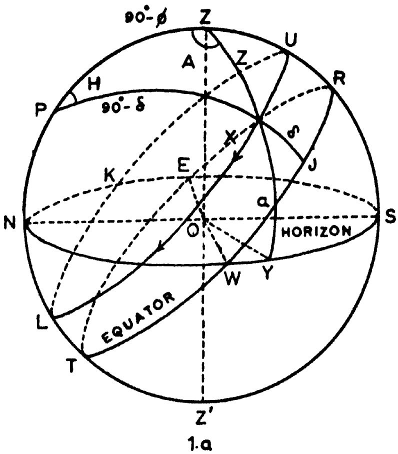
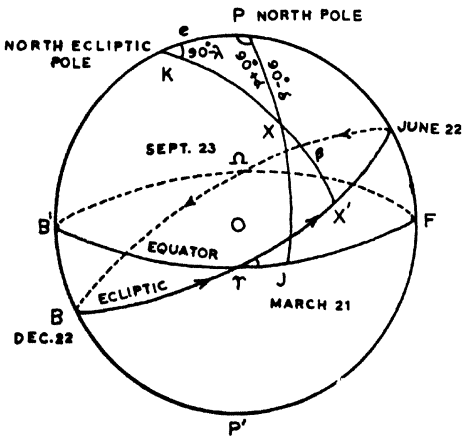


FIG. 5.1a *Horizontal and Equatorial coordinates*

(*a*) *Horizontal System of Coordinates.* In the horizontal system of coordinates, the horizon N E S W and the vertical (circle) ZNZ′ are taken as the circles of reference. Let X be a star and let the vertical ZX meet the horizon in Y. Then the arc NY, i.e., $\angle NOY = \angle PZX$ (measured less than 180°) along either NES or NWS is called the 'azimuth east' or 'azimuth west' of X. The other coordinate is the arc YX measured along the vertical YXZ from the horizon, i.e., $\angle YOX$. This angle is called the 'altitude' of X. Instead of altitude we may take the arc ZX called the 'zenith distance' as the second coordinate of X.

(*b*) *Equatorial System of Coordinates.* Here the celestial equator T W R ET and the meridian Z P N TZ′ are taken as the reference circles. We draw the meridian of X, i.e., the great circle passing through the celestial poles and X, cutting the equator in J. The angle ZPX between the observer's meridian PZR and the meridian PX though the star X measured westward is called the 'hour angle' of the star. The angle XOJ or the arc JX of the meridian of the star measured from the equator to the star is called the 'declination' of the star X. Declination is called north or south according as X lies in the hemisphere containing the north or the south celestial pole.

Since the meridian of the observer will be rotating about the axis PP′ due to the rotation of the earth, the hour angle of the star will be changing. If, instead of taking the observer's meridian as the reference circle, we take a fixed meridian as the reference circle, we can take the angle between this meridian and the meridian of the star as the second coordinate which will not be affected by the diurnal motion of the earth. We know that earth revolves round the sun completing one revolution in a year. Due to this annual motion of the earth, the sun appears to describe a circle, with reference to the very distant stars, round the earth. The apparent orbit of the sun on the celestial sphere is called the 'ecliptic'. The celestial equator and the ecliptic cut in two points. The point γ, where the sun's declination changes from south declination to north declination, is called the vernal equinox as this event takes place on March 21 which is the beginning of the spring season. It is called equinox for on this date the day and night are of equal duration. This point is also called the first point of Aries as it lies near the first star of the constellation of Aries. The other point of intersection Ω, where sun's declination changes from north to south, is called



1.b

G. 5.1b *Equatorial and Ecliptic coordinates* respectively the Zenith and Nadir. Similarly, if we extend the axis of rotation of the earth, then the points P and P′, in which it cuts the celestial sphere, are called respectively the 'north and south celestial poles'. Also let us extend the horizontal plane and a plane passing through the observer's position and at right angles to the polar axis to meet the celestial sphere in the great circles N W S E N and T W R E T. These great circles are respectively called the 'celestial horizon' and the 'celestial equator'. Evidently the angular measure of the great circular arc PZ is equal to the co-latitude of the observer. Moreover, the points N, W, S and E on the horizon mark the four fundamental directions, namely north, west, south and east for the Observer at 0.

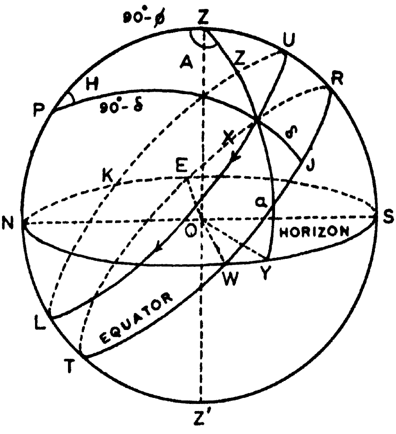


FIG. 5.1a *Horizontal and Equatorial coordinates*

(*a*) *Horizontal System of Coordinates.* In the horizontal system of coordinates, the horizon N E S W and the vertical (circle) ZNZ′ are taken as the circles of reference. Let X be a star and let the vertical ZX meet the horizon in Y. Then the arc NY, i.e., $\angle NOY = \angle PZX$ (measured less than 180°) along either NES or NWS is called the 'azimuth east' or 'azimuth west' of X. The other coordinate is the arc YX measured along the vertical YXZ from the horizon, i.e., $\angle YOX$. This angle is called the 'altitude' of X. Instead of altitude we may take the arc ZX called the 'zenith distance' as the second coordinate of X.

(*b*) *Equatorial System of Coordinates.* Here the celestial equator T W R ET and the meridian Z P N TZ′ are taken as the reference circles. We draw the meridian of X, i.e., the great circle passing through the celestial poles and X, In Chart 1, the central star is the pole star towards which the north end of the earth's axis points, and hence it does not show relative diurnal motion as do the other stars in the sky. The numbers at the end of the radial lines denote the right ascension in hours (converted from degrees to hours according to the formula $360° = 24$ hours). The circles are the declination circles and the number written on each gives the declination, in degrees, of all the points situated on that circle. For any observer, from terrestrial latitude 40°N and more, the stars shown in this chart will never set below the horizon and hence they will be visible to the observer throughout the whole night. These stars are, therefore, called the north circumpolar stars. The outer circle of the chart is divided into 12 equal parts and each part is associated with a month.

To use the chart, find the approximate date in the outer circle. If you are observing on May 15, for example, face north and hold the chart so that the middle of the section marked May is at the top. The line running through the chart from the top to the bottom will coincide with your meridian at 9 p.m. standard time, whatever your longitude may be. The stars at the bottom of the chart will be close to the northern horizon, while those at the top will be above the pole star (Polaris). The best way to use the chart is to hold it over your head as you face north. Since the stars at the bottom are those which are close to the northern horizon, hold the bottom towards the north and the top towards the south. In this position the right side of the chart will be east and the left side, west.

Suppose you want to find the stars that will be on your meridian, say at 11 p.m. Turn the chart in the counter-clockwise sense from the position at 9 p.m. through two hours of right ascension (R.A.) so that the middle of the section marked June is at the top. Take the chart overhead so that its bottom is directed towards the north and the top towards the south. Similarly, to use the chart on the same night at 1 a.m., 3 a.m., and 5 a.m., rotate the chart from its position at 9 p.m. through 4, 6 and 8 hours of R.A. in the counter-clockwise sense so that the middle of the sections marked July, August, September come at the top. On the other hand, if you wish to find as to which stars will be on your meridian at 7 p.m. on the same night, turn the chart in the clockwise sense through 2 hours of R.A., bringing the middle of the section marked April at the top, and then follow the instructions for using the chart, given in the last paragraph.

The most conspicuous group of stars in this chart is the Big Dipper which consists of seven stars and forms part of the constellation Ursa Major, the Great Bear, which is difficult to trace. The stars marked α, β are called the pointers as the direction α β points towards the north celestial pole, situated near the Pole Star (Polaris) which forms the handle tip of the Small Dipper, consisting also of seven stars and forming part of the constellation of Ursa Minor, the Small Bear.

The Pole star (*Dhruva*) has guided navigation through centuries on account of its fixed position in the sky, unaffected by the daily motion of the earth. The distance between the two pointers is about 5° of arc and to locate the pole star draw a line through β and α pointer stars and extend it about five times.

Other important constellations in this chart are Cassiopeia (the Lady in the Chair), Cepheus (the King) and Draco (the Dragon). Cassiopeia resembles a huge W or M and to locate it, draw a line from star ϵ in the Big Dipper through the Pole Star and extend it almost over equal length. If you like to recognize it as the Lady's Chair, α and β stars will form the the bottom of two legs. Cepheus gives the appearance of a building with a steeple. Draco is a very inconspicuous constellation. The head of the dragon is formed by a V-shaped group of stars about half way between Cassiopeia and the Big Dipper bowl, while the tail is marked by the faint stars between the two Dippers.

In Charts 2 to 5, the curves drawn from left to right are the declination circles, while those running from the top to the bottom are the hour circles. The declinations in degrees and the R.A. in hours are marked on these circles. The instructions for using the charts are similar to those for the Chart 1. Select the chart in which the month of observation lies, face north, and hold the chart above your head with its bottom pointing north. As you hold the chart in this position, the right side will be east and the left side, west. You will observe the stars lying towards the north in this position, but to observe the stars towards the south, you have to face south without changing the orientation of the chart.

Finally, Chart 6 gives the south circumpolar stars visible from mid-southern latitudes. The south celestial pole is at the centre of the cross at the centre of the chart. There is no bright star to mark the south celestial pole (as is Polaris for the north celestisal pole), but there is an infallible guide for the navigators to locate it. The small and large Magellanic clouds and the south celestial pole form the vertices of more or less an equilateral triangle.

Legends Associated with the Constellations

In this book we have referred to the constellations listed below. The reader is advised first to familiarize himself with their shapes and the important stars in them, and then to look at them carefully in the sky on convenient dates and at convenient times. He may then read the following legends about them and look at these constellations again. Once the mind is prepared in this manner, the reader will perhaps begin to see in the various constellations, a pictorial presentation of the legends, like the stills of a cinema film.

CHART 1

1 URSA MAJOR AND URSA MINOR. (*Vrihat Sapta Rishi; Laghu Sapta Rishi*). According to Greek mythology, the bear was originally the beautiful nymph, Callisto, with whom Jupiter, the most powerful of the gods, was in love. When Juno, Jupiter's wife, became jealous of Callisto's beauty and threatened her, Jupiter transformed her into a bear. Callisto's young son, Arcas, almost killed the bear when he was hunting, not knowing that it was his mother. Jupiter transformed Arcas also into a bear and placed the mother and the son side by side in the heavens as Big and Small Bears.

The most famous star in Ursa Major is ζ Ursa Majoris, named Mizar, with its faint companion, Alcor. Another important star in this constellation is α Ursa Majoris, named Dubhe. Both of these stars are Navigational Stars. The sanskrit names for the α, β, ... η Ursa Majoris are the following: *Pulaha, Kretu, Adri, Pulastya, Angirasa, Vasistha* (*Arundhathi* as its companion), and *Maruchi.*

2 CASSIOPEIA (*Kashyapa*). Cassiopeia, the famed lady of the Chair, was the wife of Cepheus and mother of Andromeda. She was very proud of her beauty and always boasted that she was fairer than the sea nymphs. Her vanity brought upon her the wrath of the gods in the form of the ravaging of her sea coast by a monster and a demand from Neptune, the sea god, for the sacrifice of Andromeda.

The constellation is often called 'Cassiopeia's chair' as the five stars forming a W and the sixth faint star suggest this form.

This constellation contains two navigational stars, namely, β and δ Cassiopeia, called respectively the Caph and Ruchbah, the Arabic for camel's hump and knee. They are so called because the ancient Arabs recognized the constellation as a kneeling camel.

3 CEPHEUS (*Kapish*). Cepheus, husband of Cassiopeia, stands by her side in the heavens.

This constellation contains two bright pulsating stars, namely β and δ Cephei.

CHART 2

1 CANES VENATICI. The Astronomer Hevelius (1611-1687) thought of this constellation as a pair of hunting dogs. The formation of stars in no way suggests these animal forms; however, Hevelius probably fancied the idea of a pair of dogs barking at the heels of the bear (Ursa Major).

2 COMA BERENICES or Hair of Berenice (*Kesha*). Berenice was a beautiful Egyptian queen. In gratitude for the safe return of her husband from war, she got her beautiful locks shorn with a sword and put in the temple of Venus, who according to Roman mythology, is the goddess of love. Some thief stole the tresses, however, and this was regarded as a great calamity. The royal astronomer then put people's minds at ease by remarking that the gods were so pleased by the queen's sacrifice that Jupiter himself had placed her hair in the heavens.

This constellation is well discernible with the help of an opera or a field glass.

3 VIRGO or the Maiden (*Kanya*). Virgo was originally the virgin goddess of justice, Astraea, who became so disgusted with the ways of men that she cast her lot with the stars, far away from the earth.

The most important star of the constellation is Spica, which is a navigational star and, according to mythology, represents an ear of wheat held in Virgo's left hand.

CHART 3

1 CYGNUS or the Swan (*Hamsa*). Cygnus presents a beautiful sight in the sky. It is often called the Northern Cross, though the stars that form the cross are only some of those that form the swan.

Certain ancient writings suggest that Cygnus represented Orpheus, the musician who was placed by the gods in heaven after his death as a reward for his superb music.

α Cygnus, called Deneb, lies in the head of the cross and in the tail of the swan.

2 LARA or the Lyre (*Veena*). Just to the east of Cygnus is the constellation of Lyra. It is a beautiful constellation formed by a parallelogram with a triangle joined to it. The shape of lyra resembles that of a turtle; it has no resemblance to a lyre as we know it at present. However, the discrepancy is explained by the following story of the invention of the lyre, as narrated in mythology. Mercury made the first lyre by piercing a turtle shell and attaching strings to it. The ancient Greek word for turtle is the same as for lyre. Thus it appears that the constellation was first thought of as a turtle. It is befitting that Lyra is placed in the heavens by the side of Cygnus (the musician).

The most outstanding star of the constellation is α Lyrae, named Vega (*Abhijit*). Vega is the brightest star that we can see in the northern latitudes in summer, and the third brightest star in the whole sky. It is a navigational star.

3 HERCULES (*Bheema*). To the west of Lyra lies the constellation of Hercules. It resembles an H in shape and is named after the mythological Greek hero of the same name.

Between the ζ and η stars, there is one of the most beautiful star clusters in the whole sky, called the globular cluster M 13 (the thirteenth object in the catalogue prepared by the French astronomer, Messier). To the naked eye it looks like a speck of haze. It consists of more than 50,000 bright stars more or less like our sun.

4 CORONA BOREALIS or the northern crown (*Uttar Kireet*). Just to the west of Hercules and east of the constellation of Bootes is a beautiful arc of stars called Corona Borealis.

The most prominent star of this constellation is Alphecca, the Arabic for the Bright One of the Dish, as the Arabs conceived the constellation as a dish.

5 OPHIUCHUS AND SERPENS or Serpents (*Sarpa-dhar*, *Sarpa*). Just to the south of Hercules is the constellation of Ophiuchus, bearer of the serpents. The prominent stars of this constellation form a five-sided figure.

Serpens, though considered as a separate constellation, has its stars closely intermingled with those of Ophiuchus. A small but conspicuous triangle lying below Corona Borealis indicates the snake's head. Several bright stars give the appearance of twisting coils of the serpent round Ophiuchus.

The constellation as a whole represents Aesculapius, the Greek god of medicine. Aesculapius was such an expert that he could even bring back the dead to life. Consequently Pluto, the god of Hades (the abode of departed spirits) became short of labourers. He complained to Jupiter about it and Jupiter killed Aesculapius with a thunderbolt and placed him in the sky.

6 SCORPIUS or the Scorpion (*Vrishchik*). It is situated just below Ophiuchus and is one of the most beautiful constellations. The arrangement of the stars truly suggests the form which its names indicate.

The most important star of this constellation is Antares. It is given this name which signifies 'rival of the planet Mars', on account of its reddish hue.

7 SAGITTARIUS or the Archer (*Dhanu*). It lies east of Scorpius. The most prominent feature of this constellation is the central dipper and the triangle formed by the γ, δ, ϵ stars.

In mythology Sagittarius represents the learned centaur (a man-horse with a human body above the waist and a horse's body below) Chiron, tutor of Aesculapius and other Greek heroes.

CHART 4

ANDROMEDA (*Devayani*). Andromeda lies south of Cassiopeia and three of its fairly bright stars α, β, γ Andromedae appear more or less in a straight line. The α Andromedae is named as Alpheratz and is also a star of the constellation Pegasus. Alpheratz is situated at the north eastern corner of the Great Square of Pegasus (*Khagaswa*).

As we have already mentioned, beautiful Andromeda was the daughter of Cassiopeia. Neptune, the sea god, punished her for the vanity of her mother by tying her with chains to the rocks along the sea coast where she would be devoured by Cetus, a sea monster.

CHART 5

1 ORION or the Giant-Hunter (*Mriga*). Orion is the most magnificent constellation in the sky. The figure of Orion is roughly rectangular with three fairly bright stars set along a straight line in the middle.

In mythology Orion is the mighty hunter (figure 5.3) who boasted that no animal on earth could conquer him. The scorpion, therefore, stung him on the foot to punish him for his vanity. Betelgueuse [(Bet-el-geuse) (*Arudhra*)]; i.e., α Orion, is one of the largest stars known, whose diameter is about 100 times that of the sun. It is a red star situated in the right shoulder of the hunter. Bellatrix (γ-Orion) is in the left shoulder, while Rigel (β-Orion) is in the left leg. The central star of the belt is Alnilam (ϵ Orion). All these four stars are navigational stars.

FIG. 5.3 *The Orion constellation*

2 *Taurus* or the Bull (*Vrishabha*). Taurus is situated to the north-west of Orion and is made up of two groups of stars: (*i*) a V-shaped cluster called the Hyades, with a red star, Aldebaran (*Rohini*), and (*ii*) another group of stars, called Pleiades, lying further west. The Hyades form the Bull's head, with

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country near about January when the sun entered the region where the Pisces (the fish), Cetus (the sea monster), Eridanus (the river) and Capricornus (the sea goat) are located (see Chart 5). The choice of water animals to be associated with these constellations which, with the help of the sun, brought them rains was but natural. Similar superstitious ideas gave birth to the pseudo-science of astrology, according to which the stars and planets influence the affairs of man in some mysterious manner. Astrology came into vogue near about 1200 B.C. chiefly because the people of those times did not know the nature of the physical universe. Is it not regrettable that this relic of the Dark Ages of science still persists in spite of the fact that the science of astronomy has brought to us so much understanding of the reality about the heavenly bodies and about the physical laws which govern them?

CHAPTER VI

Galaxies

For describing the physical universe evidently two approaches are available: (*i*) to start from the smallest unit and build up to the biggest units found in the universe, or (*ii*) to start with the largest unit and then dissect it into smaller units, discussing each unit in its turn. We shall adopt the second approach.

The following tree gives the various units that we have to discuss:

- Observable Universe
  - Super Galaxies
    - Galaxies
      - Star Clusters
        - Stars
          - Planets
            - Satellites
          - Asteroids
          - Comets
          - Meteors
      - Nebulæ
      - Inter Stellar Dust

Super Galaxy

The observable universe consists of a large number of aggregations of matter, each organized from organizations of a smaller scale. The largest recognized organizations are called the super galaxies which are organized groups of galaxies. A super galaxy may be treated as an island in the boundless ocean of space. A large number of such island universes have been observed, which exist quite independently of each other. As an example of a super galaxy we may take a closed group of galaxies in the constellation of Serpens or the cluster galaxies in the Virgo constellation. Figure 6·1 shows the distribution of 100

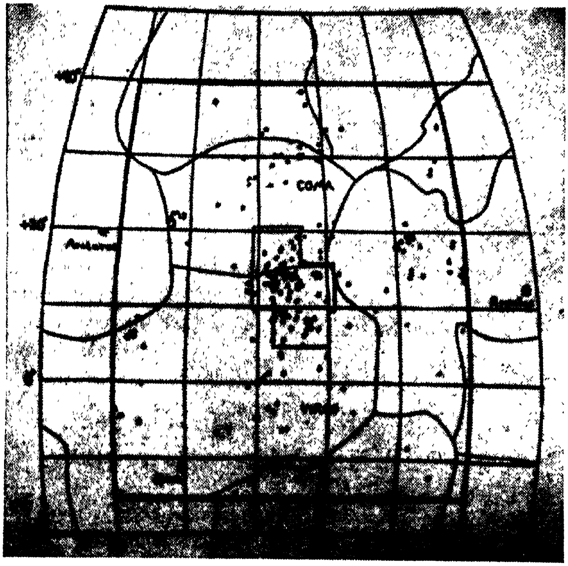


FIG. 6.1 *Cluster galaxy in Virgo. The dots represent the galaxies*

galaxies up to the 13th magnitude in cluster of galaxies in Virgo. However, this cluster contains a much larger number of faint galaxies, and if we go down, up to the 15th magnitude, i.e., if we include galaxies which are six times fainter, the number of observable galaxies is about 200.

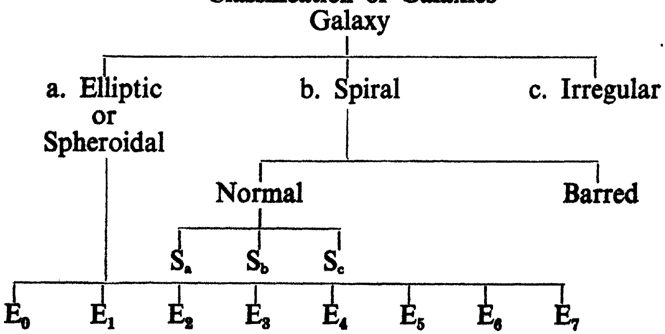
A word of caution ! When we say that a particular object lies in a particular constellation, it does not mean that it has any relation with the constellation except that it lies near the line of sight passing through the constellation.

The various galaxies in a super galaxy are generally independent of each other. Their apparent nearness is simply the outcome of their enormous distances from us. In fact, these component galaxies may be thousands of light years distant from each other.

Galaxies are themselves complex organizations made up of: (*i*) stars, along with their families, if any, (*ii*) nebulæ, i.e., gas, and (*iii*) dust. These ingredients of a galaxy are distributed in an irregular form. Besides, not all galaxies contain nebulæ and dust.

At this stage an instructive simile suggests itself. Imagine the fleets of various nations standing at various locations on the vast bosom of an ocean. Each fleet may consist of a number of warships, cargo ships, torpedo boats, etc. Their number may vary from fleet to fleet, independently. The ships in each fleet may differ from one another in respect of size, shape, and nature. Evidently, here a fleet corresponds to a super galaxy, an individual ship in a fleet to a galaxy, and the contents of a ship to the contents of a galaxy, namely, stars, nebulæ and dust. If we carry the simile further, we may also say that each super galaxy may exist independently of the rest, as the fleet of one nation may float quite independently of the fleets of the other nations. Under normal conditions the various ships in a fleet stand side by side without menacing each other's safety. But once in a while during a violent storm, these ships may collide with each other and destroy themselves. To come back to the galaxies, what about cosmic accidents and wars? Yes, wars seem to be possible there also. We shall show some evidence later about collisions between galaxies, clouds of dust and nebulæ and refer to encounters between stars, etc. However, we may mention that these cosmic wars strictly observe all the laws of nature, in contrast to our wars on earth where the laws of ethics are the first to be destroyed.

Classification of Galaxies



From a consideration of the shapes of their projections on the plane perpendicular to the line of sight, the galaxies may be divided into three broad classes. The tree on page 83 gives the classification and sub-classification of the galaxies:

a. The elliptical galaxies are in fact spheroidal. These may be further subdivided according to their ellipticity, e,

$$e = \frac{\text{Major Axis—Minor Axis,}}{\text{Major Axis}}$$

into eight broad classes: E_0, E_1, E_2, E_3, E_4, E_5, E_6, E_7 where the sub-script denotes the nearest integer to the number obtained by multiplying the ellipticity by ten.

It is of interest to note that the most flattened image so far observed corres-

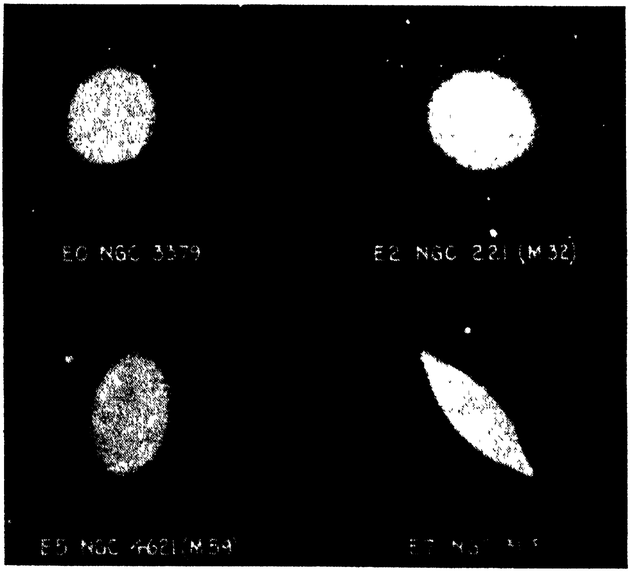


FIG. 6.2 *Spheroidal galaxies E_0, E_2, E_5, E_7*

ponds to 0.7 ellipticity, i.e., the major axis is never more than 3 times the minor axis. Figure 6·2 shows galaxies with ellipticity 0 (spherical), 0.2, 0.5, 0.7.

b. The class of spiral galaxies is divided into two sub-classes: (*i*) Normal spirals, and (*ii*) Barred spirals.

(*i*) A normal spiral galaxy is characterized by a bright circular or elliptic nucleus from which emerge two, or occasionally more, arms of approximately spiral shape, coiling round the nucleus. The normal spirals constitute the principal branch. The normal spirals are further sub-divided into three classes, S_a, S_b, S_c according to the degree of openness of the spiral arms. S_a fits almost continuously on the class E_7 of the most flattend elliptical galaxies.

(*ii*) The class of barred spirals is characterized by the presence of two bar shaped projections from which emerge the spiral arms.

The following are typical examples of the spiral galaxies:

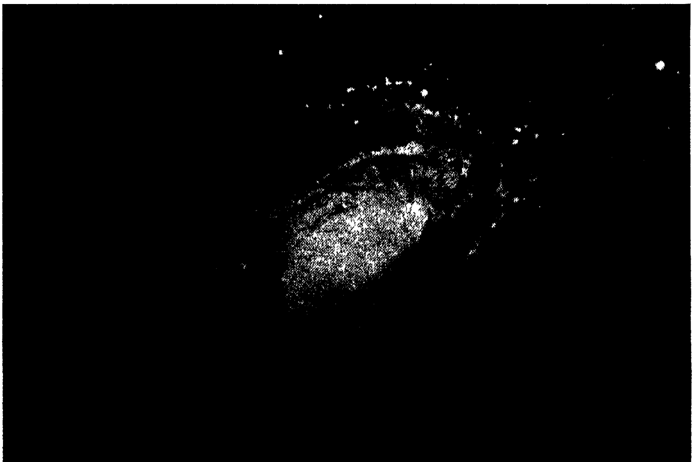


FIG. 6.3 *A photograph of spiral galaxy M 81 in Ursa Majoris taken by the 200-inch Palomar Reflector. The white dots in the spiral arms represent stars.*

FIG. 6.4 *Spiral galaxy M101 in Ursa Majoris resembles our own galaxy*

M 81 This spiral galaxy is situated in Ursa Major constellation and is about a million l.y. (light-years) distant from us. The photograph (Figure 6.3) is taken by the 200-inch Hale reflector telescope and shows the nucleus, which is elliptical in shape, and the two spiral arms emanating from the two extremeties of a diameter. In the spiral arms we see condensations which are stars formed in them.

M 101 This galaxy is also in the Ursa Major constellation. This beautiful pin-wheel like galaxy (Figure 6·4) probably looks to us much like our own galaxy, i.e., the Milky Way, would appear to a hypothetical observer looking at it from an enormous distance, the broad-side on. We belong to the interior of our galaxy and hence we cannot comprehend directly how our galaxy would look to an outside observer. However, the radio telescopes have helped us in constructing a picture of our galaxy.

FIG. 6.5 *Spiral galaxy M* 31 *in Andromeda. The two distinct white patches, one above and the other below, represent two other ellipitical galaxies.*

M 31 It is in the Andromeda constellation and is about 900,000 l.y. distant from us. Its diameter is about 50,000 l.y. We have mentioned these numbers to give the readers some idea about the cosmic distances and the sizes of galaxies. Under favourable conditions it is visible to the naked eye near υ-Andromeda. It (Figure 6·5) is one of the most magnificent of all galaxies. The photograph shows its two elliptical companions.

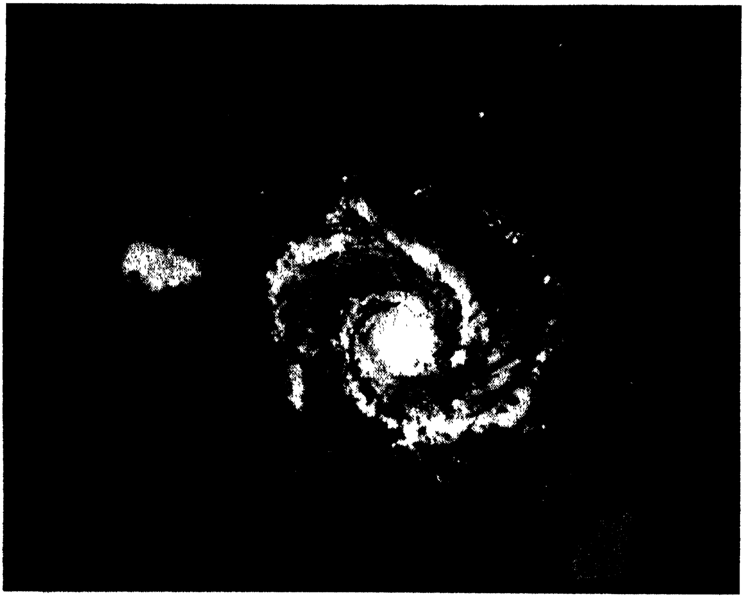


FIG. 6.6 *Spiral galaxy M 51 in Canes Venatici. Mark the large mass at the end of one of the spiral arms; probably this is another galaxy.*

M 51 The galaxy M 51 (Figure 6·6) is in the Canes Venatici constellation. The large mass at the end of one of the spiral arms makes it decidedly an unusual galaxy.

(*c*) The irregular galaxies, as the name implies, do not possess any regular shape. Figure 6·7 represents two irregular galaxies called the Large and the Small Magellanic Cloud (evidently the term 'cloud' is a misnomer). We have chosen

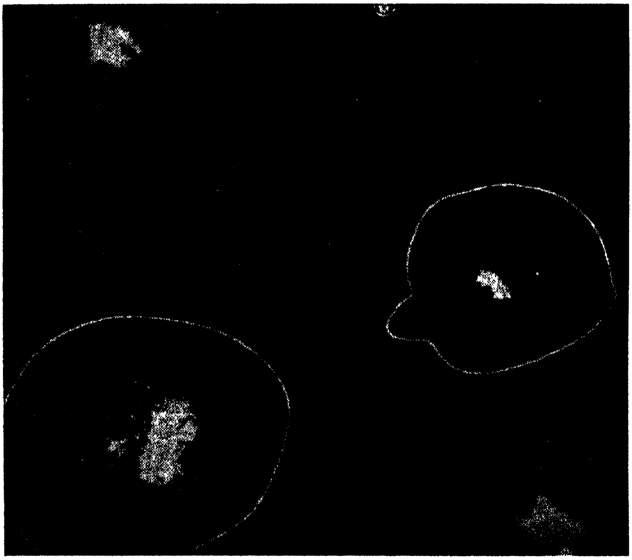


FIG. 6.7 *The Magellanic clouds, typical examples of irregular galaxies.*

Magellanic clouds as the illustration of this class of galaxies, as they are associated with the name of the great Portuguese circumnavigator, Magellan. Pigafetta, who was an associate of Magellan in his voyages, described these galaxies in his official records of their first round-the-world tour of 1518-20. These galaxies were of great help to them in the southern hemisphere as they located the south pole: these galaxies and the south pole form approximately the vertices of an equilateral triangle.

The Large Magellanic Cloud is one of the nearest galaxies to our own galaxy and is situated at about 72,000 l.y. from us. The Small Magellanic Cloud is about 82,000 l.y. from us. These distances may be compared with the distance of the sun from us, which is about 8 l.m. In the photograph taken with the help of an optical telescope the two galaxies appear to be unconnected, but the radio telescopic observations in the 21 cm wavelength show that the Magellanic clouds are linked together by a tenuous gas cloud. Moreover, they affect each other by their mutual gravitational attraction which causes them to rotate about each other. We have evidence of some galaxies which are linked with each other by a bridging arm of luminuous matter or merely by gravitational attraction. Some galaxies, especially those in cluster galaxies which are elliptic, get fantastically distorted by their mutual gravitational attractions. There is evidence of collisions between the galaxies. The story of collisions between galaxies

FIG. 6.8 *NGC 1275 consisting of two spiral galaxies in collision*

sounds like fiction but radio telescopes have provided confirmation of such events.

The two pictures in figures 6.8 and 6.9 show the evidence suggesting collision between galaxies:

NGC 1275 The photograph in Figure 6.8 shows two spiral galaxies in collision situated at about 170 million light years. One of the two spiral nebulæ is the tightly wound spiral S_a and the other more open spiral of type S_c. The open spiral shows great distortion. The collision is energetic enough to excite the interstellar gas to radiate characteristic spectral lines, and with the help of Doppler effect we can calculate their velocities as 5200 and 8200 km/sec.

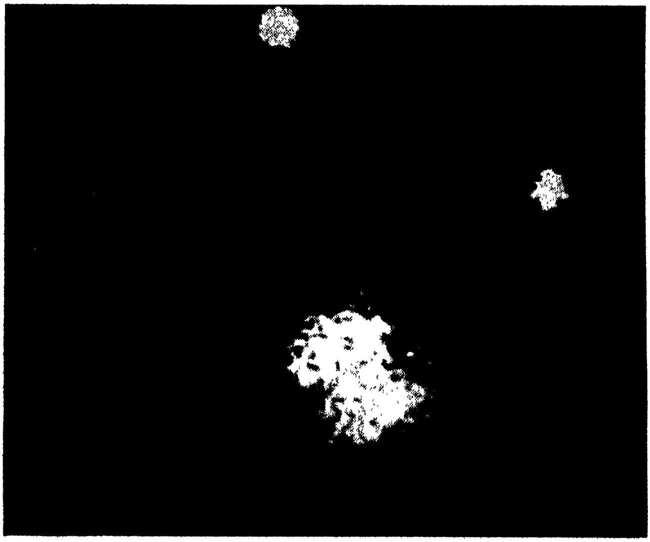


FIG. 6.9 *Cygnus A, two galaxies in collision emitting strong radio waves. The two distinct white patches represent other galaxies.*

This galaxy is also a strong radio source, but the dimenson of the radio source is much smaller than the dimension of the pair and hence it appears that the radio emission arises from the nucleus of one of the two colliding galaxies.

CYGNUS A It is situated at a distance of 550 billion miles from us. It is a very strong radio source. Thd recognition of this radio source as two galaxies in collision has a very exciting story. On seeing the photograph (Figure 6.9), Baade conjectured that it showed two galaxies in direct collision. In his enthusiasm he mentioned this to Minkowskii, who challenged Baade's conjecture and demanded a spectral proof. A famous bet was made, with a bottle of whisky as the stake. Baade won the bet. Cygnus A is the strongest radio galaxy. The radiation in 3 cm wave length shows strong polarization, indicating the

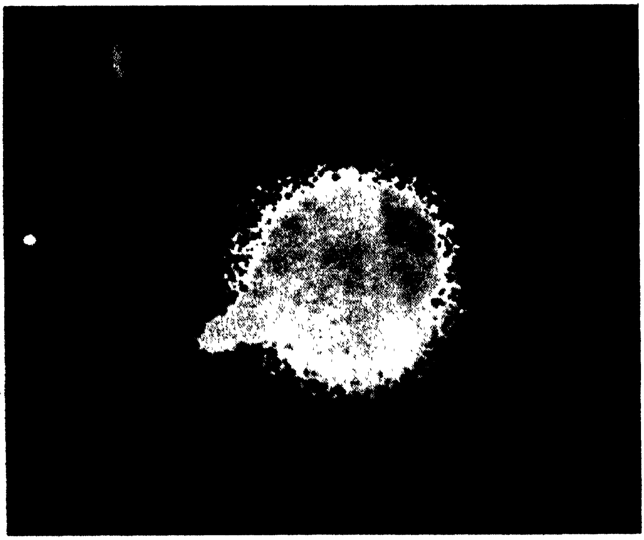


FIG. 6.10 *M 87 is a powerful source of radio waves. Mark the bright jet extending on the left from the spherical nucleus.*

presence of strong magnetic field. It appears certain that the synchrotron mechanism is responsible for the radio emission.

M 87 Figure 6.10 shows a peculiar galaxy M 87 which is a powerful source of radio waves. The projection on the left represents a bright jet extending from the spherical nucleus which emits polarized light. It is suspected that this galaxy has a magnetic field. This galaxy is one of the most intense sources of radio waves in the sky. The jet itself constitutes a double radio source. It is surmised that synchrotron mechanism is responsible for these radio emissions.

Quasars

Quasi Stellar Sources (Quasars) and Quasi Quasars are mysterious astronomical objects which resemble stars in their optical appearance, but are associated with extremely intense radio emissions. Moreover, they show large red-shifs in their spectral lines. We are as yet unable to say whether these red-shifts represent the Doppler effects arising from their motions or represent the relativity effects arising from their enormously large masses.

We may consider B.C. 273, as an example of a Quasar. It is a double radio source of 13th magnitude and the red-shift, as measured by Schmidt in 1963 in its prominent spectral line, is 0.158, which is unexpectedly large. If this red-shift is a gravitational effect as predicted by the general Theory of Relativity, then its mass must be greater than 10^{11} times the solar mass condensed in a radius of 10^{17} cm.

Quasi-stellar Galaxies

Many objects, which were hitherto regarded as very faint blue stars in our own galaxy, have been recently (1964) found to be actually a very strange variety of extremely distant galaxies. These objects differ from the Quasars in not being strong radio sources. Sandag has found that, among the blue objects with magnitude 19 or more, the Quasi-stellar galaxies (QSG) out-number the blue stars in our galaxy by a ratio of 25 to 1. There are about 83 of them brighter than the twelfth magnitude over the entire sky.

From the red-shift data, we find that a QSG with twelfth magnitude must be about 230 million parsecs (1 parsec=3.258 l.y.). According to rough estimates, there are about 20,000 times more normal galaxies than the QSG within the sphere of radius of about 230 million parsecs. Thus the QSG are cosmically a rare phenomenon; nevertheless, they are much commoner than Quasars by a factor of about 500.

The actual physical nature of the Quasars and QSG is not known, but astronomers believe that Quasars are in fact QSG going through a temporary phase of intense radio emission.

Distribution of Galaxies

We shall now take up questions of the following type: How many galaxies are there in the universe ? How are they distributed in space ? and so on.

(*a*) *Apparent Distribution of Galaxies on the Celestial Sphere.* The apparent distribution of galaxies on the celestial sphere shows, to a large extent, symmetry about the galactic plane, i.e., the mid-plane passing through the Milky Way, with the greatest number of galaxies appearing near the galactic poles. The number falls down as we progressively approach the galactic plane. In fact, the galactic plane marks the centre of a narrow belt in which no galaxies appear at all. This region is known as the zone of avoidance (Figure 6.11). We have to be cautious

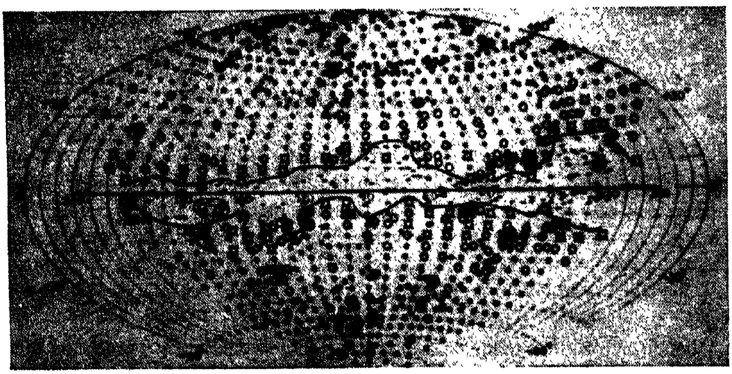


FIG. 6.11 *The Zone of Avoidance. Mark the oval window near the right end of the central belt.*

in interpreting this zone. It does not mean that there are no galaxies situated in this zone; in fact the truth seems to be otherwise. This zone is the result of obscuration of the extra-galactic objects by the interestellar dust (extremely minute particles of solid existing in space, between the stars) in our galaxy which is most extensive and effective in and near the galactic plane. This conclusion is supported by the observation through a small window of less obscuration in this region with the help of a powerful telescope. We find some galaxies situated in this portion of the zone of avoidance.

(*b*) *Tendency to Group or Cluster.* Bright galaxies show a tendency to group or cluster together. It is estimated that on an average there is a recognizable cluster of galaxies for every fifty square degrees of the sky. Some of these clusters are known to have more than 800 members. We have already seen the picture of 100 members of the Virgo group of galaxies.

(*c*) *Number of Galaxies Observed.* It is impossible to say how many galaxies are there in the universe. However, the following statement will give some indication in this direction: The 100-inch telescope had recorded 1780 galaxies per square degree of sky, i.e., about 75 million galaxies over the whole celestial sphere. It is estimated that the 200-inch Hale telescope with its increased penetrating power will record about a billion galaxies! However, it is evident that we shall never be able to estimate the number of galaxies in the universe whose observable boundary depends on the power of our instruments.

Problem of Red Shift

As early as 1914, it was noted that the spectra of galaxies showed the red shift, i.e., an apparent increase in the characteristic wave lengths of the atoms radiating them, or, alternately, an apparent decrease in their frequency. This phenomenon is usually interpreted as 'Doppler effect'. If the red shifts in the spectra be interpreted as the Doppler shift, then the conclusion that the galaxies are receding from us is inescapable. Also, by noting the red shift we can calculate the velocity of recession. These calculations show that the galaxies possess much higher velocities than those of the high velocity stars in our own galaxy. During the last quarter of the century, spectra have been obtained from fainter, i.e., more distant galaxies, using larger telescopes and faster photographic plates. In fact, we are now in possession of reliable spectra of more than 100 galaxies. The examination of these spectra suggests that all the observed galaxies are receding from us and that their velocities are proportional to their distances so that the farther is the galaxy, the faster it is going away from us. To have some idea about these velocities we give the following table:

Distance of a galaxy in million l.y.	3.5	250
Velocity of recession in miles/sec	330	24,000

A simple calcuation shows that the velocity increases at the rate of 100 miles per second over a distance of a million light years. Consequently, a galaxy at a distance of about 2000 million light years will possess a velocity equal to the velocity of light ! This distance then sets a natural limit to the observable universe, for a ray of light leaving a system receding with the velocity of light will never reach us, i.e., we shall never be able to observe it. However, there is considerable doubt on the interpretation of the red shift in the spectra of the galaxies as Doppler effect. We have recorded this surprising observation here as it has a profound effect on the theories of the origin of universe called cosmological theories.

Cosmological Theories

We can straight away answer the following question: Is the universe bounded or does it extend infinitely ? Apparently, the answer should be that the universe is unbounded. For otherwise, if the universe is bounded by a surface, the surface divides the space into two parts: the inner and the outer. Hence, if the universe is bounded, the question arises: what is outside the boundary of the universe ?

At present, there are, effectively, two theories about the origin of the universe: (*i*) the Evolutionary Theory and (*ii*) the Steady State Theory.

(*i*) *The Evolutionary Theory.* This theory is an outcome of Einstein's General Theory of Relativity, and the form which is at present in vogue was developed by Abbe Georges Lemaitre. According to this theory the universe evolved by a single act of creation from a primeval atom which contained the entire matter which forms the universe today. This atom must have consisted of a high concentration of protons and neutrons and was perhaps of a size not larger than the present size of the solar system. The matter in the primeval atom must have been highly crushed and in a highly unstable state. Consequently, the atom exploded with great violence, and radio-active disintegration commenced. After about a thousand million years, this matter occupied space roughly corresponding to as many light years. At that time the material was almost entirely hydrogen gas uniformly distributed throughout this space. After this stage the matter might have settled down sufficiently for gravitational forces to introduce some degree of stability. During this stage, condensations began to form in the gas, and at some epoch, which the theory is unable to predict exactly, it is believed that the condensations developed into galaxies. The galaxies would be subjected to a repulsion represented by the cosmic constant in Einstein's equation so that they would recede from one another with speeds proportional to their mutual distances in accordance with the observed red shift interpreted as the Doppler effect.

On this theory, we must expect that the clustering of galaxies will increase as we recede further and further into space since these regions of the universe are considerably younger than our own immediate neighbouring galaxies and have not yet had time to undergo the same large dispersion. This statement, that the galaxies which we observe farther off are younger, requires some explanation. Suppose we make an observation on a galaxy which is 1000 million light years away from us. It is clear that we are observing the light which started from this galaxy 1000 million years ago when the universe was comparatively younger and hence more packed. Thus a comparison between the near and far galaxies amounts to a comparison of the present-day physical conditions with those at an earlier stage in the evolution of the universe, when the galaxies were younger and more highly packed. Thus, if the observations show such a clustering of faint galaxies, the evolutionary theory will get support. This fact is exhibited in Figure 6·12 schematically. It is necessary to mention the paradox about the age of the universe that this theory introduces. If all the galaxies started from a single point, an event which is highly improbable, we can easily calculate, noting the distances of the faintest galaxies and using the fact that their velocities are proportional to their distances at all stages, that the age of the universe is roughly one billion years. In contradiction to this, the geological evidence shows that our earth is twice as old as the age of the universe ! This paradox again throws doubt on the interpretation that the observed red shift is due to Doppler effect but then the question arises: if the red shift does not arise from the Doppler effect, then what is it due to ?

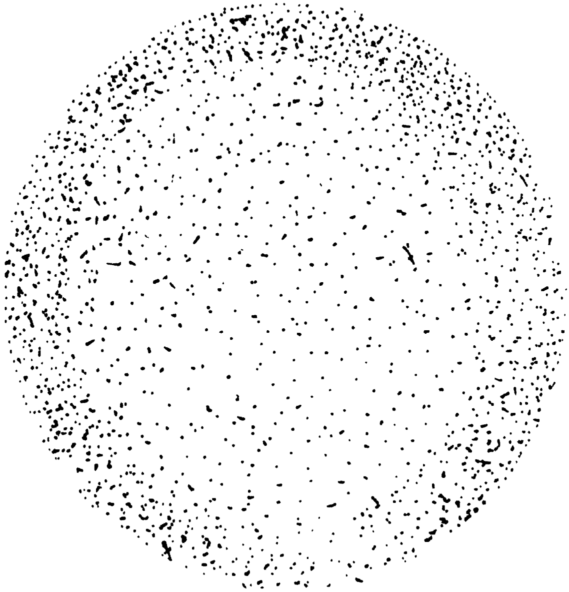


FIG. 6.12 *Distribution of galaxies on the evolutionary theory, with the observer at the centre, the dots represent the galaxies.*

(ii) Steady State Theory. The British Scientists, Fred Hoyle, H. Bondi, T. Gold and W. H. McCrea have proposed an alternate theory called the Steady State Theory. This theory appears aesthetically more satisfying but has its own difficulties.

As in the Evolutionary Theory, in this theory, too, it is assumed that the galaxies recede beyond the observable horizon but at each instant the universe presents the same aspect because new galaxies are formed to take their place. Moreover, the universe has no beginning and can have no end. To maintain this steady state, it is postulated that matter, in the form of protons, is being continually created at the rate of about one proton per cubic mile per year. This appears to be a small rate but is enormous when we consider the entire visible universe, and it amounts to about 10^{18} tons per second !

On this theory, it is clear that the average age and separation of the galaxies will not depend on their distance from us. Thus, the Steady State Theory predicts uniformity against the clustering of galaxies far off from us. We can check the merit of these two theories only when we have a reliable count of the nearby galaxies and the distant, faint galaxies. In spite of a considerable effort on the part of astronomers with optical and radio telescopes, no decision could be made so far in favour of one theory or the other.

We wish to close this section on the optimistic note that with our more refined means of observation and with the possibility of manned explorations into space in the near future, we shall be able to unfold those mysteries of the universe which are baffling us today !

CHAPTER VII

Interstellar Gas and Dust

WHEN we look at the sky on a clear night, we see innumerable shining dots having fixed positions relative to each other. These are the stars belonging to the galaxy to which our sun, and hence necessarily our earth also, belongs. If we examine the figures of galaxies given in the preceding chapter carefully, we shall not fail to notice innumerable stars in their outer parts, specially in the spiral arms. The central parts of the galaxies also contain numerous stars but they are situated so close to each other that our telescopes are unable to resolve them into separate stars. Are these stars hanging in vacuum, or is the space between them (interstellar space) filled with some form of matter ? Observations indicate that in general the stars are embedded in an extremely rarefied gaseous medium (more or less nearing vacuum). Sometimes, the interstellar space also contains extremely minute particles of solids, popularly called the 'interstellar dust' suspended in the gas. In the present chapter we shall discuss important questions about interstellar gas and dust and defer the discussion of stars to a subsequent chapter. Before we proceed to discuss these questions, we would like to point out that most of our information about the interstellar gas and dust depends on the observations relating to our own galaxy (see the following chapter). The extragalactic systems are so far off that they are not amenable to detailed observation.

Interstellar Gas

(*a*) *Chemical Composition.* Interstellar gas is detected through the dark absorption lines (Fraunhofer lines) it produces in the spectrum of the distant stars. The stars generally emit radiation in all wave lengths. The cooler gases in their atmospheres absorb their characteristic wave lengths according to the well known laws of spectroscopy discussed in Chapter II. It is generally difficult to say whether the Fraunhofer lines present in the spectrum of a star are due to absorption in its atmoshpere or in the interstellar gas. This is particularly true for the elements sodium and calcium. However, in the atmospheres of very hot stars, the sodium and calcium atoms are more or less completely inoized and hence they cease to be an important source of absorption. Therefore, if in the spectra of very hot stars, the characteristic absorption lines of sodium and calcium are present, the conclusion that the interstellar gas contains these elements is justified. Such observations have proved beyond doubt that the interstellar gas contains sodium and calcium atoms.

The observations of T. Durham at Mount Wilson Observatory revealed the existence of patches of hydrogen with temperatures of the order of 10,000° K in the interstellar gas. The concentration of hydrogen atoms in these patches was about a million times greater than the concentrations of sodium and calcium atoms. This established the presence of hydrogen in the interstellar gas. But such hot patches of hydrogen are rare and most of the interstellar gas is very cool with a temperature around 100° K. Optical means fail to detect the presence of cool neutral hydrogen atoms. However, as pointed out in Chapter IV, a neutral hydrogen atom does emit a spectral line in the wave length close to 21 cm. This emission falls in the radio waveband and hence can be detected by a radio telescope. Thus, what could not be achieved by an optical telescope has been achieved by a radio telescope. The presence of the compounds of hydrogen and of other elements can be detected by their characteristic absorption lines.

On the basis of these optical and radio observations we can say with certainty that the interstellar gas contains the following:

(*i*) neutral sodium, calcium, potassium and iron
(*ii*) ionized calcium and titanium
(*iii*) molecules of CN (Cyanogen), CH (mythelidene) and CH^+
(*iv*) hydrogen.

Hydrogen is overwhelmingly the most abundant element in the interstellar gas by a factor of 100,000 or so.

(*b*) *Density of Interstellar Gas.* The average density of the interstellar gas lies between 10^{-24} to 10^{-22} g/cc. Talking in terms of atoms, it amounts to about 1 to 100 atoms/cc. These densities are about a ten thousand millionth part of the densities obtainable in the most perfect vacuum that can be produced in the laboratories. Thus, by laboratory standards, more or less a vacuum prevails between the stars. However, we shall presently see how fascinating a phenomenon these few atoms, present in every cubic centimetre of the interstellar space, can produce.

No doubt, the average density of the interstellar gas is fantastically low; yet, in view of the enormous space it occupies, it is surmised that its total mass in a galaxy is comparable to the total mass of the stars present in it.

(*c*) *Phenomenon of Nebula.* The interstellar gas in patches is found to shine with fascinating hues. These shining aggregations of interstellar gas are called the nebulæ. We shall now answer the question: what makes a nebula shine ? If we analyse the observed nebulæ carefully, we find that in general there are four causes which make the interstellar gas radiate.

(*i*) *Radiation from a Star or a Group of Stars.* Observations reveal that in

FIG. 7.1 *Great nebula in Orion*

the case of most of the nebulæ there is a very hot star or a group of very hot stars embedded in them. The atoms of the surrounding gas remain submerged in the radiation of these stars at all times. According to the well known laws of atomic physics, the electrons in these atoms absorb fixed quanta of energy and go over to higher energy levels. The electrons in these levels are unstable and consequently jump down to lower energy levels. In this process, absorption and emission continue at all times and the gas shines by the radiation it emits. Figure 7·1 shows the Great nebula in Orion. A group of hot stars makes it shine.

(*ii*) *Collision between Dust Clouds.* Sometimes, when dust clouds collide, the temperature at the interface between these clouds is increased so much that it begins to glow.

Figure 7·2 shows the Horse-head nebula in Orion, which is made luminous

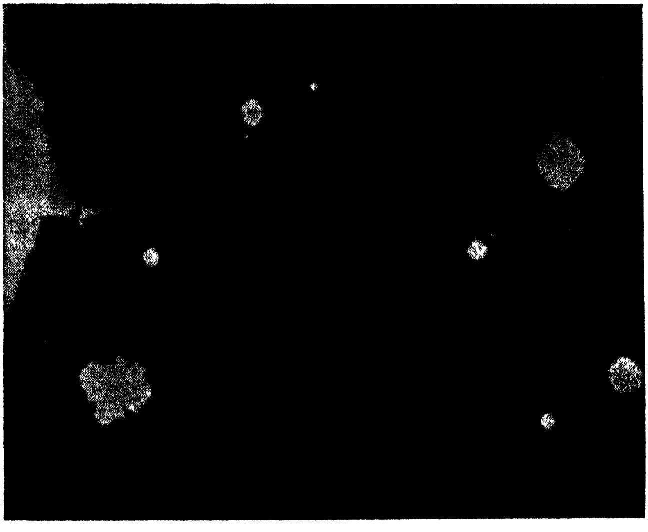


FIG. 7.2 *Horse-head nebula in Orion. Note the shining interface between the two colliding clouds in the middle of the plate.*

by the collision of two dust clouds. The interface is clearly visible in the figure.

(*iii*) *Collision between the Flying Layers of Nebula*. Figure 7·3 gives the Crab nebula. It represents the debris of a high stellar explosion. The gases are

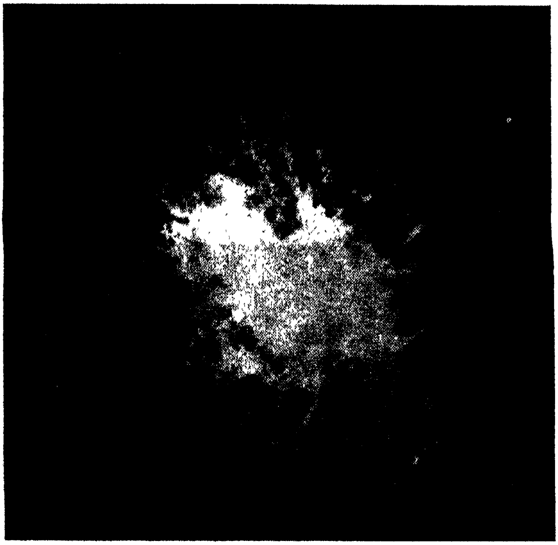


FIG. 7.3 *Crab nebula*

made to shine by the collision among the flying layers of matter, though a hot central star also produces some luminosity.

Figure 7·4 shows the Veil nebula in Cygnus. This is the debris of the star that exploded some 50,000 years ago. The initial velocity of the gases is estimated to be about 5000 miles/sec. The present velocity of the gas is about 175 miles/sec. This slowing down of the velocity has resulted from the collision between the atoms. This also suggests that when the velocities get sufficiently low the nebula will cease to shine.

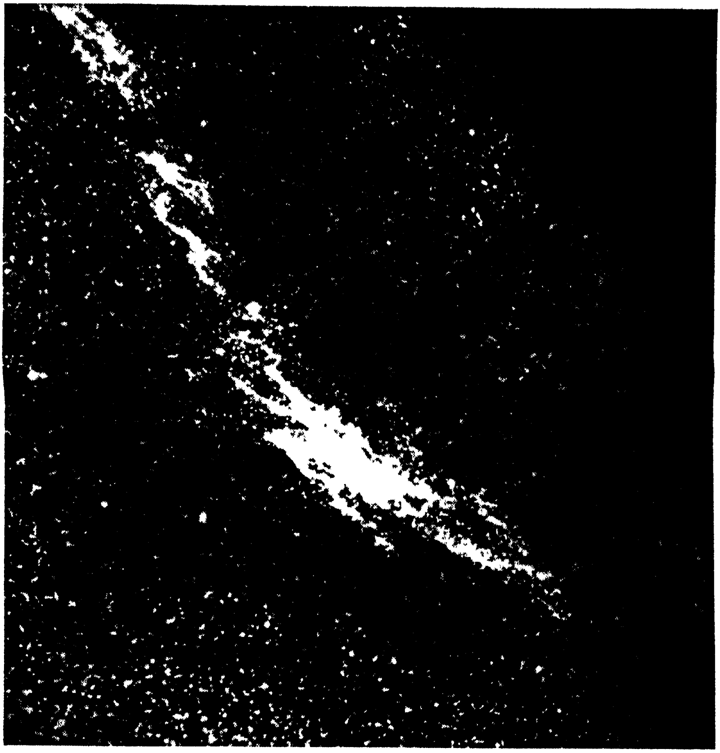


FIG. 7.4 *Veil nebula in Cygnus*

(*iv*) *Ring nebula.* Figure 7·5 shows the Ring nebula in Lyra. It is perhaps the product of a mild stellar explosion. The gases that have come out of the central star shine by the radiation from the central star itself which is extremely hot. The central star appears as a dot in the centre.

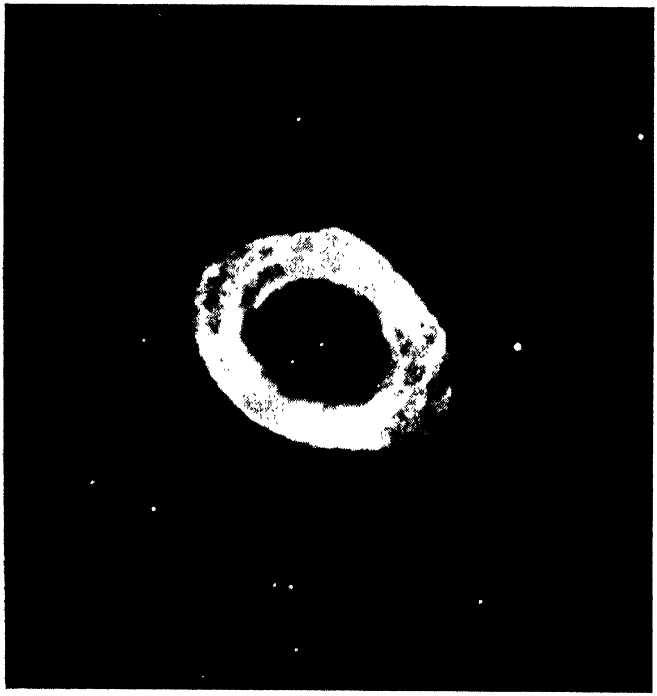


FIG. 7.5 *Ring nebula in Lyra. The white dot at the centre represents the star.*

Interstellar Dust

(*a*) *Evidence for the Existence of Interstellar Dust.* We have already pointed out that the atoms absorb light in their characteristic wave lengths. They also scatter light, i.e., change the direction of the radiation falling on them in a random

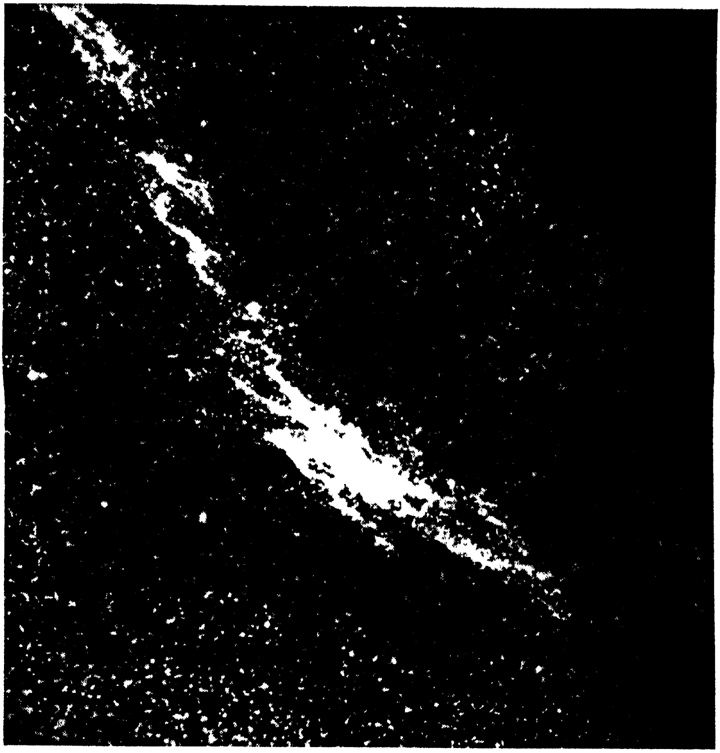


FIG. 7.4 *Veil nebula in Cygnus*

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However, on account of its enormous distance from us, even the 200-inch telescope is unable to resolve the stars separately except for the extremely big stars called the supergiants. In the photograph shown below, the dark central strip represents the interstellar dust.

FIG. 7.6 *NGC* 4565. *Mark the central dark strip representing the interstellar dust. The galaxy is in fact a spiral galaxy viewed from the edge-on position.*

Figure 7.7 shows NGC 147 which is an elliptical galaxy in the Andromeda constellation and is one out of a group of fifteen galaxies. It contains a large number of bright and faint stars but no gas and no dust.

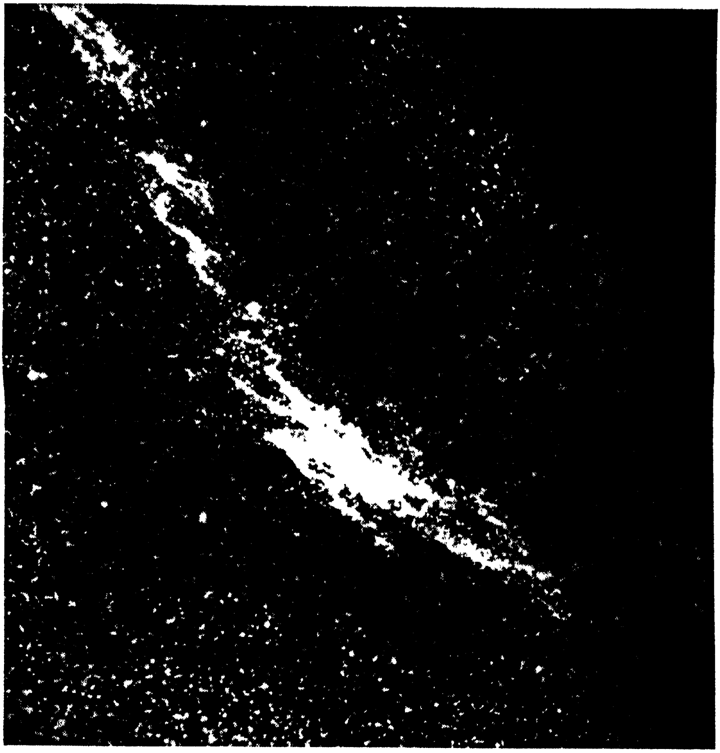

FIG. 7.4 *Veil nebula in Cygnus*

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CHAPTER VIII

Our Galaxy and Stellar Systems

EVEN the nearest galaxy is so far off that even the biggest telescopes are unable to show up the stars, except the very bright ones individually. Consequently, in discussing the stars and stellar clusters, we have to confine ourselves mostly to our own galaxy. Even in our own galaxy the stars are situated so far from the earth that all of them, with the exception of the sun, give point images. Therefore, we cannot say anything about the surface features of these stars. The best we can do is to study our sun as thoroughly as our means allow and then surmise about the conditions prevailing on the surfaces of other similar stars. We shall, therefore, start this chapter with a description of our galaxy, and then deal with stellar clusters. We shall take up the detailed discussion of the stars in the next chapter.

The Milky Way

If, on a clear night when there is no moon, we look at the sky, we see a broad belt of faint luminous haze which extends in the sky from horizon to horizon and whose width varies from 45° to less than 5° (Figure 8·1). It extends even to the invisible part of the sky and, in fact, encircles it. This is popularly known as the Milky Way. The bright stars which are conspicuous to the naked eye are concentrated towards the Milky Way. In fact, all the stars which we see and about a hundred thousand million (10^{11}) other stars, which we cannot see without the help of a powerful telescope, belong to our galaxy. Our sun is just one ordinary member of this galaxy.

Shape and Size of our Galaxy. Since we belong to this galaxy, we cannot look at it as a whole as an outsider could. Hence it is impossible to know its true shape through optical means. Besides, we are situated near a periphery in a spiral arm. Our galaxy also contains interstellar dust which is most effective in obscuring our view precisely towards the centre of the galaxy, a direction in which we must look if we wish to know about its structure. However, the

FIG. 8.1 *The Milky Way. This photograph has been taken in South Africa with a wide-angle camera. The bright patch on the left, below the shadowy outline of the plate holder, represents the largest and brightest star clusters. These clusters lie about* 30,000 *l.y. from us, towards the galactic centre. Mark the dark patches representing the obscuring interstellar dust. Near the righthand bottom periphery, the two white spots represent the Magellanic clouds.*

most sensitive instruments, specially the radio telescopes, have revealed that our galaxy is a spiral galaxy of type S_b, like M 101 in the Ursa Major constellation. Moreover, it is not spherical but is a flattened system resembling a bun (Figure 8.2). Its diameter is about sixty times its average thickness.

According to the latest investigations, the diameter of our galaxy is about 150,000 l.y. and the maximum thickness is about 20,000 light years. The sun is

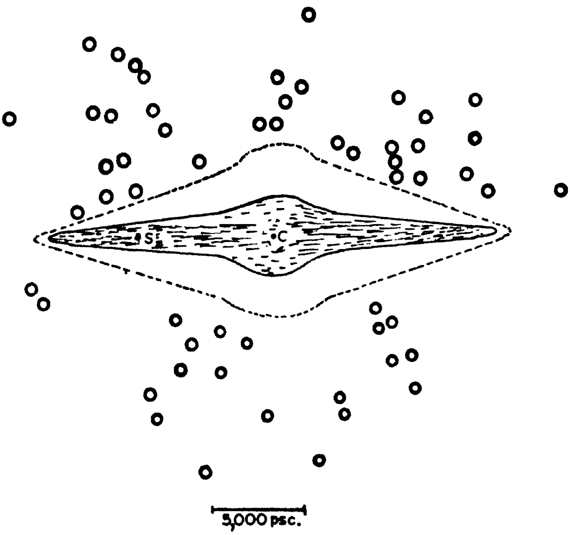

FIG. 8.2 *Schematic representation of our galaxy*
C = *centre of the galaxy*
S = *the sun*
O = *gloubular clusters*
:.:..:: = *obscuring dust*
· ·· · = *extreme limit of the star systems*
——— = *extreme limit of the obscuring dust*

not in the centre, nor is it in the thickest part, as we might expect our sun to be! It is about 30,000 light years distant from the centre of the galaxy, in one of the spiral arms.

Rotation of the Galaxy. Observations lead to the definite conclusion that our galaxy is rotating about the axis perpendicular to the galactic plane (i.e., the mid-plane of our galaxy) passing through the centre. The most convincing evidence of the rotation of the galaxy is provided by the relative motion of the stars nearer and farther than the sun from the galactic centre. The sun is overtaken and left behind by the first group of stars and leaves behind the second group of stars (Figure 8·3). We, therefore, conclude that the galaxy rotates about the central axis. Also, it does not rotate as a whole like the wheel of a cart. The angular velocity of the stars depends on their mean distance from the centre of mass of the galaxy. It decreases as we move farther and farther away from the centre. It is estimated that the velocity of the stars in the neighbourhood of the sun is about 170 miles/sec, and that they complete a round of the centre of galaxy in about 225 million years : This rotation is also the cause of the flattened shape of the galaxy instead of the perfect form, namely, the spherical.

Do other galaxies also rotate ? Yes, observations indicate that all the observed galaxies are in rotation.

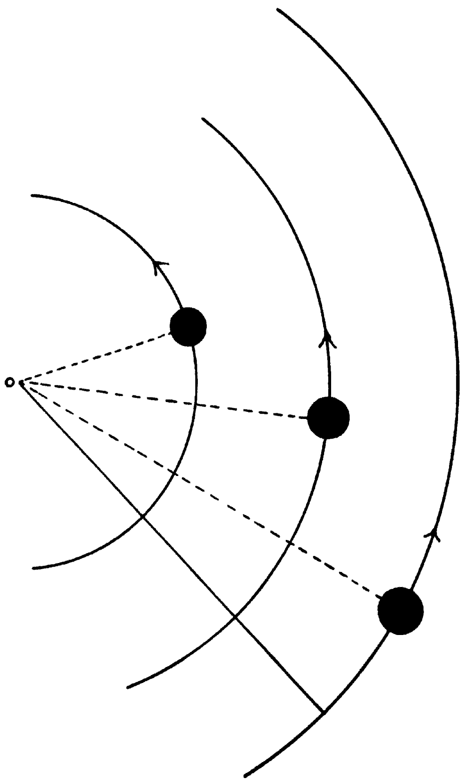

FIG. 8.3 *Differential rotation of a galaxy*

Number of Stars and Mass of the Galaxy. As we have already pointed out, a galaxy of the size of our galaxy, contains about a hundred thousand million (10^{11}) stars and it is also believed that nearly half of the matter of a galaxy is in the form of stars and half in the form of gas and dust. This means that a galaxy has the mass of the order of the combined mass of two hundred thousand million suns. We shall later learn that the mass of our sun is 2×10^{33} grammes or approximately 2×10^{27} tons ! From this we can imagine what enormous quantities of matter the galaxies contain.

Star Clusters

In certain parts of the sky, stars show a tendency to collect together. We are using the phrase 'collect together' in relation to cosmic dimensions. These dense regions of stars are called clusters. Our galaxy contains many such clusters out of which the following two types are very distinct and well marked: (*a*) Galactic clusters and (*b*) Globular clusters.

(*a*) *Galactic Clusters.* They derive their name from the fact that they tend to lie near the galactic plane. The stars in these clusters are loosely distributed so that a telescope shows them separately in a distinguishable form. In the case of some galactic clusters we can see the stars even with a naked eye. The following are the well known galactic clusters which can be seen without the aid of a telescope.

1 *Hyades.* The Hyades cluster (Figure 8 4) is in the constellation of Taurus and is nearest to us. Its distance from us is nearly 130 light years.

This cluster has at least 150 stars which appear to be unrelated with each other from their positions. However, if we consider their proper motions, they all appear to converge towards a point east of Betelgeuse, and it is in this sense that it forms a cluster. The brightest star in Figure 8·4 represents Aldebaran which does not belong to the cluster as it has an independent proper motion of its own.

2 *Pleiades.* The Pleiades (Figure 8·5) cluster also lies in the constellation of Taurus. It contains hot stars and illuminates a nebula and hence we conclude that the space between its stars is filled with gas. Hyades, on the other hand, contains comparatively cooler stars and does not illuminate any nebula.

FIG. 8.4 *The Hyades cluster*

3 The double cluster in Perseus and Praesepe in Cancer and some other clusters appear as foggy patches to the naked eye and are resolved into stars with a slight optical aid.

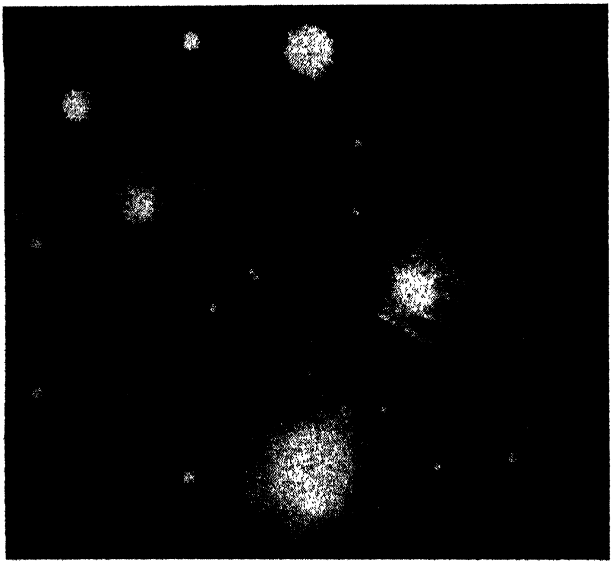

FIG. 8.5 *The Pleiades. It is one of the nearer galactic star clusters about 5,000 l.y. from us. The stars produce extended images due to the reflection of their light from the nearby dust clouds.*

Number of Galactic clusters. In addition to those mentioned above there is a large number of galactic clusters which are invisible to the naked eye. So far about 400 galactic clusters have been listed. Their actual number must be much bigger than this as, on account of dust clouds in the Milky Way, we can probe only up to about 20,000 light years towards the centre, a direction in which we expect them to occur in abundance.

Number of Stars in a Galactic Cluster. Each cluster may contain from less than 20 to a few thousand stars as in the Perseus cluster.

(*b*) *Globular Cluster.* As their name implies, globular clusters are spherical in shape. They lie away from the galactic plane in contrast to galactic clusters.

Each cluster consists of thousands of stars which are collected more densely at the centre than at the periphery. For the observers in middle northern latitudes, the best known globular cluster, faintly visible to the naked eye, is the great cluster in Hercules (Figure 8·6).

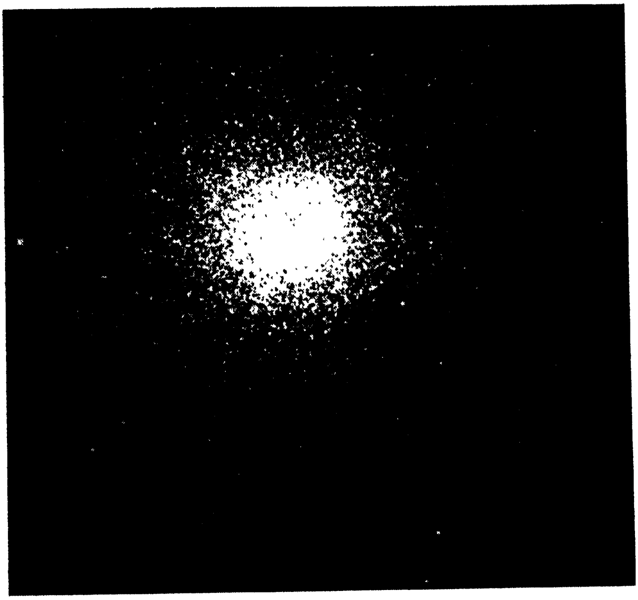

FIG. 8.6 *The globular cluster in Hercules. The central spherical white patch represents innumerable stars situated close to each other. Note that there is no obscuring dust in the cluster.*

We need the help of a telescope to realize that the following four stellar systems are also globular clusters:

1. M 22 in Sagittarius
2. M 55 in Sagittarius

3. M 3 in Canes Venatici
4. M 5 in Serpens

An observer in southern latitudes can see the following globular clusters with the naked eye.

1. OMEGA CENTAURI which is situated near the northern edge of the Milky Way in the vicinity of the Southern Cross.

2. 47 TUCANE which is situated west of the small Magellanic cloud, only 17° from the south celestial pole.

These clusters are the brightest. The nearest globular clusters are situated at a distance of about 22,000 light years.

(*a*) *Number of Observed Globular Clusters.* So far about 100 globular clusters have been recorded in our galaxy.

(*b*) *Structure of the Globular Clusters.* The greater part of a globular cluster is contained within a sphere of radius of about 50 light years. The most congested part, where the stars run together in the photographs, lies within a sphere of radius of about 15 light years.

(*c*) *Number of Stars in a Globular Cluster.* Any one of the nearest globular clusters contains at least fifty thousand stars bright enough to be observed. These are giant stars and very hot blue stars of the main sequence (Chapter IX).

(*d*) *Gas and Dust in Globular Clusters.* The globular clusters, in contrast to galactic clusters, contain little or no gas and dust. The stars in the globular clusters show high velocities of dispersion in comparison with the stars in galactic clusters, and form stable spherical systems. Besides, the spectra of the stars in these two systems suggest that the galactic clusters are young and hot showing metallic lines, while the globular clusters are old and comparatively cool showing weak metallic lines, CN bands and strong CH bands. This conclusion finds support from the locations of these two systems. Perhaps, the globular clusters were also formed in the galactic plane which is rich in gas and dust at a stage when this material was in high turbulent state. Subsequently, they moved away from the plane. The turbulent motion of the matter diminished as time passed so that the subsequent generations of stars possessed velocities in decreasing order.

Magnetic Field in our Galaxy

Our galaxy has a weak magnetic field of the order of 10^{-5} gauss, i.e., about hundred-thousandth of the magnetic field at the surface of the earth. We have no optical means of detecting such a feeble field, but there are some indirect evidences which suggest the existence of such a field. We give below just a few of them:

(*i*) The light from many distant stars is found to be plane-polarized. Since this effect is present in the light from stars of diverse types, its origin must be interstellar. Moreover, such a widespread effect can be produced only by a magnetic field which is capable of orienting the elongated ferro-magnetic grains present in the interstellar space along its lines of force.

(*ii*) Our galaxy is an extended radio source. Explanation of the emission of these radio waves requires the existence of magnetic field of this order.

(*iii*) As mentioned earlier, our galaxy has spiral arms, which are subjected to the gravitational attraction of its nucleus. Moreover, the gas present in these arms tends to expand and dissipate away. The stability of the spiral arms requires some widespread mechanism to balance these disruptive forces. We cannot think of any mechanism other than the magnetic field.

Distribution of Hydrogen in our Galaxy

Hydrogen is the most abundant element in our galaxy. As pointed out earlier, the ionized hydrogen can be detected optically through its thermal radiations. The neutral hydrogen can only be detected through its non-thermal radiation in 21.1 cm wave length by a radio telescope.

There are two very active groups working on the radio emissions from our galaxy at 21.1 cm wave length, one in the northern hemisphere at Leiden (Holland) and the other in the southern hemisphere at Sydney (Australia). Their observations put together show that about 2 per cent of the total mass of our galaxy is in the form of neutral hydrogen. Besides, the study of the distribution of the neutral hydrogen has established, beyond doubt, the spiral structure of our galaxy. This discovery is indeed one of the most remarkable achievements of the past half century !

CHAPTER IX

Stars

What Do We Mean by a Star ?

We can roughly describe stars in the following manner: Stars are huge, more or less spherical masses of glowing gases, some large and some small, some hot and some comparatively cooler, each held together by its own gravity and producing within itself a large amount of radiant energy which it pours out into space. We emphasize that the ability to emit energy is the characteristic property of a star. In fact, we see a star in the light it emits. Our sun is an example of a star. It is, of course, a very average type of star, having nothing spectacular about it. The main importance of the sun from the point of view of scientific study, as we pointed out earlier, is that it presents a disc image on a photographic plate on account of its nearness to us and hence we can study the details of its surface phenomena. This study helps us in surmising about the conditions prevailing on stars similar to our sun. We shall discuss our sun in detail shortly. But, before we do so, we shall take up some general questions about the stars.

Important Types of Stars.

(*a*) *Double and Multiple Stars.* In a galaxy there are very few single stars like our sun. According to recent estimates about 80 per cent of the stars are either double stars or multiple stars. By a double (or binary) star we mean a pair of stars moving round their common centre of gravity in stable equilibrium.

(i) VISUAL BINARY. A binary should be distinguished from a pair of stars lying very close to the line of sight that appear to move together as if physically linked with each other. But these stars are, in fact, so far off from each other that they are not affected by their mutual gravitation and hence they will retain the same positions relative to the line of sight. A visual binary, whose components can be seen separately with the help of a telescope, on the other hand, will present a different phenomenon. Its components will appear to change periodically their positions relative to the line of sight. By noting their positions relative to the line of sight and the distant stars forming the stationary background at various epochs, it is possible to construct their orbits and determine their period of revolution. The orbit of a binary whose orbital plane is perpendicular to the line of sight will be easily constructed by this method. If the line of sight lies in the orbital plane this method will fail.

The pole star is a visual binary, so is Sirius, the dog star.

(ii) ECLIPSING BINARY. Often the components of a binary star are so close to each other that even the most powerful telescope is unable to show them separately. We have then to use some indirect evidence to establish that a given star is really a binary. In some cases, if we plot the intensity of radiation against time, we notice regular periodic fluctuations. Such stars are called eclipsing binaries as the light fluctuations are produced by the periodic eclipsing of one component by the other. This method will be effective if the line of sight lies in the orbital plane of the components of a binary. The star

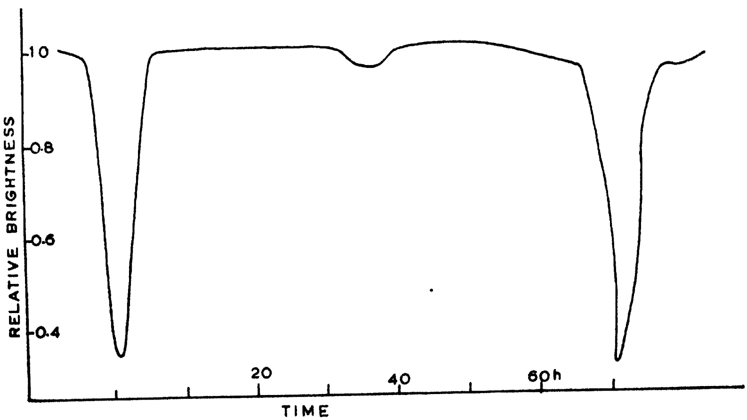

FIG. 9.1 *A section of the light curve for the typical eclipsing binary β Persei (Algol) with period* 69 *hours*

CHAPTER IX

Stars

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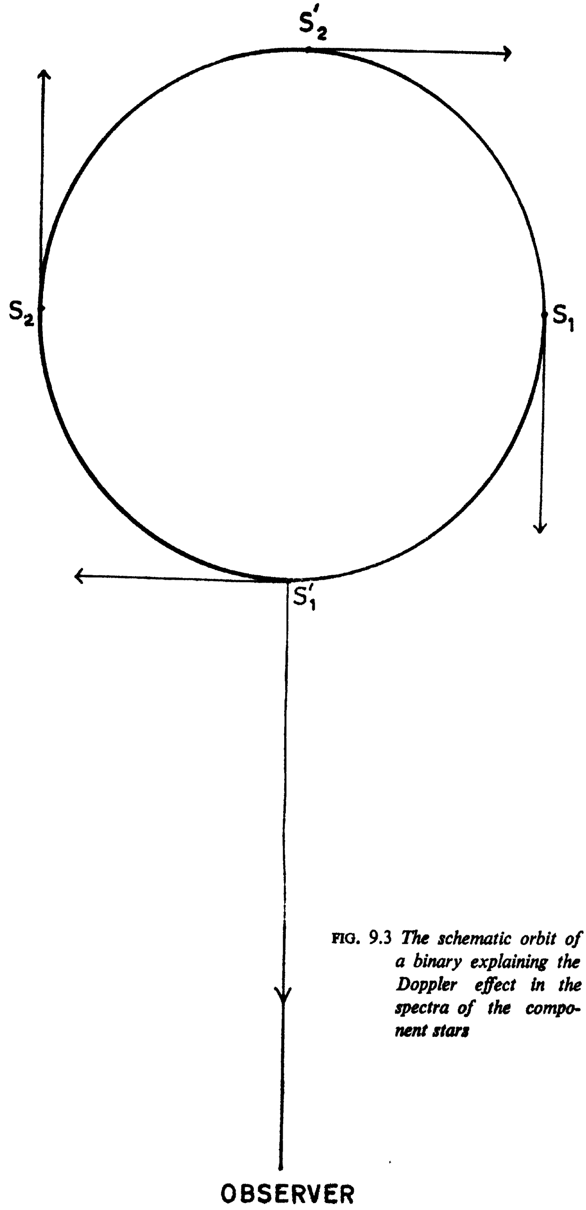

FIG. 9.3 *The schematic orbit of a binary explaining the Doppler effect in the spectra of the component stars*

We can explain the light curve in Figure 9.1 in the following manner. Usually one of the components (secondary) of the binary is much less massive than the other (primary). Later we shall learn that the larger the mass, the brighter is the star, so that the primary is more luminous than the secondary. In the primary eclipse, a portion of the much brighter surface of the primary is hidden behind the fainter secondary (S_1) so that the drop in brightness is very pronounced (Figure 9.2). In the secondary eclipse, the fainter body (S_2) is hidden behind the primary, so that the drop in brightness is very little.

(iii) SPECTROSCOPIC BINARIES. In some cases the binaries can only be detected through the study of the spectrum. Such binaries are called spectroscopic binaries. Let us consider a binary whose orbital plane is not at right angles to the line of sight. Due to the motion of the components around their common centre of gravity, they revolve round each other. This motion due to their closeness cannot be telescopically detected. Let us consider their spectrum which will contain the contributions of both the stars. When one star of a binary (S_1) is moving towards the observer the other (S_2) is receding from him as shown in Figure 9.3. The spectrum lines of the first are displaced towards the violet end of the spectrum, while that of the second towards the red end. At this epoch the common spectrum lines are doubled. After a quarter period of a revolution, neither star (S'_1 or S'_2) possesses any velocity in the direction of sight, so that the lines produced by both are superimposed. After another quarter period, the first star will be receding from the observer and the second star will be approaching him. Once again the lines will appear as double but in reverse order. These considerations will establish decisively whether a given star is a spectroscopic binary or not. Mizar in Ursa Major is a spectroscopic binary.

(*b*) *Intrinsically Variable Stars.* An intrinsically variable star also shows variation in its apparent brightness but it arises due to real fluctuation in its luminosity, i.e., energy radiated by it per second, and not on account of eclipsing effect. The intrinsic variables are broadly classified as: (*a*) irregular, and (*b*) periodic. If the light curve of an intrinsic variable does not repeat (or nearly repeat) itself regularly, the star is said to be an irregular variable. On the other hand, if the light curve is recurrent with in a certain definite period, the star is said to be periodic. The periodic variables are subdivided into three broad classes from the consideration of the length of the period: (*i*) cluster variables

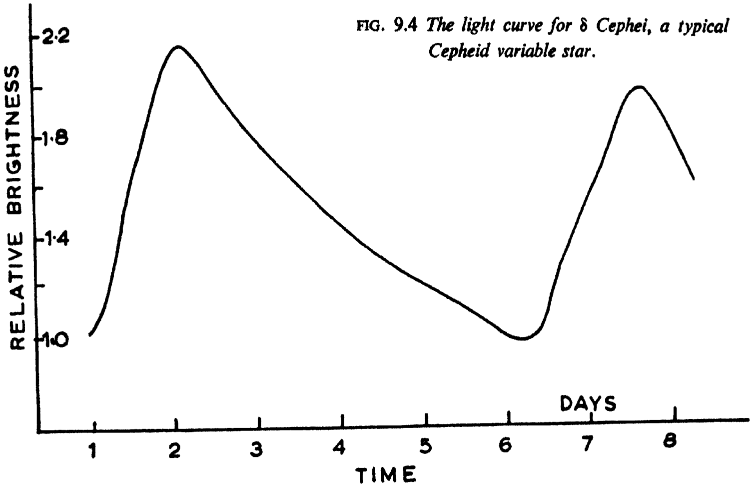

FIG. 9.4 *The light curve for δ Cephei, a typical Cepheid variable star.*

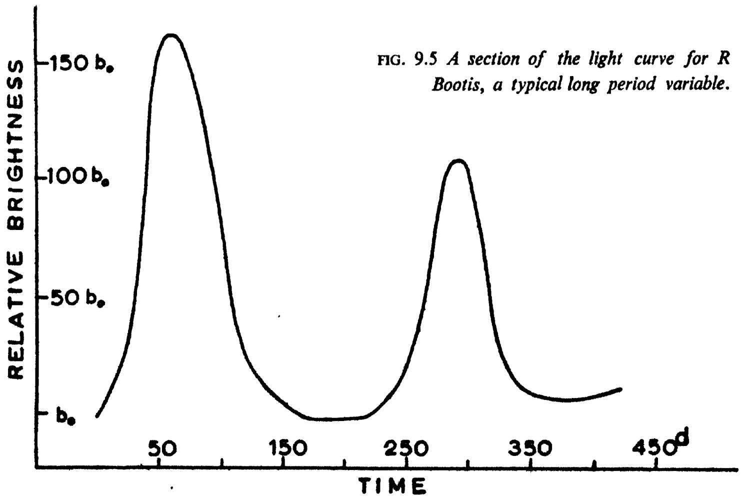

FIG. 9.5 *A section of the light curve for R Bootis, a typical long period variable.*

with periods less than a day; (*ii*) Cepheid variables with periods greater than a day but less than 100 days; (*iii*) long period variables with periods greater than 100 days.

(*i*) The cluster variables were first discovered in globular clusters, and hence the name. A typical example of this class is RR Lyrae with period 0.567 days. At present more than 2000 cluster variables are known. The light curves of these stars resemble more or less the sinusoidal curve and have no intervals of constant brightness as found in the light curves of eclipsing variables.

(*ii*) δ Cephei with period $5^d\ 9^h$ is a typical star of this class. In fact the name of this class is derived from the name of this star. The light curve (Figure 9.4) of this star shows a fairly rapid rise from minimum to maximum brightness and comparatively a much slower decline from maximum to minimum brightness over a period. The magnitude of the star changes from 4.6 to 3.7. The light curves of some Cepheids, like η Aquilae, show humps during decline.

(*iii*) The class of long period variables differs from the previous two classes not only in the matter of period but also in the nature of the light curve. The light curve of a long period variable may show moderate differences between even successive cycles and the intervals between maximum brightness can differ even by a month. Moreover, the apparent brightness of a long period variable may change by a large factor. For example, the apparent brightness of χ Cygni changes by a factor of 4000 during a period. Figure 9.5 gives the light curve for the typical long period variable R Bootis.

(*c*) *Novae and Super-novae.* Occasionally some stars suddenly attain extremely large brightness and then slowly fade away (Figure 9.6). Such stars are called novae or 'new stars'. These are not new stars but are termed as novae due to their sudden coming into prominence from obscurity. Generally, the luminosity of a very faint star during the course of a couple of days shoots up about 100,000 times and then slowly declines. The most brilliant nova appeared in 1572. Tycho Brahe took a large number of observations on it and hence it is named after him as Tycho's Star. At the time of maximum brightness it was visible even in the day. So far slightly more than 100 novae have been recorded. The difference between a nova and a super-nova is only one of scale.

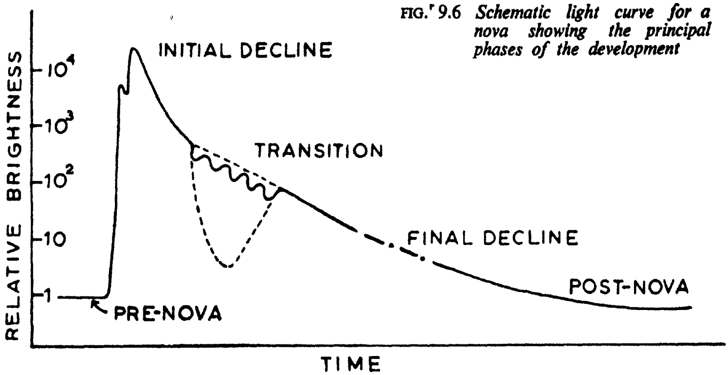

FIG. 9.6 *Schematic light curve for a nova showing the principal phases of the development*

Cepheids

The theory of cepheid variability was proposed by Harlow Shapley and mathematically developed by Sir Arthur Eddington in 1926. According to

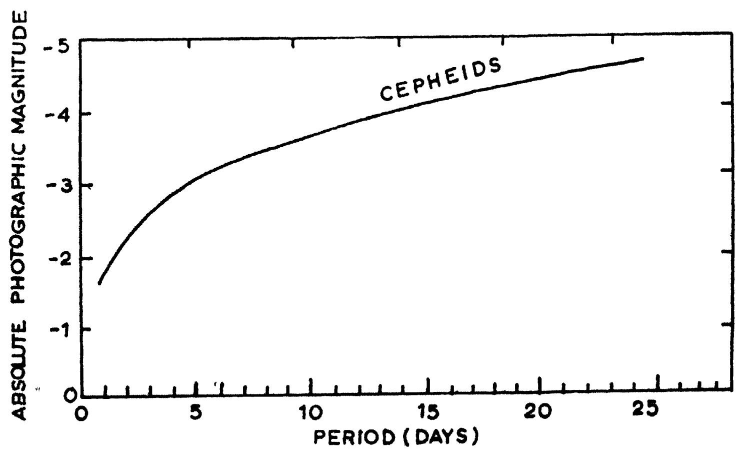

FIG 9.7 *The Period-Absolute Luminosity curve for Cepheid variables*

this theory, the star pulsates like a giant heart, i.e., its radius periodically expands and contracts. During the expansion phase, its radius increases by about 10 per cent of its mean value. However, the pulsation theory does not explain all the facts about the cepheids. The most important property of the cepheids is that their periods are directly related to their absolute luminosities. Figure 9.7 gives the relationship between the period and absolute luminosity for cepheids discovered by Miss Leavitt of Harvard University in 1913. With the help of this relation we can find the distance of a cepheid by measuring its period and apparent brightness I_{app}. Knowing its period we find its absolute brightness I_{abs} from Figure 9.7. Now if we neglect the absorption of radiation in the space intervening between the cepheid and us and if D is the distance of the cepheid, then D is proportional to the square root of the ratio of the absolute and apparent intensities.* Now, if an astronomical system contains cepheid variables we can determine the distance of the cepheids, and hence the approximate distance of the system, by this method. In fact, this method has been used in finding the distances of the galaxies, like the small and large Magellanic clouds, which contain cepheid variables. This fact has earned for the cepheids the title of *Yardstick for the Universe.*

Observational Data for a Star

The two basic observations for a star are its apparent magnitude and spectrum. A third additional datum for a special class of stars is mass.

(*i*) *Mass of a Star.* We can measure the masses of binary stars. As we have pointed out earlier, the binary stars occur in pairs and revolve about their common centre of mass under their mutual gravitational attraction. If we can measure the period T and the maximum separation a, then from Kepler's third law

$$T = \frac{2\pi a^{3/2}}{\sqrt{G(M_1+M_2)}} \text{ so that } M_1+M_2 = \frac{4\pi^2 a^3}{GT^2}$$

The last formula gives the total mass M_1+M_2 of the pair, and if one of them, say M_2, is much smaller than M_1, which is usually the case, we get the mass M_1 of the primary star. This is also the usual method of finding the mass of the

* This fact is demonstrated in the section on the apparent and absolute brightness of a a star, on page 130.

sun using the period of rotation of a planet like the earth, and of the earth or any other planet using the period of rotation of a satellite.

(*ii*) *Distance of Stars.* We generally measure the distance of celestial bodies close to us using the principle of parallax. This method is, in essence, the same as that used by a surveyor in measuring the distance of the places which are not directly accessible to him.

Treating the far-off star X as fixed during half a revolution of the earth around the sun, we measure the inclination of the star to the major axis AA′ of the earth's orbit round the sun at A and A′ (Figure 9·8). Knowing the angles $\angle XA'A$ and $\angle XAA'$, and 2a, the distance d is given by the formula,

$$\frac{d}{2a}=\frac{\sin \angle XAA'}{\sin \angle A'XA}, \text{ where } \angle A'XA=180^\circ-(\angle XA'A+\angle XAA').$$

However, the stars are very far away from us so that the parallax $\angle A'XA$ will be too small to measure with any accuracy. In some cases we can use the cepheid variables to find out approximately the distances of the stellar systems as explained in the section on cepheids.

Parallax is employed to define a practical unit of distance in astronomy. In fact, it is customary to define the parallax of a star with reference to the semi-major axis a of the earth's orbit rather than the major axis 2a as we have done above. Thus, if p radians is the parallax of a star situated at a distance d (measured in the same units as a), then we can prove that $\frac{d}{a}=\frac{1}{p}$, regarding p to be very small. Now a=93,005,000 miles is taken as the astronomical unit (AU) for measuring distances in the solar system. On this scale, d/a measures the distance of the star in astronomical units. Also 1 radian of angle=206, 265 seconds of arc (on the scale π radians=180°), we have the following relation between the distance d of a star in astronomical units and parallax p in seconds of arc:

$$d=\frac{206,265}{p}.$$

With the help of this formula we define another unit of distance called the parsec which is employed in measuring stellar distances. We define parsec as the distance of a star which shows parallax of one second of arc. Thus

$$\begin{aligned} 1 \text{ parsec} &= 206,265 \text{ AU} = 19.2\times10^{12} \text{ miles} \\ &= 3.258 \text{ l.y.} \end{aligned}$$

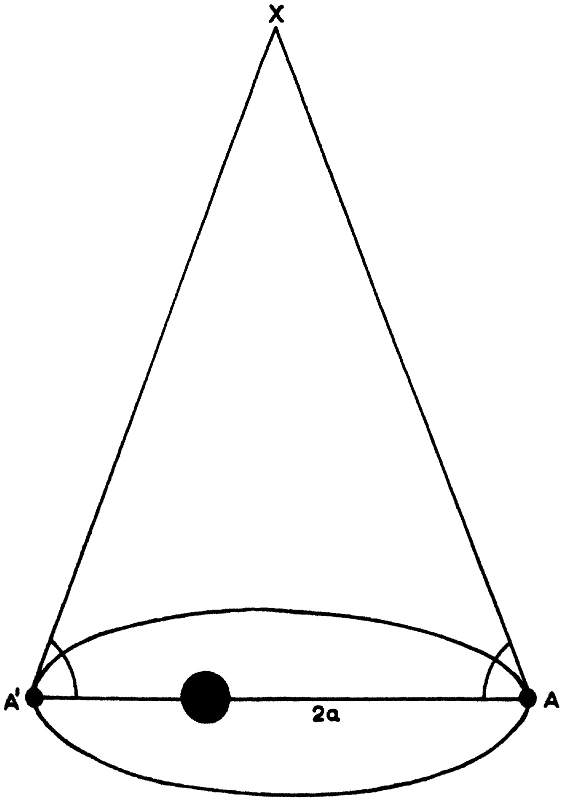

FIG. 9.8 *The Parallax method for determining stellar distances*

(*iii*) *The Apparent and Absolute Brightness of a Star*. An observer measures the apparent brightness of the star, i.e., the energy of radiation received by him per unit area. It is certainly different from its intrinsic brightness, i.e., the energy radiated by its surface per unit area. In defining a relation between the apparent and intrinsic brightness of a star, the distance of the observer should come into consideration as seen below. If R and I be the radius and the intensity of the star, then the total energy radiated by the star $=4\pi R^2 I$. Now let us draw a spherical surface centred at the star and passing through the position of the observer situated at distance d from the star. The energy radiated by the star will spread over the entire surface of this sphere if there is no absorption in the intervening space between the star and the observer. Thus the energy crossing every unit area of this sphere, i.e., the apparent brightness at the position of the observer will be $\frac{4\pi R^2 I}{4\pi d^2}$. Thus the intensity decreases as the square of the reciprocal of the distance of the observer from the star. However, if we are interested only in comparing the intrinsic brightness of two stars, we may compare their absolute brightness defined as the apparent brightness that would be measured by the observer if both the stars were situated at some standard distance, conventionally taken as 10 parsec. In comparing the absolute brightness we have clearly removed the distance factor. From this we can calculate the ratio of their luminosities, i.e., the ratio of the total energies generated inside the stars per unit time.

(*iv*) *Effective Temperature.* If we look at the stars carefully we find that each star shows its characteristic colour. These colours are closely related to their effective temperatures: dull red indicates a fairly cool star; yellow, white, blue indicate progressively higher and higher stellar temperatures. The precise way of determining the stellar temperature is through spectrum analysis.

(*v*) *Spectrum.* The most important observation about a star is its spectrum. This not only indicates the presence of the elements present at the source but also enables us to determine the effective temperature T_e of the source from Wien's law.

The determination of the chemical composition of a star from its spectrum needs some comment. The spectrum indicates the physical conditions prevailing in the outer layers of a star. We can certainly say that an element whose characteristic lines appear in the spectrum must be present in the atmosphere. However, we cannot infer the absence of an element if its characteristic lines are absent in the spectrum. For example, the sun's normal spectrum does not show helium lines but we can infer the presence of helium from the spectrum analysis of some of the hotter stars in the neighbourhood of the sun.

(*vi*) *Radius of a Star.* If we know the luminosity and effective temperature of a star, we can calculate its radius, assuming that it radiates as a black body, with the help of Stefan's Law.

$$L = (4 \pi R^2) . \frac{1}{4} . a c T_e^4 .$$

Analysis of Data

Before we can hope to find some general characteristics of the stars, we

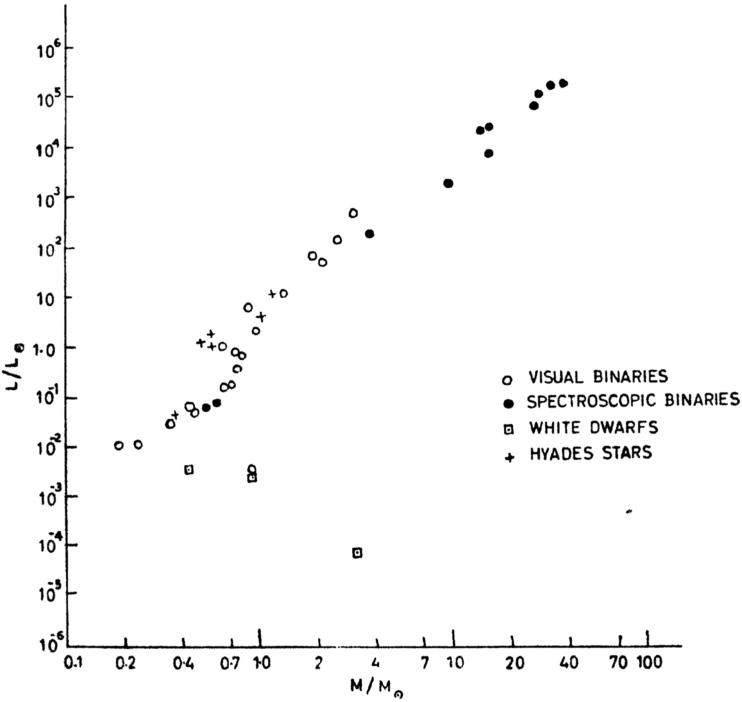

FIG. 9.9 *Mass-luminosity diagram for stars*

must classify the available data about them. It is customary to prepare three plots for this purpose. We shall discuss them one by one.

(*a*) *Mass-luminosity Diagram.* If we plot the luminosities of the stars against their masses (Figure 9·9) we discover the following important facts about the stars:

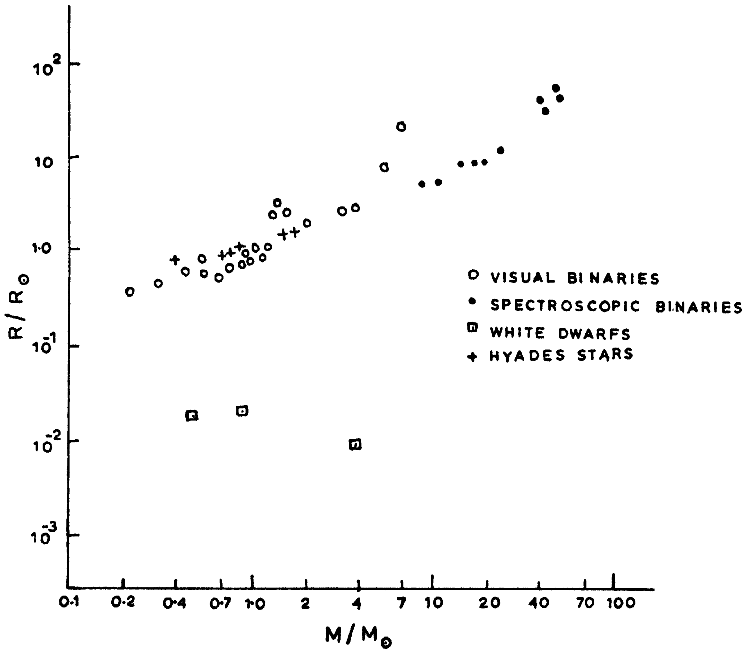

FIG 9.10 *The Mass-radius diagram for stars*

(*i*) For the majority of the stars their luminosity is proportional to the $\frac{7}{2}$ power of their masses. These stars are said to form the main sequence.

(*ii*) There are some stars which are under-luminous when compared with the main sequence stars of the same masses. These are called the white dwarfs.

For example, Sirius B has a mass approximately equal to that of the sun, yet its luminosity is only 3/1000 times the luminosity of the sun.

(*iii*) The observed stars possess masses lying between 1/10th of the solar mass and 45 times the solar mass.

(*b*) *Mass-radius Diagram.* Another important plot about the stars is the one in which the radii of the stars are plotted against their masses (Figure 9·10). This plot again separates out the white dwarfs from the main sequence stars. We find that compared with an average star of the same mass, a white dwarf has much smaller radius and therefore exceedingly high mean density. The following table records mean densities of three well observed white dwarfs:

TABLE I

Star	Mean density (g/cc)
Sirius B	6.8×10^4
O_2 Eridani B	9.1×10^4
Van Maanen 2	6.8×10^6

It is also clear that the radii of these white dwarfs are of the order of 1/100th of the solar radius. On account of their smaller size they are called dwarfs.

From Stefan's law it is clear that if we compare a white dwarf with a main sequence star with the same luminosity, in view of the much smaller radius of the former, it must have much higher effective temperature. This explains why they are called 'white' dwarfs.

(*c*) *Hertzsprung-Russell* (*H.R.*) *Diagram.* For studying the evolution of stars another plot, called the Hertzsprung-Russell diagram, is prepared. Here we plot (Figure 9.11) the absolute visual magnitudes (i.e., luminosities of the stars) against the colour, (i.e., effective temperatures of the stars).

According to the colour, the stars are divided into ten broad classes designated by the letters O, B, A, F, G, K, M, R, N, S in which the effective temperature decreases progressively from O to S. O and B stars are hot enough to heat the interstellar gas around them and produce the H II (ionized hydrogen) regions. All the stars belonging to the same colour class possess like spectra.

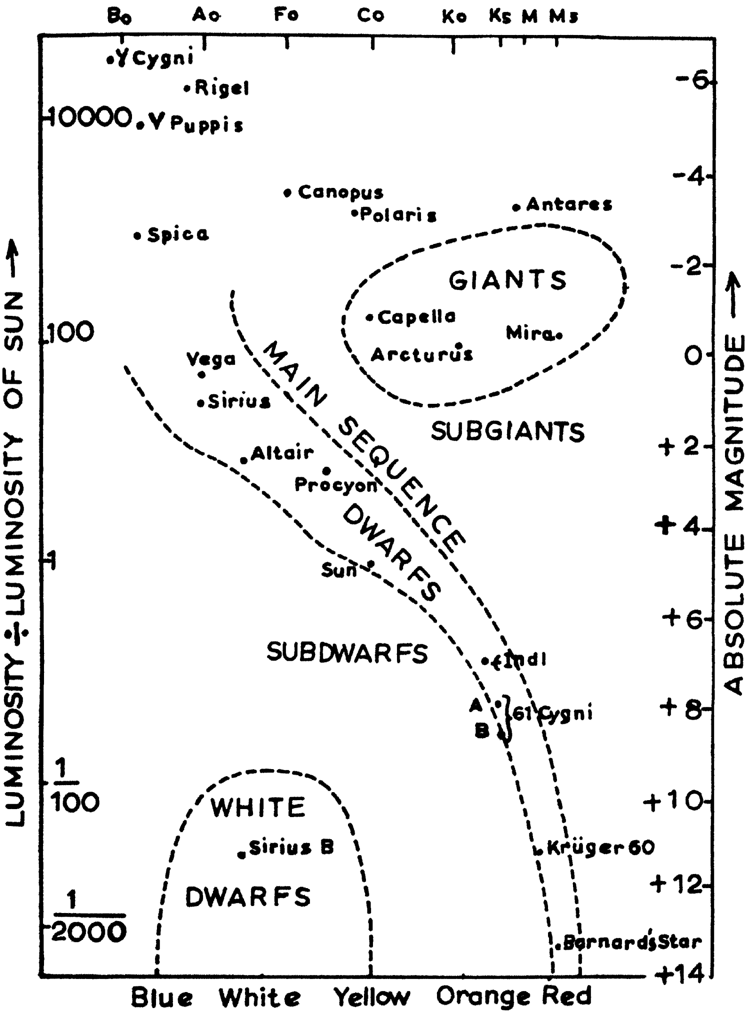

FIG. 9.11 *The Hertzsprung-Russell diagram*

Class B is characterized by the presence of lines of neutral helium, silicon ionized from one to three times, a number of other ionized elements and strong hydrogen lines. In class A, helium lines disappear and characteristic spectrum lines of most of the highly ionized atoms become weaker while the hydrogen lines dominate the spectrum. In class F, hydrogen lines grow weaker and lines of neutral and ionized iron, calcium, sodium, strontium, manganese etc., appear. Class G stars show more and stronger lines of metals, particularly two lines of Ca^+ (singly ionized calcium atoms) designated as H and K lines with wave lengths 3968.492A° (CaI) and 3933.682A° (CaII). The hydrogen lines are less strong than in F class. In class K, the H and K lines become extraordinarily strong; the lines of the metals are stronger than hydrogen lines and for the first time molecular bands appear. In class M, the molecular bands are stronger and the most prominent are those of titanium oxide TiO. Extremely few stars lie in the classes R, N, S and the spectra of these stars are very complicated. We record below some characteristic features of the spectra of these classes:

Type	*Spectral characteristics*
R	Strong CH bands
N	Strong absorption C_2 and CN bands
S	Absorption bands of zirconium oxide (ZiO), Yttrium oxide (YO) and Lanthanum oxide (LaO)

Our sun belongs to class G, its effective temperature being 6000°K.

Through the H.R. diagram we introduce the various classes of the stars and their approximate location: Main sequence, dwarfs, sub-dwarfs, white dwarfs, blue dwarfs, sub-giants, giants, super giants, etc.

We give below the effective temperatures prevailing in various spectral classes:

Type	*Colour*	*Effective Temperature (in °K)*	*Chief spectral characteristics*
O	Blue	25000	Hydrogen, Ionized Helium
B	Blue-white	12000-25000	Hydrogen, Helium
A	White	8000-11000	Hydrogen, Ionized metals
F	Straw	6200- 7800	Ionized metals
G	Yellow	4600- 6000	Ionized and neutral metals
K	Orange	3500- 4900	Neutral metals
M	Red	2600- 3400	Molecules

From Figure 9.11 we find that a great majority of stars lie on a diagonally placed belt which is known as the main sequence. The most luminous stars of the sequence are its hottest stars. In fact, they are most luminous because they are hottest, their diameters being all comparable in size. The sun, Proxima Centauri, the bright companion of Sirius, and Procyon, all belong to main sequence. A small class of stars, which lie above the main sequence, possess greater luminosity than the stars of the same spectral type (i.e., the same effective temperature) in the main sequence stars. This suggests that they are more luminous on account of bigger diameters and consequently these stars are called giant stars. Arcturus is a giant star. A much smaller class of stars which possess much higher luminosities than even the giants is called the super giant class. Super giants are the biggest and most luminous stars known. Rigel, Deneb, Betelgeuse and Antares belong to this class.

All the stars in the main sequence in contrast are called the dwarfs.

We have already discussed the white dwarf class. We note that the stars in each of the above classes show a scatter about their mean lines. This is a very significant fact and presently we shall see that this scatter is due to the difference in chemical composition, specially the abundance of hydrogen and helium.

Constitution of the Stars

The luminosity and spectral class of a star remain unaltered over a considerably long period of time. This shows that each star is in stable equilibrium under its own gravitation over a considerable period of time, i.e., each layer exactly supports the mass lying above it and is supported by the layers lying below it. Besides, each layer should allow as much of radiation to flow through it as would maintain the steady temperature gradient and the star must produce energy at a constant rate. The important parameters about a star are its mass, chemical composition (cc.), radius and luminosity. On general considerations we can show that these quantities are connected by a relation of the type of f (M, R, L, cc.)=0. Thus, given any three of these parameters, the fourth is determined. Consequently, if two stars having the same mass and radius have different luminosities, they will differ in chemical composition etc. This consideration permits us to explain the scatter of the stars about the mean lines in M-L, M-R and the Hertzsprung-Russell diagrams. In essence, the above result is called the Vogt-Russell Theorem. It is easy to understand that such a relation between these four parameters of a star should hold. The mass and chemical composition are prescribed for a star. Thus, if a layer is not in hydrostatic equilibrium with the surrounding layers, the star would either contract or expand and attain such an equilibrium. So the hydrostatic equilibrium prescribes the radius of a star. Again, if the layer does not allow the required amount of energy to pass through it, it will either get heated or cooled, changing the pressure in the layer breaking the hydrostatic equilibrium. Consequently, a star would have to adjust its luminosity and/or radius.

Besides, we shall see later that a star generating energy through thermonuclear reactions burns hydrogen as a fuel and hence its chemical composition goes on altering. Though this change in chemical composition becomes significant only after thousands of years, the star does evolve, slowly and imperceptibly, all the time undergoing change in luminosity and radius as demanded by the Vogt-Russell Theorem.

Evolution of a Star

Without going into details, we may trace the life-history of a star.

Contractional Phase. We shall regard a mass of matter in the interstellar cloud as a star when it is held together under its own gravitational forces. The star continues to contract under its own gravitation. The study of this phase of evolution of a star is clearly a time-dependent, fluid dynamical problem and hence it is extremely complicated. It is, however, evident that a star contracts non-adiabatically as some of the gravitational energy liberated during contraction is radiated away by it and some is used up in heating it. During the contractional phase the entire star is in radiative equilibrium, i.e., the energy is transported by radiation. Also, during this phase, its chemical composition does not alter.

Approach to Main Sequence Stage. When the star arrives near the main sequence stage, it is sufficiently heated for the onset of the thermonuclear reactions involving Proton, Deuteron, Lithium, Beryllium and Boron. In Table 2 we record some of these important reactions:

TABLE 2

	Reaction	Critical Temperature for onset in °K
1. Deuteron:	${}_1D^2+{}_1H^1\rightarrow{}_2He^3$	5.4×10^5
2. Lithium:	${}_3Li^6+{}_1H^1\rightarrow{}_2He^3+{}_2He^4$	2.0×10^6
3. Lithium:	${}_3Li^7+{}_1H^1\rightarrow2{}_2He^4$	2.4×10^6
4. Beryllium:	${}_4Be^9+2{}_1H^1\rightarrow{}_2He^3+2{}_2He^4$	3.2×10^6
5. Beryllium:	${}_4Be^{10}+2{}_1H^1\rightarrow3{}_2He^4$	4.9×10^6
6. Boron:	${}_5B^{11}+{}_1H^1\rightarrow3{}_2He^4$	4.7×10^6

We shall first explain the entries in Table 2. A symbol ${}_pX^q$ represents a nuclear particle with atomic number p and mass number q. The atomic number denotes the number of protons each with mass 1.672×10^{-24} grammes and charge 4.803×10^{-10} e.s.u. (electrostatic units) present in the nucleus. Thus, the atomic number also gives the charge of the nucleus in terms of the charge of a proton. Since a normal atom is neutral, i.e., with total charge zero, and the charge of an electron is equal to the charge of a proton with the negative sign, we conclude that in a normal atom there will be as many electrons circling round the nucleus as is the atomic number. The mass number gives the nearest whole number to atomic weight. Thus the atomic weight of hydrogen is 1.00808 on the scale on which the atomic weight of carbon is 12. Therefore, the mass number of hydrogen is 1. We have mentioned earlier that the nucleus of an atom consists of protons and neutrons where neutron is a particle with charge zero and mass 1.675×10^{-24} grammes, which is very nearly equal to the mass of a proton. Thus q gives the total number of protons and neutrons in the nucleus of ${}_pX^q$. We therefore conclude that it contains $q-p$ neutrons.

Atoms having the same atomic number but different mass numbers are called isotopes. Thus the nuclei of isotopes will contain the same number of protons but will differ in the number of neutrons. Since the chemical properties of an atom are determined by the number and arrangement of the electrons in it, all isotopes will show the same chemical properties. In our notation, ${}_pX^{q-1}$, ${}_pX^q$, ${}_pX^{q+1}$. . . are all isotopes of the element X.

In Table 3 we record the atomic weights of the elements and their isotopes which occur in our discussion in this section.

TABLE 3

Element	Hydrogen		Helium		Lithium		Beryllium	
Isotopes	$_1H^1$	$_1D^2$	$_2He^3$	$_2He^4$	$_3Li^6$	$_3Li^7$	$_4Be^9$	$_4Be^8$
Atomic weight	1.00808	2.01464	3.01693	4.00371	6.01659	7.01786	9.01463	8.00656
Element	Boron		Carbon		Nitrogen		Oxygen	
Isotopes	$_5B^{10}$	$_5B^{11}$	$_6C^{12}$	$_6C^{13}$	$_7N^{14}$	$_7N^{15}$	$_8O^{15}$	$_8O^{16}$
Atomic weight	10.0159	11.01243	12.00000	13.00703	4.00687	15.00422	15.0012	15.99946

We shall now describe the nuclear reaction in Table 2 one by one:

1 One deuteron consisting of a proton and a neutron combines with a proton to produce one nucleus of helium three, $_2He^3$, which is a lighter isotope of helium consisting of two protons and one neutron. The normal $_2He^4$ nucleus consists of two protons and two neutrons.

2 One nucleus of the light isotope of lithium, $_3Li^6$ consisting of three protons and three neutrons combines with a proton to give one helium three nucleus and one normal helium nucleus.

3 One normal lithium nucleus, $_3Li^7$ consisting of three protons and four neutrons combines with one proton to give two normal helium nuclei.

4 One normal beryllium nucleus $_4Be^9$ consisting of four protons and five neutrons combines with two proton to give two normal helium nuclei and one helium three nucleus.

5 One nucleus of heavy isotope $_4Be^{10}$ of beryllium consisting of four protons and five neutrons combines with two protons to give three normal helium nuclei.

6 One normal boron nucleus $_5B^{11}$ consisting of five protons and six neutrons combines with one proton to give three normal helium nuclei.

We note that in each reaction the sum of the mass numbers of the particles on the side of the arrow is equal to the sum of the mass numbers of the particles on the other side. The same statement is true about the atomic numbers also.

We may mention in passing that in each of the thermonuclear reactions a certain amount of mass is transformed into energy in accordance with Einstein's mass-Energy equivalence relation $E=Mc^2$, where M is the mass transformed in grammes, E is the energy released in ergs and c is the speed of light in vacuum in cm per second. Thus, in the Deuteron Reaction, we have

Mass converted into energy=Mass of deuteron+Mass of proton−Mass of one helium three nucleus=$[2.01464+1.00808-3.01693]\times$Mass of a hydrogen atom$=0.00579\times1.672\times10^{-24}$ grammes.

$\therefore$ Energy released per reaction$=8.7\times10^{-6}$ ergs. In a similar manner we can calculate the energy liberated in each of the reactions listed in Table 2.

A reaction starts in the central zone of a star where the temperature is the highest when the critical temperature recorded in Table 2 is attained there. This release of nuclear energy heats up the star and consequently slows down the contraction of the star. During the subsequent stages, a star derives more and more energy from nuclear reactions and less and less from gravitational contraction. Ultimately, when the star arrives at the main sequence stage, the nuclear energy source completely replaces the gravitational source.

Evolution along the Main Sequence Stage. Since the thermonuclear processes are highly temperature dependent, most of the energy is generated in a central core of finite extent. To maintain the equilibrium of the star, the energy must be rapidly transported. At some stage, in massive stars (i.e., stars with mass greater than that of the sun), radiation is unable to cope with the situation and convection currents are set up. Thus, at this stage, a star will consist of a convective core round its centre and a radiative envelope. This happens actually when the star has been heated up to such an extent that, (*a*) p-p (proton-proton) chain reaction, or (*b*) CN—(carbon-nitrogen) cycle, described below, has set in.

(*a*) *p-p-chain reaction* (critical temperature $T_c\sim10^7$ °K)

This chain of reaction consists of three steps:

(*i*) ${}_1H^1+{}_1H^1\rightarrow{}_1H^2+\beta^++\nu$.

Two protons combine to give a deuteron, a positron (β^+) and a neutrino.

(*ii*) ${}_1H^2+{}_1H^1\rightarrow{}_2He^3+\gamma$

One deuteron and one proton combine to give one helium three nucleus with the emission of a gamma ray (γ). Reaction (*i*) and (*ii*) have to be repeated twice to give 2 nuclei of ${}_2He^3$ for the third step of reaction:

(*iii*) ${}_2He^3+{}_2He^3\rightarrow{}_2He^4+2{}_1H^1$

Two ${}_2He^3$ nuclei combine together to give one normal helium nucleus and two protons.

The net result of these three reactions is that four hydrogen nuclei have been converted into one helium nucleus.

Energy liberated per chain reaction=26.207 MeV (Million electron volts) where $1\text{MeV}=1.6\times10^{-6}$ ergs.

(*b*) *CN-cycle* (critical temperature $T_c \sim 10^{7}$°K)

The CN–cycle consists of the following six steps:

(*i*) ${}_6C^{12}+{}_1H^1\rightarrow{}_7N^{13}+\gamma$

One carbon nucleus combines with a proton to synthesize a nucleus of nitrogen isotope with the emission of a gamma ray.

(*ii*) ${}_7N^{13}\rightarrow{}_6C^{13}+\beta^{+}+\gamma$

One ${}_7N^{13}$ nucleus disintegrates into a nucleus of stable isotope ${}_6C^{13}$ of carbon with the emission of a positron and a gamma ray.

(*iii*) ${}_6C^{13}+{}_1H^1\rightarrow{}_7N^{14}+\gamma$

One ${}_6C^{13}$ nucleus combines with a proton to synthesize a nucleus of nitrogen with the emission of a gamma ray.

(*iv*) ${}_7N^{14}+{}_1H^1\rightarrow{}_8O^{15}+\gamma$

One nitrogen nucleus combines with a proton and synthesizes a nucleus of the unstable isotope ${}_8O^{15}$ of oxygen with the emission of a gamma ray.

(*v*) ${}_8O^{15}\rightarrow{}_7N^{15}+\beta^{+}+\nu$

The unstable nucleus ${}_8O^{15}$ disintegrates into a stable nucleus ${}_7N^{15}$ of nitrogen with the emission of a positron and a neutrino.

(*vi*) ${}_7N^{15}+{}_1H^1\rightarrow{}_6C^{12}+{}_2He^4$

One ${}_7N^{15}$ nucleus captures a proton and synthesizes a nucleus of carbon and a nucleus of helium. Total energy liberated per cycle =25.026 MeV. We note that the carbon atom with which we stårted in step (*i*) is recovered in the final step, so that carbon acts only as a catalyst in this cycle. Here also four hydrogen nuclei have been converted into a helium nucleus.

We note that in both p-p chain and CN-cycle four protons combine together to yield a nucleus of a helium atom and that below 2×10^{7}°K p-p chain dominates, while above 2×10^{7}°K, CN-cycle dominates; in the intermediate temperature range both of these reactions operate.

In the convective core of these massive stars, there is thorough mixing so that it has uniform chemical composition, of course different from the radiative envelope.

In the case of stars of masses comparable with the solar mass, radiation continues to be an efficient mode of transport of energy. Thus in the absence of mixing by convection, non-uniformity in the chemical composition inside the star continues to mount up. Moreover, these stars develop a convective envelope near the surface in which the energy is transported by convection. This difference in the behaviour of the massive and solar type stars on the main sequence is exhibited in the future course of their evolution off the main sequence stage. For example, the massive stars move more or less directly to the right in the Hertzsprung-Russell diagram and enter the region of super giant stars (Figure 9.12). However, such stars are rare. The stars, which begin to move to the right somewhat lower down the main sequence, enter the region of cepheid variables. The stars, which begin to evolve towards the right, lower and lower down the main sequence, have evolutionary tracks which not only move on to the right but also ascend in the diagram towards the region of higher luminosity. These tracks pass through the giant star region.

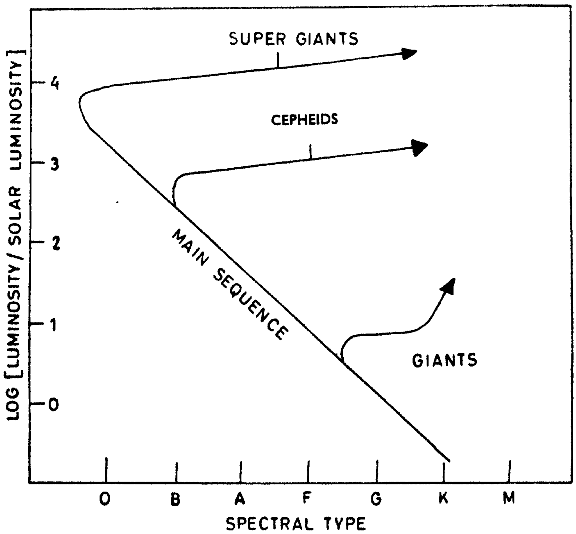

FIG. 9.12 *Evolutionary tracks of the main sequence*

Helium Burning Stage. When the entire hydrogen in the core is consumed, p-p chain and CN-cycle cease to operate and at this stage the central temperature is not high enough (10^{8}°K) for the commencement of the three-alpha reaction:

$$_{2}He^{4}+{}_{2}He^{4}+95KeV\rightarrow{}_{4}Be^{8}+\gamma$$
$$_{4}Be^{8}+{}_{2}He^{4}\rightarrow{}_{6}C^{12}+\gamma+7.4 \text{ MeV}.$$

(The energy generated per reaction is equal to 1.17×10^{-5} ergs.)
Hence the star falls back on gravitational contraction for the supply of energy till the central temperature and density rise to the order of 10^{8}°K and 10^{5} g/cc respectively.

Subsequent Evolution. When all the nuclear energy sources are exhausted the star tries to maintain itself on gravitational contraction but now the star has attained such high densities that the contraction is extremely slow. The star has arrived at the white dwarf stage. The star then consists of highly crushed matter due to pressure ionization. The equation of state for this matter deviates very much from the perfect gas equation $p=R\rho T$ and in particular the gas pressure p depends mostly on the density ρ, and the temperature (T) effect becomes insignificant. This state of matter is called the degenerate state. The pressure of a completely degenerate gas is proportional to 4/3 or 5/3 power of the density (i.e., $p\propto \rho^{4/3}$ or $p\propto \rho^{5/3}$) according to whether the relativistic effect is taken into account or not. The star continues to radiate its stored up thermal energy. Ultimately, when the star has cooled down sufficiently, it disappears from sight. This entire cycle of evolution takes a few billion years. It is interesting to note a result obtained by S. Chandrasekhar, the distinguished Indian astrophysicist, namely, that a completely degenerate configuration cannot have a mass greater than 1.64 times the mass of the sun approximately. This means that when a star with mass greater than this critical mass settles down to the white dwarf stage, it must throw out the excess mass by some mechanism such as the supernova process.

CHAPTER X

Our Sun

WE have pointed out earlier that the sun is the only star which forms a disc image in a telescope. Consequently, it is the only star whose surface features we can study. This fact makes the study of the sun interesting and informative.

Important Data about the Sun

Size, Shape and Mass. To the naked eye, the sun appears to be spherical with well-defined bounding surface, called the photosphere (sphere of light). Its diameter is 864,000 miles or 1.4×10^{11} cm, which is approximately 109 times the diameter of the earth. Its mass is about 2.24×10^{27} tons or 2×10^{33} g and is approximately 333,434 times the mass of the earth. Its mean density is only 1.42 g/cc, though its central density, according to recent theoretical studies, is about 110 g/cc, i.e., the matter at the centre of the sun is about 110 times heavier than water or about 14 times heavier than steel.

In the following table we give some important data about the sun:

Average distance from the earth = 93,000,000 miles
= 8 *l*.m.

Absolute magnitude = 4.85
Energy radiated = 4×10^{33} ergs/sec
Surface temperature = 6000°K (approximately)
Central temperature = 2×10^{7}°K

Each square centimetre of the solar surface shines with the intensity of 300,000 candles.

Telescopic Appearance. The telescopic studies reveal two important surface features: (*i*) Limb-darkening, and (*ii*) Sunspots.

Helium Burning Stage. When the entire hydrogen in the core is consumed, p-p chain and CN-cycle cease to operate and at this stage the central temperature is not high enough (10^{8}°K) for the commencement of the three-alpha reaction:

$$_{2}He^{4}+_{2}He^{4}+95KeV \rightarrow _{4}Be^{8}+\gamma$$
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SUNSPOTS. Most of the time, one or more blemishes are visible on the sun's surface. These are called the sunspots (Figure 10.2). The fact that the sunspots appear dark in comparison with the photosphere indicates that the sunspots are

FIG. 10.2 *Sunspots. The three photographs on the left represent, from top to bottom, the same unipolar spots taken in white light, calcium light and hydrogen light, respectively. The three photographs on the right represent a bipolar star taken respectively in white, calcium and hydrogen light. The spots show their most distinctive feature in the calcium light. The large bright patches round the spots represent the calcium vapour clouds called the flocculi. The photographs in hydrogen light show much finer details consisting of both bright and dark filaments. The difference in the calcium and hydrogen photographs arises from the actual differences in chemical composition.*

considerably cooler than the surrounding photosphere. In general, the centres of the sunspots have temperatures of the order of 4600°K; they may be as low as 3700°K in some cases.

A convenient way of seeing a large sunspot is the following. Punch a very fine hole in a cardboard piece, hold it close to the eye and look at the sun through it or project the image of the sun on a piece of white paper placed in a dark room. In the latter case, we can obtain a one-inch image of the sun on a white paper placed at a distance of 10 feet from the pinhole.

Sunspots

The spots appear in a variety of sizes. The smallest ones measure about a few hundred miles or so across. Such spots are very numerous. At the other end of the scale, we often find single spots whose diameters may measure 20,000 miles, or more. A double group may extend over 100,000 miles. The largest spot on record was observed in 1947. It covered more than one per cent of the total area of the apparent solar disc, i.e., 6000 million square miles which could have contained 100 earths. Any spot larger than 25,000 miles in diameter can be readily seen by the naked eye.

The individual spots are temporary phenomena. The life of a spot is usually correlated with its size. The smaller spots are short-lived, lasting a day or so, while the larger spots may last for several weeks.

The spectroscopic studies of the sunspots reveal two important effects: (*i*) the Doppler effect, and (*ii*) the Zeeman effect.

Doppler Effect. The presence of the Doppler effect suggests that the material flows out with an average velocity of 2 km/sec. This outward flow probably takes place along the magnetic lines of force which become tangential at the edge of the spot. This is called the Evershed effect. It is a matter of pleasure to record that this effect was discovered by Evershed at the Kodaikanal Observatory.

Zeeman Effect. The amount of splitting of the spectral lines indicates that the sunspots are associated with fairly large magnetic fields. Magnetic fields as high as 4000 gauss have been observed in some of the spots. However, in general, they tend to saturate at about 3000 gauss. The magnetic field at the centre of each spot is perpendicular to the solar surface. From the study of the state of polarization we can determine the polarity of the spot. The polarity is said to be positive if the lines of force emerge out of the spot; similarly by negative polarity we mean that the magnetic lines of force are directed inside the spot. Our general experience is that the two poles of a magnet cannot be separated. Let us see how the sunspots behave in this respect. Statistics gathered regarding the spots indicate that about 10 per cent are unipolar, about 90 per cent bipolar and about one per cent multipolar. Do the unipolar spots break the rule? Perhaps not. A unipolar spot perhaps arises through the weakening of the magnetic field of a companion in a bipolar spot.

Spot Cycle

If we observe the sun regularly for a number of years, we can obtain a valuable information. Early in the 19th century, for the first time, a German amateur astronomer, Schwabe, set himself to the task of observing the sun regularly over the long period of 20 years. Each day he noted down the number of spots which were visible on the solar disc. From this simple but persistent observation, he discovered that the number of spots varies in a fairly regular manner. At a spot minimum, no spots may be visible for days or even weeks together; then, gradually, their occurrence becomes more and more frequent till, at the spot maximum, there is hardly any day when several spots or groups of spots are not visible. After this, the number begins to fall till the minimum is again reached. This cycle from minimum to maximum and again to minimum occupies on the average about 11 years. This interval is called the Eleven-Year Spot Cycle.

Distribution of Spots with Latitude on the Solar Surface

Observations reveal that spots do not occur in all the latitudes on the solar surface with equal frequency. They are, in fact, confined to an equatorial belt extending from 40°S to 40°N with a very few spots occurring in the narrow belt between 5°S and 5°N. In latitudes higher than 40°N or S, they are extremely rare and have never been observed in the neighbourhood of the poles.

The Sun's Rotation. Galileo was the first astronomer who used the sunspots to measure the period of rotation of the sun. He arrived at the value of 27 days for it. Following the method of Galileo, Sporer near about 1860 discovered that the period of rotation is not the same in all solar latitudes. Moreover, he found that the angular velocity decreases as we go from the equator to the poles (Figure 10.3).

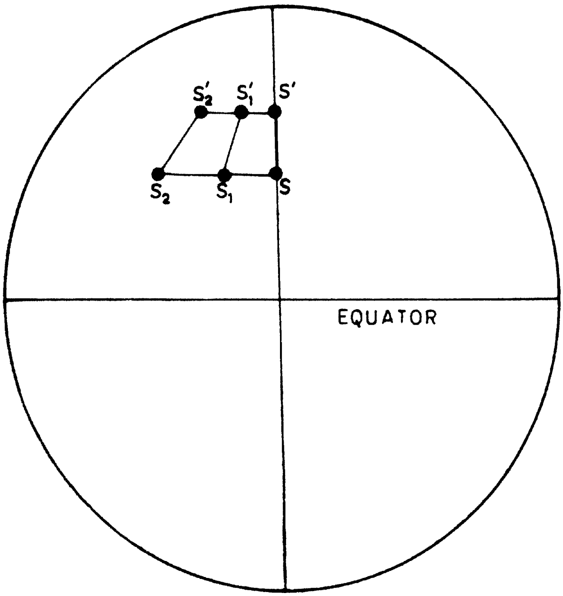

FIG. 10.3 *Differential rotation of the sun as deduced from the motion of the sunspots, S and S'*

The following table records the rotational periods in days against the latitudes on the solar surface:

Latitude (°N or °S)	Rotational Period in days
0	25.0
10	25.2
20	25.7
30	26.5
90	34.0

For comparison, we record that the earth rotates as a rigid body in a period of 24 hours.

Faculae and Photospheric Granulation

A careful study of the solar surface reveals, in addition to the limb-darkening and the sunspots, three very interesting phenomena: (1) Faculae, (2) Granulation, and (3) Dark filaments.

Faculae. Faculae(little torches) consist of numerous irregular patches and curly filaments. They are, on the average, 15 per cent brighter than the photosphere. The appearance of the faculae *precedes* the formation of the spots and

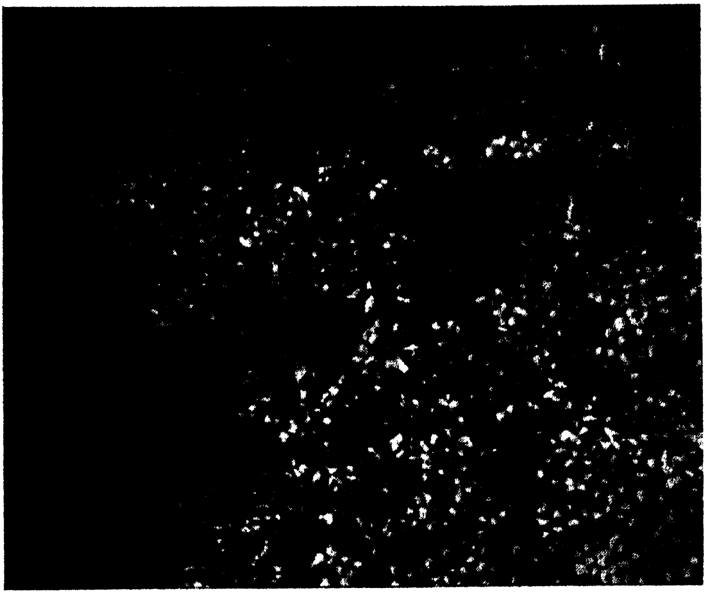

FIG. 10.4 *Solar granulation. The central dark area represents a sunspot.*

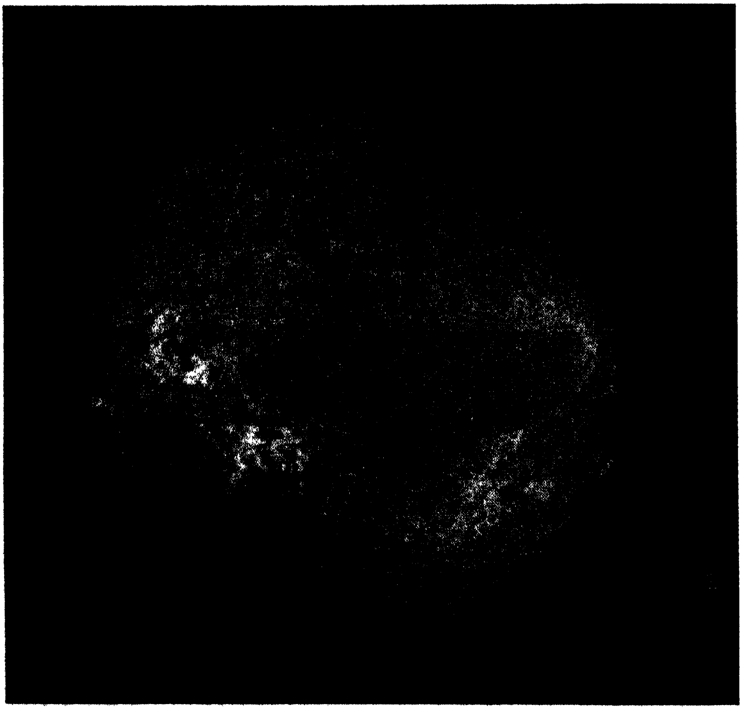

FIG. 10.5 *Dark filament*

they survive even after their disappearance. Faculae extend on much wider areas round the dark spots. According to the current theories, they are clouds of calcium vapour in the atmosphere situated at considerable heights above the photosphere.

Granulation. Even if we neglect these faculae, the texture of the photospheric surface is not uniform. It is granular and appears to be made of innumerable contiguous grains (Figure 10.4). These grains are slightly brighter than the photosphere and are from 450 to 1300 miles in diameter. According to Keenan, at any given moment, more than two and a half million granules are visible over the entire disc of the sun. It is surmised that granules are the crests of waves of unequally heated photospheric material. Even today the actual cause of granulation is not known for certain.

Dark Filaments. Another important feature of the solar surface is the appearance of dark filaments (Figure 10.5), which are comparatively long-lived. It is surmised that they are the projections on the photosphere of comparatively cool clouds of gases called the prominences, which we shall discuss shortly.

Solar Atmosphere

At the time of the total solar eclipse, when the bright photosphere is hidden behind the moon, the atmosphere of the sun becomes visible by its own radiation. The spectrum of this radiation is called the flash spectrum. Observations under these circumstances indicate that the solar atmosphere should be divided into three layers:

(1) Reversing layer, (2) Chromosphere, and (3) Corona (Figure 10.6).

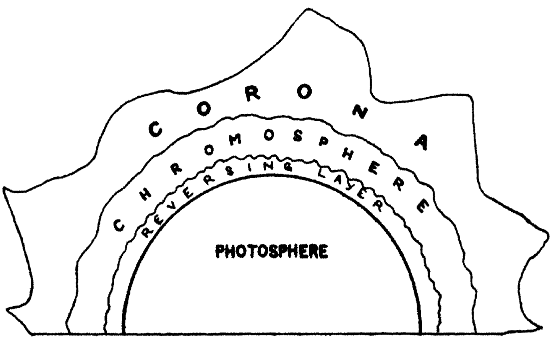

FIG. 10.6 *Schematic representation of the sun and its atmosphere*

Reversing Layer. The lowest part of the atmosphere is called the reversing layer. It extends to about 500 miles above the photosphere. It emits radiation in a large number of wave lengths and hence looks white much like the ordinary sunlight. According to the well-known laws of spectroscopy, it will absorb the radiation in these very wave lengths from the light coming from below the atmosphere and produce Fraunhofer lines in the solar spectrum. Hence, it is called the reversing layer.

Chromosphere. The zone next to the reversing layer extending to another 5000 to 7000 miles is called the chromosphere. It looks scarlet owing to the great intensity of a particular spectrum line of hydrogen.

Corona. The remaining part of the atmosphere is called the corona (Crown). It is far from being spherical. The corona is faint and pearly white. It resembles a white dahlia. Those who have seen the corona would never forget its ethereal beauty. By observing the intensity of the radio waves coming from the Crab Nebula, when it is near the line of sight of the sun, it has been estimated that the corona certainly extends in the sun's equatorial plane up to a distance of about 80 solar radii. Perhaps the mean particle density of the electrons in the corona is 10^3 per cubic centimetre. Towards the poles of the sun, the electrons form into streamers that lie along the direction of the magnetic field.

The form of the corona appears to vary with the sunspot cycle. At the spot maximum, it has a roughly circular outline. At the spot minimum, the corona appears elongated in the plane of the sun's equator and flattened near its poles (Figure 10.7). The cyclic changes in the general form of the corona appear to be related to the changes in the arrangement of the magnetic lines of force about the sun.

Million Degree Temperature in Corona. The analysis of the spectrum of the radiation from the corona shows the lines due to the atoms of iron, calcium, argon and nickel ionized to the extent of the loss of ten to fifteen electrons. The flash spectrum of the corona taken at the time of solar eclipse shows hydrogen and helium emission lines. From this we infer the existence of the temperature of the order of a million degrees somewhere in the corona. In fact, observations indicate that, quite contrary to our expectation, the temperature in sun's atmosphere increases from less than 5000°K in the reversing layer to about 35,000°K in the chromosphere and to about 10^6°K in the corona. This increase

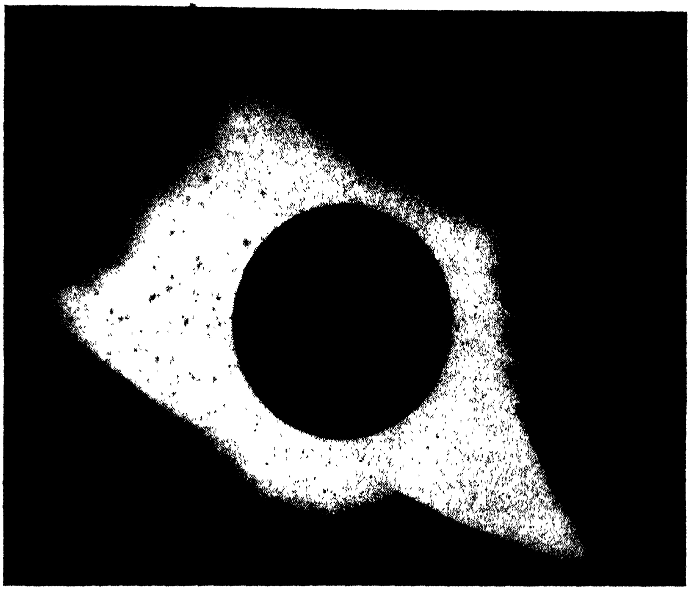

FIG. 10.7 *Solar Corona*

in the temperature has been duly confirmed by the intensities of the radio waves emitted by the corona in the wave length band extending from 1 metre to 10 metres.

What causes this enormous increase of temperature in the chromosphere and corona is an open question even today.

Spicules and Prominences

Careful observations show that the chromosphere is decidedly non-uniform. It consists of tiny 'spicules' that interlace like grass blades. There is yet another striking phenomenon noticeable on the surface of the sun: huge clouds of chromospheric material appear to hover above the surface of the sun; sometimes the material shoots up rapidly to great heights and sometimes it appears to fall down on the solar surface. These are called the Prominences.

Spicules. The spicules are several hundred miles in diameter and extend upwards to heights of 5000 to 10,000 miles. In the equatorial regions the spicules are inclined to the normal with the solar surface, whereas near the poles they are predominantly radial. This is a very significant fact if we remember that the sun also possesses a general magnetic field of the order of 1 to 2 gauss which conforms to a field due to a dipole placed at the centre, more or less along the axis of rotation. The lines of such a field will be more or less radial near the poles and more or less parallel to the surface near the equator. Thus it appears that the general magnetic field plays a significant role in shaping a spicule.

Moreover, the rates of development and activity of the equatorial and polar spicules also seem to differ. The polar spicules are considerably more rapid than the equatorial spicules. According to W. O. Roberts, a polar spicule forms as a sort of a blister on the solar surface. The swelling increases until the 'skin' appears to burst. At this moment a jet spurts out from a peak to form a spicule. The luminosity of the gas rapidly fades as the jet rises and simultaneously the swelling subsides. The spicules complete this cycle in 2 to 12 minutes with an average life of 4 to 5 minutes. Figure 10.8 gives the life history of a polar spicule.

Another important point to be noted about the spicules is that their cores do not appear to fall back upon the surface and we may even conclude that the hot material of the spicules goes to form part of the corona.

Prominences. Prominences come in a variety of sizes and shapes. Some are just bigger than the largest of the spicules, while the others are so different in size and shape from the spicules that they need a separate discussion. Most of the prominences consist of delicate interlacing threads and the mass resembles a strand of wool yarn in which fibres occupy a small fraction of the total volume.

The prominences appear in the regions above the top of the chromosphere and look dark in projection against the solar disc so that the prominences must be regions of local cooling in the corona.

In each of the solar hemisphere, there are two zones of maximum frequency of occurrence of the prominences: one lying between the latitudes 20° and 40°

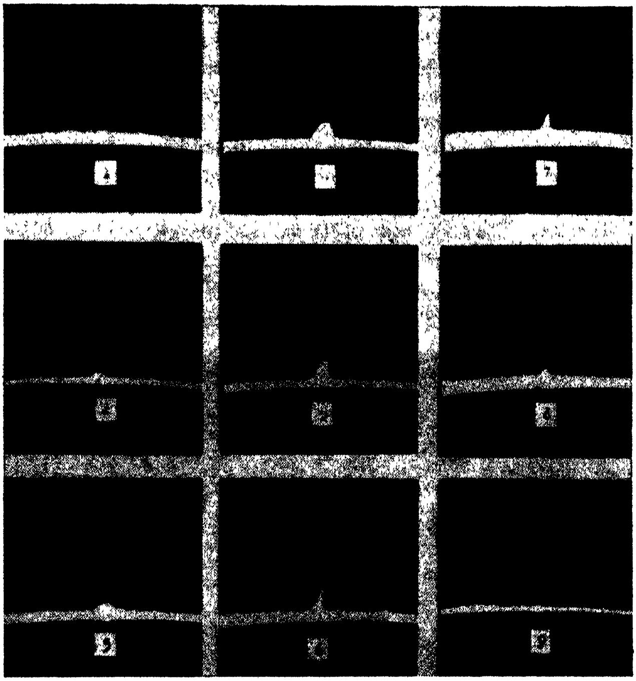

FIG. 10.8 *The life history of a comparatively long-lived polar spicule. The successive frames have been taken at* 0, 2, 3, 5, 7, 9, 11, 13 *and* 17 *minutes.*

and the other lying between the latitudes 50° and 60°. The frequency distribution of the prominences in the first zone follows the sunspot cycle, i.e., maximum and minimum number of prominences occur at the sunspot maximum and minimum, respectively. The frequency of the prominences in the second zone is approximately half a cycle out of phase with the first zone, i.e., in this zone the prominences break out two or three years after the sunspot maximum.

mospheric material appear to hover above the surface of the sun; sometimes the material shoots up rapidly to great heights and sometimes it appears to fall down on the solar surface. These are called the Prominences.

Spicules. The spicules are several hundred miles in diameter and extend upwards to heights of 5000 to 10,000 miles. In the equatorial regions the spicules are inclined to the normal with the solar surface, whereas near the poles they are predominantly radial. This is a very significant fact if we remember that the sun also possesses a general magnetic field of the order of 1 to 2 gauss which conforms to a field due to a dipole placed at the centre, more or less along the axis of rotation. The lines of such a field will be more or less radial near the poles and more or less parallel to the surface near the equator. Thus it appears that the general magnetic field plays a significant role in shaping a spicule.

Moreover, the rates of development and activity of the equatorial and polar spicules also seem to differ. The polar spicules are considerably more rapid than the equatorial spicules. According to W. O. Roberts, a polar spicule forms as a sort of a blister on the solar surface. The swelling increases until the 'skin' appears to burst. At this moment a jet spurts out from a peak to form a spicule. The luminosity of the gas rapidly fades as the jet rises and simultaneously the swelling subsides. The spicules complete this cycle in 2 to 12 minutes with an average life of 4 to 5 minutes. Figure 10.8 gives the life history of a polar spicule.

Another important point to be noted about the spicules is that their cores do not appear to fall back upon the surface and we may even conclude that the hot material of the spicules goes to form part of the corona.

Prominences. Prominences come in a variety of sizes and shapes. Some are just bigger than the largest of the spicules, while the others are so different in size and shape from the spicules that they need a separate discussion. Most of the prominences consist of delicate interlacing threads and the mass resembles a strand of wool yarn in which fibres occupy a small fraction of the total volume.

The prominences appear in the regions above the top of the chromosphere and look dark in projection against the solar disc so that the prominences must be regions of local cooling in the corona.

In each of the solar hemisphere, there are two zones of maximum frequency of occurrence of the prominences: one lying between the latitudes 20° and 40°

then called an eruptive prominence. The average upward velocities recorded for these prominences are generally of the order of 100 km/sec, but sometimes velocities as low as 10 km/sec and as high as 700 km/sec have also been observed. In extreme cases an eruptive prominence can rise as high as a solar radius. An eruptive prominence presents a fantastic sight. As the prominence rises, the matter pours down along one or more trajectories, thereby leading to an arch-like formation. Figure 10.9 represents an eruptive prominence.

FIG. 10.10 *Tornado prominence*

Sunspot Prominence. A sunspot prominence, as the name indicates, is associated in one way or the other with a spot. Coronal material condenses at a height of the order of a few thousand kilometres and then flows into the spot area like a streamer. The direction of motion of the material suggests that its movement is controlled by the magnetic field of the spot. The downward velocity of the material is of the order of a few kilometres per second. The area covered by a prominence, when it enters the spot, is of the order of a few thousand square kilometres.

Tornado Prominence. In a tornado prominence (Figure 10.10), material rises up, executing a rapid spiralling motion. Sometimes the angular velocity is so large that the vortex explodes. The diameter of a tornado may range from 500 km to about 20,000 km. It may rise as high as 100,000 km. A faint smoke-like cloud issues from the top of the vortex and often bends over in some cases touching the chromosphere.

Quiescent Prominences. A quiescent prominence looks like a slowly changing dense cloud. It has a long lifetime. Sometimes a quiescent prominence may last over a couple of months. The velocities of the material in the

FIG. 10.11 *Cone type prominence*

quiescent prominences are low and are of the order of 20 km/sec. The prominences belonging to this class are huge structures. They may have heights of the order of a few thousand kilometres. When projected against the solar disc they look like large dark filaments with widths of the order of a few thousand kilometres and lengths of the order of a few hundred thousand kilometres. They rotate with the sun and are associated with the centre of attraction. The material pours down from the prominences towards the centre of attraction.

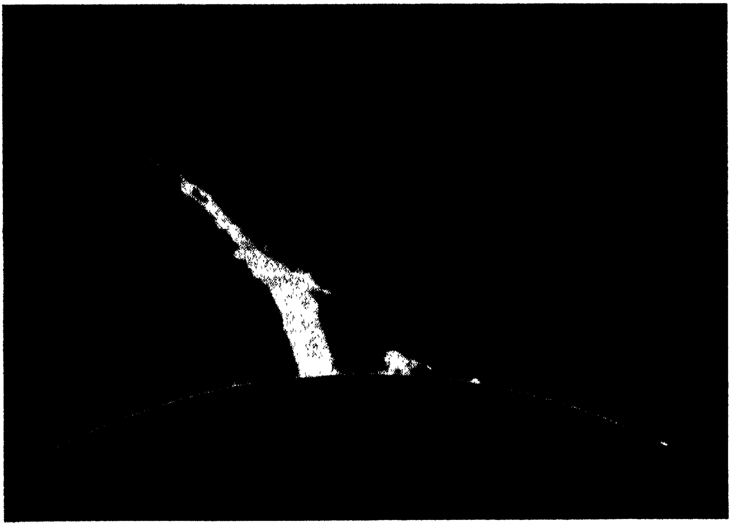

FIG. 10.12 *Surge prominence*

We shall now make some general remarks about the prominences:

1 It is probable that the general movement of the visible material in prominences is downwards. Even in an eruptive prominence, the apparent upward motion is not necessarily connected with the outward motion of the visible material but rather with the rise of the cooling effect.

2 The motion of the prominence material is not governed by the gravity of the sun alone. If gravity were the only force acting on the material it would move down from the height of 20,000 miles to the solar surface in an interval of 8 minutes, acquiring a velocity of about 80 miles/sec during the descent. We have just seen that in a quiescent prominence clouds of material remain suspended for days without any apparent change of form. In active prominences, the material velocities are usually uniform, though sometimes we observe sudden accelerations. Therefore, it is reasonable to conclude that the magnetic field associated with the spots and the general magnetic field of the sun play an important role in shaping the material motions in the prominences.

Chemical Composition of the Solar Atmosphere

From the strength of the absorption lines, the following chemical composition is estimated for the atmosphere of the sun:

Element		*Relative number of atoms in sun's atmosphere*
Hydrogen	..	8000
Helium	..	1500
Carbon	..	0.64
Nitrogen	..	1.10
Oxygen	..	2.50
Sodium	..	0.007
Magnesium	..	0.3
Aluminium	..	0.03
Silicon	..	0.33
Potassium	..	0.0016
Calcium	..	0.013
Iron	..	0.30

Helium shows no absorption lines; its abundance is determined by using the flash spectrum when the photosphere is hidden behind the sun. Figure 10.13 gives the chemical composition of the solar atmosphere and that of the earth for comparison.

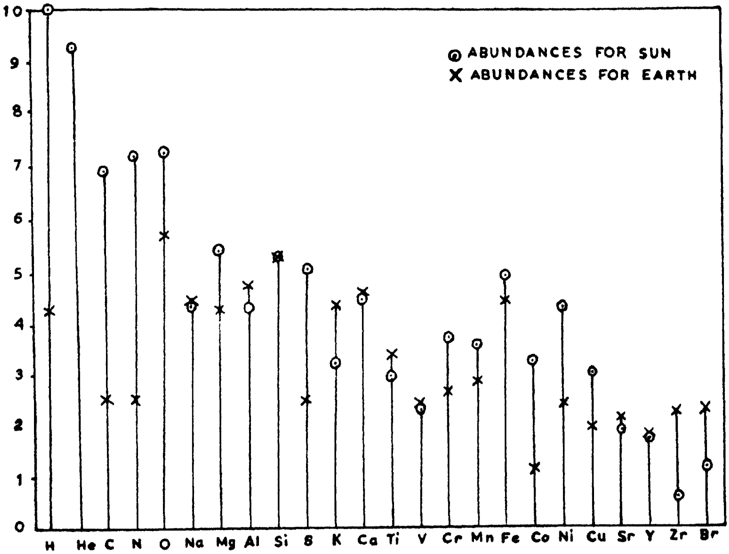

FIG. 10.13 *The relative abundances of various elements in the sun and the earth*

Solar Wind

We have mentioned earlier that somewhere in the corona, temperatures as high as million degrees Kelvin are attained. We may now ask the following question: What is the effect of such high temperature on the corona itself ?

According to the celebrated kinetic theory of gases, at these high temperatures of the order of million degrees, all atoms move at tremendously high velocities and collide with each other so energetically that they are very highly ionized. The electrons are much lighter than atoms and consequently, they acquire velocities comparable to the speed of light. Some of the ions and the electrons move so fast that the gravitational pull of the sun is unable to obstruct them from leaving the corona. This continuous outpouring of the coronal material into space is called the 'solar wind'.

The optical telescopes could not observe the solar wind. The radio telescopes have proved beyond doubt that the solar wind extends certainly up to half way to earth. It is surmized that it engulfs our earth and goes even beyond it. The radio emission from the solar wind becomes fainter and fainter as its distance from the sun increases, so much so that after some distance it is too faint to be distinguished from the background radio noise of the radio telescope itself and the universe at large.

However, there is an indirect way for studying this extended solar corona. Crab nebula, the remanent of a star which exploded long time back, is a strong radio source. It is so situated in the sky that, every year in the month of June, the radio waves emitted by it pass through the solar atmosphere on their way to the earth. The decrease in the normal intensity of the radio waves indicates the presence of solar wind in their way and its magnitude enables us to estimate the density of the charged particles in it. However, the most astounding observation is that the solar wind does not form a continuous medium as we would expect. It is found to exist in filaments separated by void spaces between them. Moreover, these filaments are not straight like the spokes of a wheel emanating from the sun; they are curved in the form of Archemedian spirals.

We can explain both these observations theoretically in a simple way if we remember that, like our earth, the sun also possesses a general magnetic field and a rotation. The solar wind consists of charged particles. These particles carry with them the general magnetic field which orients itself along the length of the filaments on account of the motion of the particles. Now the plasma can flow freely along the magnetic lines of force but is obstructed from flowing across them by a magnetic force called the magnetic pressure. Thus the magnetic field does not allow the filaments of plasma to form a continuous medium. And, then the rotation of the sun gives these filaments the curved shape of the Archemedian spirals. Accurate measurements made by IMP I Satellite in 1963 have confirmed, beyond doubt, these theoretical predictions.

Let us follow the solar wind on its path towards the earth. At the distance of about 20 to 25 earth-radii, an interesting phenomenon occurs. This is called the magneto-hydrodynamic shock wave. In a plasma, small disturbances travel with Alfven speed which is proportional to the magnitude of the magnetic field and inversely proportional to the square root of the material density. You will recall that, in ordinary gas dynamics, small disturbances travel with sound speed. At the distances mentioned above, the Alfven speed is of the order of 90 km/sec, while the plasma speed is of the order of 200-300 km/sec. Which means that the plasma moves with super Alfvenic velocity. Consequently, the successive disturbance waves overtake each other and give rise to what is called a shock front across which the dynamical variables, and electromagnetic and gas properties jump discontinuously. Observationally it is found that, after crossing the shock front, the magnetic field becomes turbulent and the plasma continues to move with sub-Alfvenic speed.

Let us further follow this solar plasma on its way to the earth and see how it reacts with the terrestrial magnetic field, which increases in magnitude as we approach the earth. At one stage, the solar plasma is unable to penetrate the terrestrial magnetic field and begins to flow along its lines of force giving rise to a surface called the magnetosphere. Since the motion of a charge is equivalent to an electric current, this surface of the magnetosphere behaves like a sheet of current.

If the solar wind could reach right up to the earth's surface, it would have totally distorted its magnetic field and it would no longer conform to the observed dipole field. Thus, the creation of the magnetosphere shields the terrestrial magnetic field and confines it within the magnetosphere. It is gratifying to note that the existence of the shock wave and the magnetosphere have been well established by the observations taken by Explorer 12 and 14 and the IMP I Satellite. However, the magnetosphere is not closed on all sides and in fact it is open behind the earth. The space behind the earth bounded by the current-sheet is called the wake. The magnetic field in the wake is in a highly turbulent state. In passing, we may mention that the observations by IMP Satellites tend to show that the moon is also associated with a turbulent wake.

Solar Flare

Another important solar phenomenon which has far-reaching effect on some of the terrestrial phenomena is the solar flare.

Active regions of the sun near the sunspots frequently produce tremendous local explosions. These explosions are characterized by sudden increase in the intensity of light followed by a slow decrease lasting over an hour or so. Moreover, these explosions are associated with sudden out-burst of matter in the form of jets. This phenomenon is called a 'solar flare'.

We do not know definitely even today what produces a solar flare. However, the following hypothesis is in vogue. Due to high temperature, the chromospheric material is in the form of plasma consisting of electrons, ions and neutral particles and is immersed in the strong magnetic field of the sunspots. It is a characteristic property of the magnetic field to exhibit the pinch effect in which the field lines, due to tension in them, tend to assume the shortest possible length and in doing so they press the material between them. This pinch results in a high temperature of the order of ten million degrees and a tremendous motion of plasma ensues along the magnetic lines of force. Moreover, this high temperature is sufficient to set in thermonuclear reactions, involving light nuclei like that of lithium, Berrylium, and Boron. Perhaps, this sudden release of nuclear energy causes the sudden rise in the brightness of the flare. In addition to the emission in the form of light, a solar flare is associated with high intensity emissions in the radio wave regions, arising from the synchrotron and gyromagnetic mechanisms, besides the usual electrostaic plasma oscillations. We study the behaviour of a flare in these radio emissions with considerable advantage.

Some very high energy particles in the jets rush out of the gravitational field of the sun and perhaps these particles constitute the cosmic rays which arrive on the earth few minutes after the observation of the flare. Moreover, this sudden outburst of material jet at a tremendous speed generates a blast wave which arrives in the earth's atmosphere about a couple of hours later carrying in its wake the ionized coronal material. The interaction between this coronal material and the material in the earth's atmosphere at high altitudes produces the phenomenon of auroral lights seen near the polar regions of the earth and the magnetic storms which result in radio fade-outs. We shall discuss this phenomenon in greater detail later on.

CHAPTER XI

Planets and Satellites

OUR sun has a family of nine major planets, thirty one satellites belonging to six planets, and more than 1500 hundred minor planets called asteroids, comets and meteors. We give below the names of the major planets in the order of their distance from the sun: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto (Figures 11.1a and 11.1b).

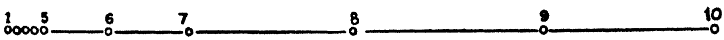

FIG. 11.1a *Relative distances of the planets from the sun*

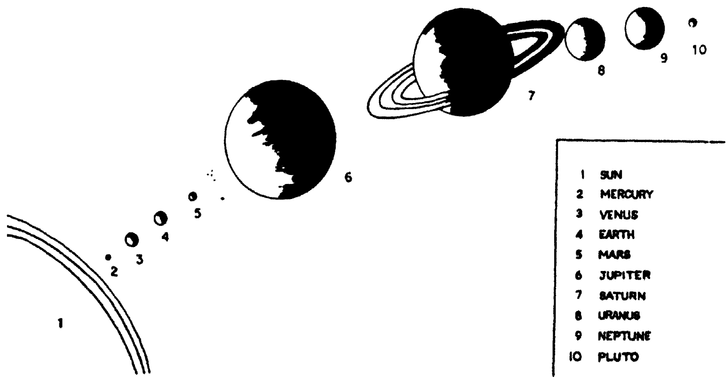

FIG. 11.1b *Relative sizes of the planets*

In this chapter we shall describe briefly some of the important features of the planets, starting from the innermost.

All planets move round the sun in elliptical paths with the sun at one of their foci. They derive the name planets (wanderers) from this fact. When this nomenclature was given to these heavenly bodies, it was believed that stars are at rest. However, as we have mentioned earlier, all the stars including our sun possess motion in space.

Mercury (Buddha)

The innermost planet is named Mercury after the messenger of the Olympian gods. Its orbital velocity varies from 36 to 23 miles/sec and is fastest among all the planets. Its distance from the sun varies from 28.5 million miles to 43.5 million miles with the average distance of 0.39 A.U. (Astronomical units) where 1 A.U. is equal to the mean distance of the earth from the sun. Therefore, its orbit is highly elongated and has an eccentricity equal to 0.2056. Leaving Pluto, its orbit is more elongated than that of any other planet. Its period of revolution is 88 days, while its synodic period (i.e., the time-interval in which it completes a round of the sun relative to the earth) is 116 days. The maximum elongation of Mercury is 28°, where by elongation of an object we mean the angle subtended by the sun and the object at the centre of the earth. Thus Mercury is never far from the sun and it is most of the time hidden in the glare of the sun. Consequently, it is very difficult to observe it in spite of the fact that it is as bright as Sirius. Besides, during half this period, i.e., a little over eight weeks, it is a morning star* (i.e., it rises above the horizon before the sun) and during the other half it is an evening star* (i.e., it sets after the sun has set).

Mercury rotates counter-clockwise about an axis which is approximately perpendicular to its orbital plane. The period of rotation is exactly equal to its period of revolution and hence just like the Moon it keeps the same face towards the sun. The temperature of the face towards the sun is 770°F, while the temperature of the face away from the sun is not much above the absolute zero—459°F. Thus Mercury is probably the hottest and the coldest of all the planets. Mercury has no atmosphere. The extreme climate and the absence of atmosphere make the presence of life on it improbable. The diameter of

*The term 'star' is a misnomer.

Mercury is 3100 miles and its mass is approximately one-eigth of the earth's mass. Its mass is determined by the deflection it produces in the orbit of Venus.

The perihelion (i.e., the point on its orbit nearest to the sun) of Mercury advances† at the rate of 574″ per century, i.e., some 43″ per century more than that could be accounted for. This phenomenon is explained on the basis of Einstein's General Theory of Relativity. In fact, it gave the first observational confirmation of the General Theory of Relativity.

Venus (Shukra)

The next planet is given the name Venus after the goddess of beauty on account of its brilliance.

Its mean distance from the sun is 67 million miles. It comes nearest to the earth than any other planet. When it is nearest to the earth, its distance is only 26 million miles. The eccentricity of its orbit is 0.0068 so that it is more or less circular.

Its mass is 0.79 times the mass of the earth, and its diameter, 7700 miles.

Its greatest elongation is 47° and it is an evening star* for 292 days and morning star* during the next 292 days.

It shows phases like our Moon (Figure 11.2) and is surrounded by a cloud-covered atmosphere. The Venusian atmosphere contains 1/1000 of the earth's oxygen and 1/10 of its water vapour. Carbon dioxide is in enormous abundance. It is not yet known what these clouds are in the absence of water vapour.

Measurements of the heat received from Venus indicates that the temperature of the visible layer is −10°F. Owing to the perpetual clouds we cannot see its surface but it is estimated that its temperature ranges from 120° to 140°F.

According to the latest observations by Mariner II, Venus possesses a very slow rotation.

Venus seems to be most congenial for life, next to the earth and Mars. However, any organism on this planet has to adapt itself to the scarcity of oxygen and water vapour and the abundance of carbon dioxide.

†The ellipse corresponding to the orbit of Mercury is not stationary with respect to fixed stars but rotates at the rate of 574 seconds of arc per century in the plane of the orbit, and in the sense of orbital motion.

*The term 'star' is a misnomer.

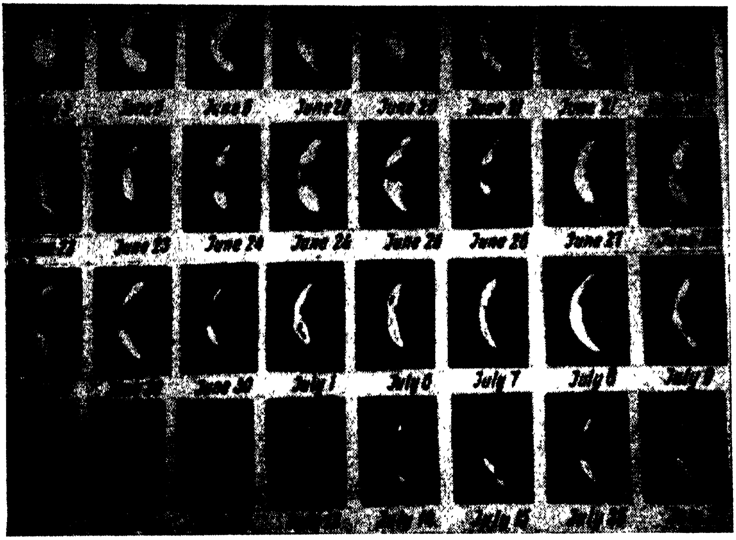

FIG. 11.2 *The phases of Venus*

Earth (Prithivi)

The next planet in this order is our earth which is conspicuous on account of the existence of well-developed life. It is the only heavenly body about which we have considerable knowledge and on which we can perform experiments. The recent investigations through rockets and space vehicles have given extremely valuable information about the earth and its atmosphere.

Size and Shape. It is well known that the earth is spheroidal in shape with equatorial and polar diameters equal to 7927 and 7900 miles respectively. The rotation of the earth is mainly responsible for this oblateness. The earth's gravity, which depends on the distribution of matter in its interior, affects the motion of the artificial satellites. Thus, by carefully studying the motion of these satellites, we can obtain a very valuable information about the interior of the earth. One of the startling findings of such observations has suggested that perhaps the actual shape of the earth is ellipsoidal with the equatorial section elliptical and not circular as has been believed so far. However, this hypothesis requires more substantial confirmation.

The earth possesses 6.6×10^{21} tons of mass and is only a tiny fraction of the mass of the sun (approximately three hundred thousandth part). The mean density is about 5.5 grammes per cubic centimetre, i.e., on an average the matter constituting the earth is five and half times heavier than water.

Internal Structure. We have very little information about the interior of the earth. In fact, we know very little even about its surface layer called its crust. The study of the earthquake waves has enabled us to build a picture of the internal structure of the earth. According to the current views, the crust extends to the depth of about 30 miles and is composed of granites and other igneous rocks i.e., rocks of volcanic origin. The sedimentary rocks (i.e., the rocks formed on the bottom of the oceans by the deposition of mud, layer by layer) appear only in the upper mile or so. This crust appears to float on deformable but exceedingly viscous layers of perhaps 100 to 200 miles thickness and has the average density roughly equal to 4.3 grammes per cubic centimetre. Between the core and the mantle, there is an intermediate shell consisting of some iron-stone mixture with densities roughly equal to the average density of the earth. The core is largely made of iron or nickel-iron. Pressure as high as 50 million pounds per square inch prevails at the centre. Consequently, the iron present here has been pressed to a density of 10 to 12 in contrast to its normal density of 7.7 at the earth's surface. The study of earthquake waves suggests that the core behaves like a liquid.

Considerable changes occur deep down below the surface. For example, the rocks in the crust under tremendous pressures fracture with considerable violence. These fractures result in shaking the outer shell of the earth, giving rise to the phenomenon of earthquakes. The other important activity gives rise to the volcanic eruptions which have played havoc throughout the course of history. Nobody can forget the destruction of the cities of Pompeii and Herculaneum by one of the most notable eruptions in historic times, namely that of Vesuvius in 79 A.D. Similarly, the eruption of the Japanese volcano of Bandai-san in 1888 A.D. resulted in a dreadful catastrophe. An avalanche of mud, earth and rocks roared down the mountain and buried a number of villages spread over an area of 27 miles round the volcano. Coming to our own country, we may mention that the Deccan region of Western India is covered for over 200,000 square miles with lava, 6000 feet deep at places. Evidently it is indicative of a vast volcanic activity in prehistoric times.

What is the cause for volcanic eruptions ? There exists no satisfactory theory about the volcanic eruptions. However, the current thinking is in the following direction. It is clear that to produce lava we need enormous heat. Perhaps the required heat is primal and the rock below the crust of the earth is already above its normal melting point but is kept in the solid state by the pressure of the overlying rocks. Release of this pressure results in lava. The ascension of this lava with its originally absorbed gases is produced probably by the shifting of the segments into which the earth's crust is broken up. However, this is mere speculation and more detailed knowledge of the interior is required before we can come to a satisfactory theory about volcanic eruptions. In passing we may mention the Mohole project which is aimed at exploring the earth's interior. The main programme of this project is to drill holes in the bed of the oceans where the surface rocks are thinnest, say about three miles deep. These holes are expected to expose the basic rock for observation.

Rotation of the Earth. The earth rotates about its axis in a period of about 24 hours. This rotation as you know, produces the phenomenon of night and day. One of the most definite and simplest proofs of the existence of the rotation of earth is the following. Let us drop a weight from a high tower. We shall find that it does not fall on the point which is exactly under the point from where it is dropped. The point of fall will be found somewhat towards the east. If the earth rotates as a rigid body moving from west to east, then the point of dropping of the weight possesses greater eastward velocity than the point vertically below it, as the former point is more distant from the centre of the earth than the latter. The falling weight retains during its fall the eastward speed with which it started, over and above its vertical motion induced by the earth's gravity. Consequently, it outstrips the point, which was vertically below it, in the direction of rotation.

Revolution of the Earth Round the Sun. The earth revolves round the sun in an elliptic orbit, with the sun situated at one of its foci. The point of the orbit at which the earth is nearest to the sun is called the perihelion, while the point at which it is farthest is called the aphelion. Although, the orbit of the earth, no doubt, is elliptic, its eccentricity is only 0.017 which is very small. Consequently, the orbit differs but slightly from the circle. On an average, the earth completes a round of the sun in 365.2564 days, an interval which defines the sidereal year.* If we regard the earth as fixed, then the sun will appear to describe an ellipse round the earth. It is, in fact, this relative motion of the sun that we observe when we see it moving from one Zodaic sign to the next. The plane of the apparent orbit of the sun is called the ecliptic, which has already been discussed. The ecliptic is inclined to the celestial equator at an angle of $23° 27' \simeq 23.5°$. This angle is called the obliquity of the ecliptic.

The average speed of the earth on its journey round the sun is approximately $18\frac{1}{2}$ miles per second. This may be compared with the speed of 1/3 miles per second imparted by the rotation of earth at a point situated on its equator.

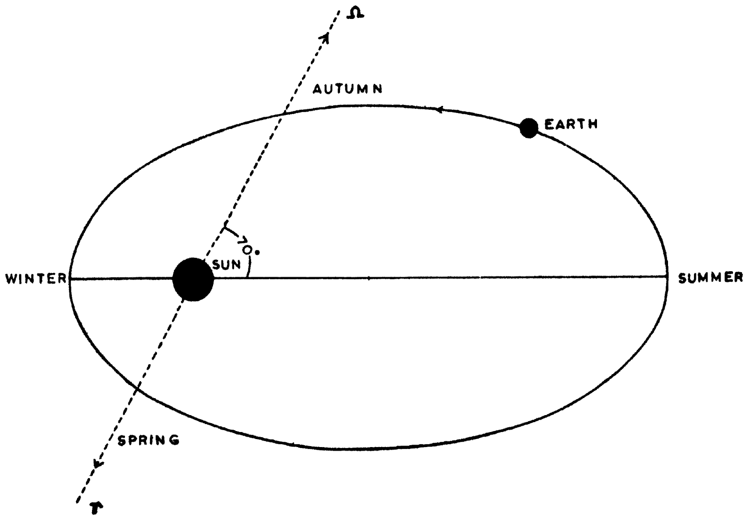

FIG. 11.3 *Earth's orbit round the sun, and its seasons*

*The tropical year, which is the length of the year from one spring equinox to the next, is slightly different. Its length is 365.2422 days.

As you know, the yearly motion of the earth, keeping its axis of rotation always pointed in the same direction, produces the phenomenon of seasons, as it is evident from Figure 11.3, that the earth is nearer the sun in winter than in summer.

Earth's Atmosphere. The statement that our earth possesses a very extensive atmosphere does not need any proof. As mentioned earlier, the atmosphere provides us with oxygen and rain, without which life would have been impossible on the earth. It saves us from frequent bombardment by the meteors, which would have made our life very insecure and uncomfortable. It also protects us from the harmful effects of the X-ray and ultra-violet radiations from the sun and other sources. This radiation is utilized in ionizing the atoms in the outer layers of the atmosphere. Consequently, we find free electrically charged particles in these layers. These layers constitute what is popularly known as the ionosphere. The ionosphere (Figure 11.4) is situated roughly beyond the height of 60 miles above the earth's surface. The lower layer of the ionosphere is called the E layer where ionization is caused by the X-rays emitted by the corona of the sun. The remaining part of the ionosphere is called the F layer. The F layer is further divided into two sub-layers, F_1 and F_2. The lower layer F_1 extends roughly from 120 to 200 miles. Rocket studies have disclosed that the main source of ionization in the F layer is the radiation from helium atoms in the wave length near 500 angstroms. Thus the F layer owes its existence to the radiations from the very hot parts of the corona.

The presence of the ionosphere has made radio communications possible. The radio waves sent by an earth-bound station are reflected by the ionosphere and sent back to the earth. The radio receiver, in fact, receives these reflected waves.

The temperature of the atmosphere at first decreases but at a height of about 15 miles it begins to increase so much so that at a height of about 35 miles it rises back to the normal ground temperature. It again drops up to the height of about 60 miles. After this it steadily rises and a temperature of the order of 1000° is reached high up in the atmosphere.

The main constituents of the atmosphere are nitrogen and oxygen but it contains some other gases like argon, carbon dioxide, hydrogen and water vapour. Table 1 on page 176 gives the composition of the atmosphere.

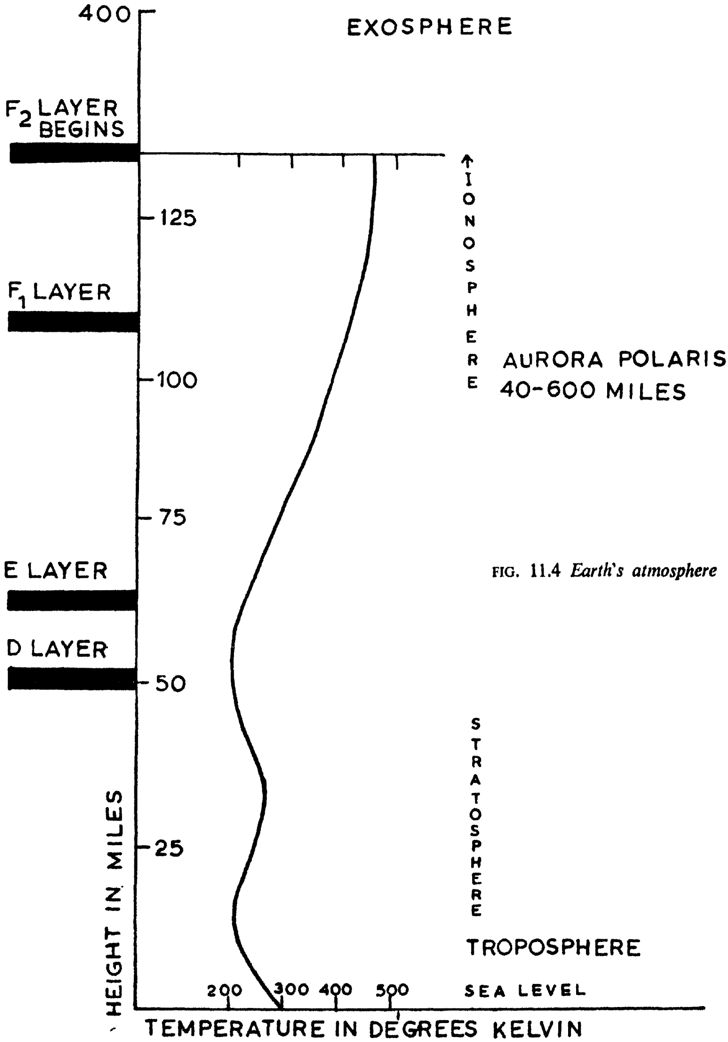

FIG. 11.4 *Earth's atmosphere*

TABLE 1

Constituent	*Percentage by volume*	*Constituent*	*Percentage by volume*
Nitrogen	78.08	Hydrogen	0.01
Oxygen	20.94	Neon	0.0012
Argon	0.94	Helium	0.0004
Carbon dioxide	0.03	Water vapour	0.0 to 2.6

In the lower layers of the atmosphere, which are kept well stirred by the winds, the chemical composition is more or less uniform. However, recent studies of the motion of artificial satellites have indicated that at a height of several hundred miles the air is mostly hydrogen. Moreover, its density fluctuates daily, being greater by day than by night. The density also shows increase with the increase in flare activity on the solar surface.

The space between the sun and the earth is not completely empty. The coronal gases of the sun extend to the earth, in fact, throughout the solar system. The density of the interplanetary matter is very small, say a few hundred particles per cubic centimetre. Even this rarefied gas with suspended dust particles is enough to produce the phenomenon of Zodiac light, a faint pale glow extending around the entire Zodiac but showing most prominently in the neighbourhood of the sun. The Zodiac light is caused by the reflection of the sunlight by the interplanetary dust.

The corpuscular radiation from the sun, chiefly the slow moving hydrogen nuclei, is emitted at the time of violent solar flares. These protons produce a very interesting phenomenon in the earth's atmosphere. The terrestrial magnetic field accelerates them, and when these fast moving nuclei collide with the atmospheric gases they begin to shine. When this phenomenon takes place in the northern hemisphere it is called the *aurora borealis.* When it takes place in the southern hemisphere, it is called the *aurora australis.* Both are called the aurora polaris. Aurorae appear in exceedingly varied form and brightness and sometimes produce great splendour. They shine out suddenly in the sky, flashing and darting, and execute the strangest rapid movements. They undergo swift changes in form and intensity. They vary greatly in colour. Generally they possess white, greenish or yellowish white hue. Sometimes they show up a brilliant rose colour tinged with violet.

Spectroscopic analysis of an aurora has revealed that the blue and violet radiations are due to nitrogen molecules and some of the green radiations ue to oxygen molecules. The characteristic lines of hydrogen have also been ound in the spectrum of aurora light. The Doppler shift of hydrogen lines ndicates that the hydrogen is in violent motion directed along the magnetic nes of the earth. The maximum velocity attained by the hydrogen atoms s about 2000 miles per second. It is almost certain that this hydrogen is of olar origin.

Recently, it has been discovered that there exist two belts of charged particles n the atmosphere of the earth called the *Van Allen Belts* (Figure 11.5). The inner

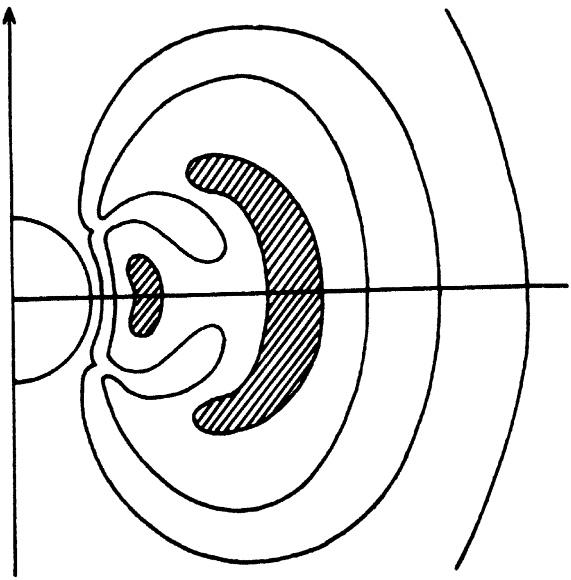

FIG. 11.5. *Van Allen belts. The shaded area represents the hemisphere of the earth. The cross-hatched areas represent the Van Allen belts.*

belt is situated a few thousand kilometres above the surface of the earth and contains both electrons and protons, produced perhaps by the neutron decay in cosmic ray showers. The outer belt extends from 3 to 5 earth radii or more and consists of high energy electrons and low energy protons. These are perhaps the particles ejected from the sun and entrapped in the earth's magnetic field which more or less conforms to that due to a dipole situated at the centre of the earth in the north-south direction.

Moon (Chandra)

Earth has one satellite, namely the Moon. The mean distance of the Moon from the earth is about 238,000 miles. Its diameter is 2160 miles about 27 per cent of the earth's diameter. Its mass is about 1/82 of the mass of the earth.

The moon has no atmosphere and we can see its surface features clearly through a powerful telescope. Due to the huge mass of the earth, its surface gravity is large enough to prevent the high velocity atoms and molecules in its atmosphere from escaping into space. In fact, a body will not be able to escape from the gravitational field of the earth unless it acquires a velocity of more than 7 miles per second. This velocity is called the velocity of escape from earth. On account of the small mass of the Moon, the velocity of escape on its surface is only 1.5 miles per second. This accounts for the fact that Moon has no atmosphere, for even if it had an atmosphere initially, the atoms and molecules with thermal velocities more than the escape velocity would have escaped into space.

The period of revolution of the Moon round the earth and the period of rotation about its axis are both equal to 27.32 mean solar days, so that the same face of the Moon will always be directed towards the earth. Hence, it should not be possible to see the other side of the Moon's surface. But the rotation of the earth, the inclination of the orbit of the Moon to its equator ($1\frac{1}{2}^\circ$) and to the ecliptic ($6\frac{1}{2}^\circ$) and the ellipticity of its orbit combine together to show about 59 per cent of its surface. Thus an earth-bound observer will never be able to see the remaining 41 per cent of the lunar surface. However, recently the Russian and American space stations have successfully televised the pictures of this hidden part of the Moon. This is one of the major achievements of the space satellites.

The lunar surface is very rugged (Figures 11.6a and 11.6b). Most conspicuous to the eye are the large planes called the maria (seas). The most numerous and the most characteristic features of its surface are the craters which are ring-like formations which resemble the terrestrial volcanic craters. The crater floors may be situated above or below the level of the surrounding area. It is very

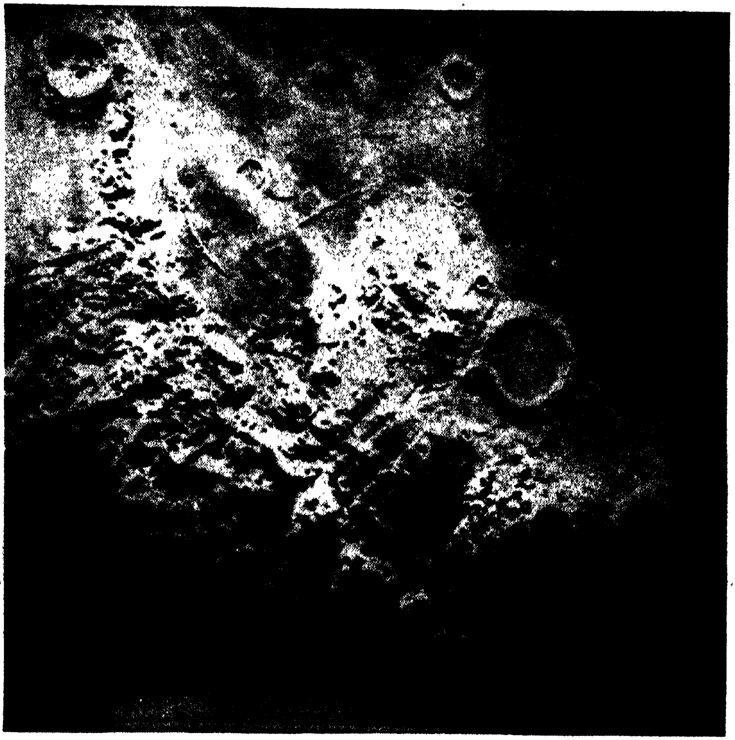

FIG. 11.6a *The lunar surface. The flat region represents the Mare. The circular structures represent the craters. The elevated portions represent the mountain ranges.*

FIG. 11.6b *Photograph of the other side of the moon received from the automatic Russian interplanetary station*

common to find a peak or a group of peaks at the centre of a crater. Some of the largest craters are as large as 146 miles across and the walls of such craters are in reality circular mountain ranges commonly rising to the height of 20,000 feet.

Besides maria and craters there are ten mountain ranges on the lunar surface. The highest of these is situated at its southern limb and has peaks well over 20,000 feet. This mountain range has been named the Doerfel Range.

Mars (Mangal)

Mars is the fourth planet in the solar system and it is named after the god of war on account of its ruddy colour. Mars is the object of the greatest interest among the planets on account of the possibility of the existence of life on it.

The mean distance of Mars from the sun is 1.524 A.U. and it describes the elliptic orbit with an eccentricity equal to 0.093 in 687 days. When nearest to the earth its distance is 34,600,000 miles and at this time it can be best observed. At this instant it is brighter than any other planet except Venus. The period of rotation of Mars about its axis is $24^h\ 37^m\ 22.7^s$, only 41.5^m larger than the earth's period of rotation. The equatorial plane of Mars is inclined at an angle of 25° to the orbital plane. Mars has a mass only 1/9th of the mass of the earth.

Mars has an atmosphere which is very thin; its mass above unit area of the surface is only 25 per cent of that above the same area on earth's surface. Spectroscopic observations indicate that there is no direct trace of water vapour in the Martian atmosphere. If water vapour is present then it must be less than 5 per cent of that present in the terrestrial atmosphere. As far as oxygen is concerned, it is certain that its abundance is less than 0.1 per cent of what it is on the earth. Carbon dioxide is present in greater abundance than in the earth's atmosphere.

The thinness of the atmosphere of Mars allows us to observe its surface distinctly. The most conspicuous feature of the surface is the presence of the white polar caps (Figure 11.7), the extent of which changes with the Martian seasons. In winter, a cap extends half-way up to the equator and in summer it almost disappears. These polar caps are in reality thin layers of snow which are not deeper than a few inches. If they had been deeper, the solar heat would not have been able to melt them completely in summer.

There is no water on the surface of Mars, otherwise it would have reflected the sunlight as a bright point which would have been observed. There are wide deserts which give the planet its red colour.

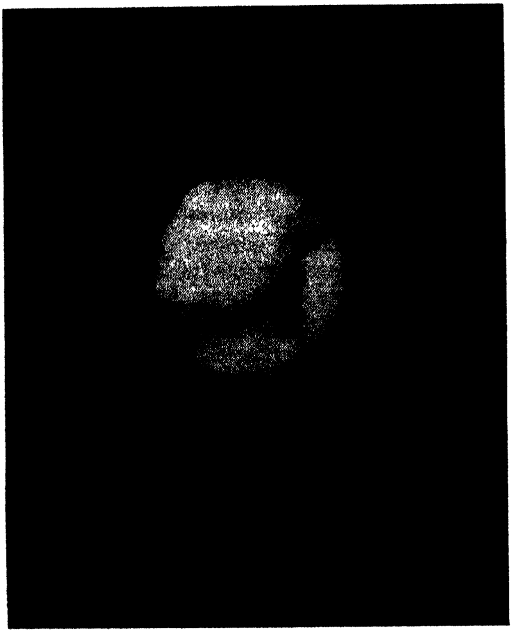

FIG. 11.7 *The Martian polar cap. The snowy white patch at the top represents the polar cap.*

Another conspicuous feature on the surface is the presence of darker areas which are green, blue-green and even grey. Careful observations reveal that these colours change to brown, to brown-lilac or to carmine. These are almost exactly the colours of the leaves that fall in summer and autumn. This suggests the possibility of some sort of vegetable growth on the Martian surface. However, there can be other reasons for these colour changes. For example, McLaughlin suggests that these colour changes may be due to the interaction of the ashes ejected by the volcanoes with the gases of the atmosphere.

The photographs taken under very favourable conditions show straight markings whose visibility changes with the Martian seasons and to some extent in the same season from year to year. There is considerable controversy about the interpretation of these markings. Some astronomers like Lowell believe that these are canals and waterways constructed to carry water from the melting polar caps to the arable lands in temperate and equatorial zones. Such an interpretation implies the existence of intelligent life. The extensive photographic study of the Martian surface by Lyot shows the absence of these regular markings. The recent study through powerful telescopes shows that some of the regular patterns which appear on Martian surface show considerable variation in character. These pieces of evidence suggest that the mythical canals are perhaps widely separated parts which the low resolving power of the telescopes puts together producing continuity. Further, if we accept that the colour changes are due to the interaction of volcanic ashes with the atmospheric gases, it may be that these markings are nothing but the deposition of ashes at locations determined by the direction of the winds. Thus, there is no finality about the existence of life or even vegetation on Mars. However, these speculations have given rise to the myth of Martian man and the flying saucers.

Mars has two satellites; the inner one is called Phobos (fear) and the outer one Deimos (dread) after the fiery horses of the chariot of the god of war. They are very tiny objects with diameter 10 and 5 miles, respectively.

Jupiter (Brihaspati, Guru)

Jupiter is the fifth planet in the solar family. Its mass is about 317 times that of the earth and its equatorial diameter is 88,640 miles, i.e., about 11 times larger than that of the earth. In fact, Jupiter is the most dominant body in the solar system, both in mass and size. This explains why the ancient Romans named it after Jupiter, the king of gods. Its average distance from the sun is 5.203 A.U. It revolves round the sun in a period of 11.86 years along an elliptical path with an eccentricity of 0.048. Its equator is inclined to the orbital plane at an angle of 3°. The period of its rotation is 9^h55^m so that its material at the equator turns round its axis with a velocity of 30,000 miles per hour. The consequent centrifugal force due to rotation is sufficient even when acting against the surface gravity which is 2.6 times that of the earth to flatten the shape of the planet so that the equatorial diameter exceeds the polar diameter by 5760 miles. Careful observations on the markings of the Jovian surface show that the angular velocity of rotation changes with latitude. It is most rapid at the equator and decreases as we go to higher and higher latitudes, as in the case of the sun.

The photographs of Jupiter show conspicuously the belts of deep red and brown against the bright creamy white background. These belts maintain their general arrangement and size although changes take place in their cloud-like structure. Occasionally bright spots appear on the dark belts and dark spots appear on the bright belts (Figure 11.8). The belts are nothing but currents in the very deep and extensive atmosphere of the planet.

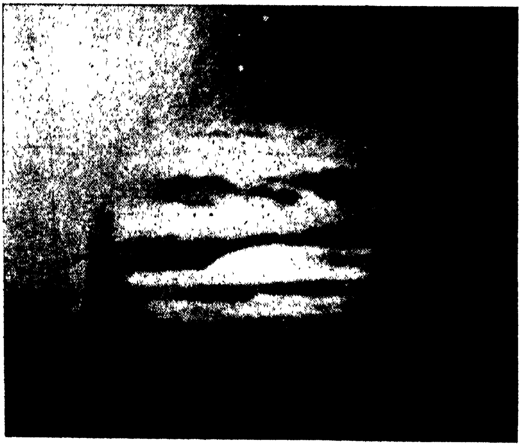

FIG. 11.8 *Jovian belts*

Ammonia and methane (marsh gas) have been identified in the atmosphere of Jupiter and it is inferred that hydrogen is also in abundance. Methane is in the gaseous form whereas much of the ammonia must be frozen into crystals. It is estimated that the temperature of Jupiter is −216°F. This low temperature is expected because every unit area of Jupiter receives only 1/27th of the sunlight received by the corresponding area on the earth's surface.

Since the inclination of its equator to its orbital plane is only 3° and its orbit is more or less a circle, the climate on Jupiter is uniform and there are no seasons. On account of the extreme unchanging cold and an atmosphere poisoned by the presence of ammonia and marsh gas, this planet is unsuitable for the existence of life.

Jupiter has 12 satellites. The four brighter ones among them were discovered by Galileo in 1610 and are hence called the Galilean satellites. The twelfth satellite was discovered as late as 1951. The satellites produce interesting phenomena of eclipses, occultations and shadowtrains. The satellites of Jupiter came into prominence when Roemer used them in determining the speed of light in 1675.

Jupiter is an exceptional planet in another way also. It is the only planet which has so far been found to send intense bursts of radio emission (18 Mc/sec.). The cause of these bursts is not clear but it is surmised that the planet has a magnetic field associated with it and the radio waves are perhaps generated by the electrons gyrating about the magnetic lines of force. This magnetic field could not be discovered by the optical studies.

Saturn (Shani)

It is named after the god of time. Its average distance from the sun is 886 million miles or 9.539 A.U. It revolves round the sun in a period of 29.458 years in an elliptic path with on eccentricity of 0.056. The planet has an equatorial diameter of 74,100 miles and is the second largest planet in the solar system. It is also the second massive planet, with 95 times more mass than that of the earth. Its mean density is 0.72 so that it would float in water.

The period of rotation of Saturn is $10^h 14^m$ at the equator. Thus its rotation is only slightly less rapid than that of Jupiter. The period of rotation increases with its latitude, so much so that it becomes $10^h 38^m$ at the poles. This rapid rotation gives the planet a spheroidal shape, the equatorial diameter being 8000 miles greater than the polar diameter.

Saturn has a deep atmosphere and we observe only the top of the atmosphere. Like Jupiter it shows belts which are also currents in the atmosphere. As in Jupiter's atmosphere, in Saturn's atmosphere, too, ammonia and methane have been identified. It is estimated that the temperature of Saturn is −243°F.

This low temperature is due to the fact that each unit area of its surface receives only 1/91 of the solar heat received by the corresponding area on the earth.

The equator of Saturn is inclined at an angle of 26°45′ to its orbital plane and hence we expect that it will experience a cycle of seasons like our earth.

Saturn has 9 satellites, but the most distinguishing feature of this planet is the presence of rings (Figures 11.1b and 11.9) revolving round it. These rings were also discovered by Galileo in 1610. The innermost ring is situated at

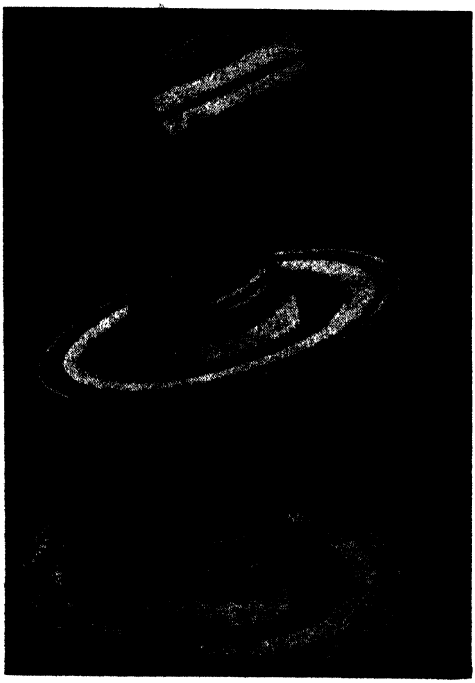

FIG. 11.9 *Saturn's rings. The photograph at the top has been taken from the edge-on position and the other two from different inclinations.*

about 6000 to 7000 miles from the surface. The rings have an overall diameter of 171,000 miles. It is difficult to measure their thicknesses due to their distances, but a rough estimate indicates that they may be 10 to 20 miles thick. These rings are highly stable.

All astronomers agree that these rings are composed of a swarm of small particles, probably of the size of dust, sand or gravel particles but not as fine as flour. They are estimated to occupy less than 1/6th of the total volume of the rings and perhaps have mass less than $\frac{1}{4}$th the mass of our Moon.

It is surmised that these rings are formed out of the material of a satellite which disrupted due to the tidal effect of the planet.

Uranus

It is named after the god of skies and was discovered by Herschel in 1781. The diameter of Uranus is 32,000 miles and it is 14.7 times more massive than the earth, yet it looks faint on account of its enormous distance from the sun. Its average distance from the sun is 19.191 A.U. or 1,782,000,000 miles. Its period of rotation is about $10^h 45^m$ which is more or less equal to that of Saturn. On account of this rapid rotation, it has a spheroidal shape with its equatorial diameter greater than the polar diameter by about 2000 to 3000 miles.

The most important feature of this planet is that it rotates from east to west in contrast to other planets which rotate from west to east. Moreover, its equator is inclined to its orbital plane at 82°.

It has an atmosphere which shows a great abundance of methane. The lack of gaseous ammonia can be explained in view of the low temperature of the order of −300°F prevailing there. At this temperature all ammonia will be frozen in the form of crystals.

It is clear that no life in the form known to us can exist at such a low temperature and in the presence of the poisonous atmosphere.

Uranus has five satellites.

Neptune

This is named after the the Greek god of the seas. It was discovered mathematically by Adams and Leverrier in 1846 in an attempt to explain the source of perturbations in the orbit of Uranus.

The average radius of its orbit about the sun is about 30.071 A.U. i.e. 2,743,000,000 miles and its period of revolution round the sun is 164.79 years.

Its diameter is 27,700 miles; its mass is 17.2 times the mass of the earth and period of rotation is $15^h\,48^m$. Its temperature is −330°F and it has an atmosphere which shows an abundance of methane. Once again, life in the form known to us cannot exist on this planet.

Neptune has two satellites.

Pluto

The most distant planet discovered so far is Pluto. It is named after the Greek god of Hades. It was discovered by Lowell and Pickering theoretically in an attempt to explain the source of perturbation in the orbits of Uranus and Neptune. It was first photographed on 21 January 1930.

Its mean distance from the sun is 39.5 A.U. or 3,670,000,000 miles. The orbit is inclined to the equator at 17° and has an eccentricity equal to 0.25, the highest value for any planet. Its diameter is estimated to be 3600 miles and mass approximately equal to the earth's mass. Probably its temperature is −350°F.

It has no satellites.

Data about the Solar System

In Table 2 we have collected the important data about the solar system for ready reference.

TABLE 2

	Mercury	*Venus*	*Earth*	*Mars*	*Jupiter*	*Saturn*	*Uranus*	*Neptune*	*Pluto*
1. Mean distance (in A.U.)]	0.387	0.72	1.0	1.52	5.2	9.73	19.2	30.1	39.6
2. Sidereal period	88 (days)	225 (days)	365 (days)	687 (days)	12 (years)	29 (years)	84 (years)	165 (years)	249 (years)
3. Obliquity	7°	3°.24	0°	1°.51	1°.18	2°.29	0°.46	1°.47	17°.19
4. Mass	0.05	0.8	1	0.1	318	95	15	17	0.9
5. Specific Density	4.1	4.9	5.5	3.9	1.3	0.7	1.3	1.6	5.5
6. Radius (10^8 cm)	2.5	6.2	6.4	3.4	69.8	57.6	25.5	25.0	6.4
7. Number of satellites	0	0	1	2	12	9 and rings	5	2	0
8. Rotational period	88 (days)	very slow rotation*	24^h	25^h	10^h	10^h	11^h	12^h	..

*According to the findings of the space vehicle, Mariner II.

Other Members of the Solar System

Asteroids. Asteroids are small planets revolving independently about the sun. The largest of these has a diameter of 480 miles, while the smallest observed has a diameter of one mile or so. They are situated approximately at 2.8 A.U. from the sun. Their discovery completed the vacant place between Mars and Jupiter in the Bode's law (described in the next chapter). The first of them, called Ceres, was discovered by Piazzi in January 1801. So far over 1500 asteroids have been discovered. Their total mass is probably less than $\frac{1}{3000}$th of the mass of the earth. Their period of rotation about the sun is 4.69 years. Their orbits are more eccentric than those of the major planets and more highly inclined to the ecliptic. The average value of the eccentricity is 0.15 and the average inclination is $9\frac{1}{2}°$.

Comets. Comets are probably the most interesting objects of the solar system on account of their diffuse appearance and the tails they possess. A fully developed comet consists of an ill-defined coma (head) with a star-like nucleus embedded in it, and a tail extending from the head. They appear in various dimensions and have surprisingly low densities. They show an extraordinary range of brightness.

So far about 1000 comets have been observed. About 400 out of these were discovered before the invention of the telescope.

Most of the comets have such eccentric orbits that they can hardly be distinguished from parabolas. Their perihelion distances range from a few hundred thousand miles to 4.5 A.U. Their periods range from 3.3 years (for Encke's comet) to 1,000,000 years or so.

The short-period comets with periods less than 100 years have well-determined orbits. So far 60 such comets have been observed and about 40 of them have aphelia and nodes within 15,000,000 miles of Jupiter's orbit.

The average diameter of the heads of the comets is about 18,000 miles and varies from 10,000 to 1,400,000 miles.

A comet, when first visible, is very faint and shows only a coma. As it comes nearer the sun, the nucleus becomes visible and the coma grows in size. A large comet begins to form the tail at about 200,000,000 miles from the sun. Its brightness increases as its distance from the sun decreases. From this it is inferred that a comet not only reflects light from the sun, as all planets and satellites do, but also emits its own radiation. The sun is ultimately the source of this radiation as the material of the comet converts the invisible ultra-violet radiation of the sun into the observed excess of visible light. Figure 11.10 shows the development of Halley's comet with time.

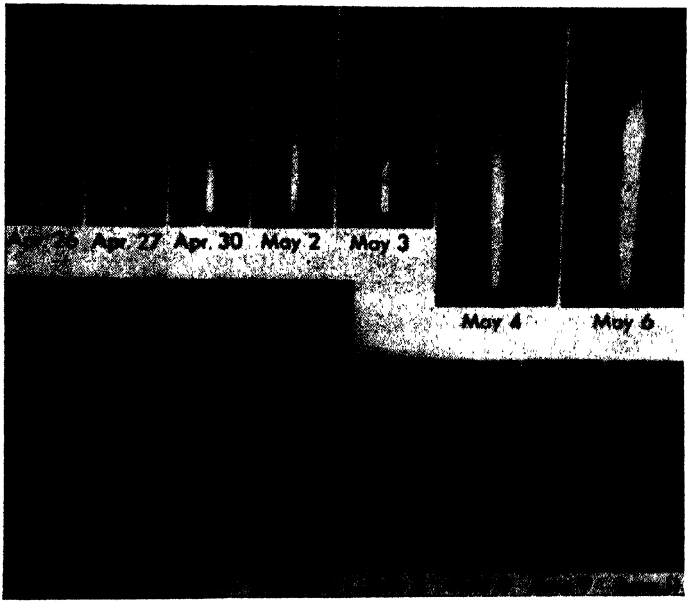

FIG. 11.10 *The development of Halley's Comet.*

The comet tails are always directed away from the sun due to the pressure exerted by the solar radiations. The comet heads are composed of gases and probably dust. The spectroscopic studies indicate the presence of molecules of CO_2, N_2, CN, CH, CO, NH (nitrogen hydride) and OH (hydroxyl) in the head. In a comet, which comes quite near the sun, the presence of metallic sodium, iron and nickel has also been detected.

According to the current hypothesis, comets are the debris of a planet which exploded to form the asteroids. The orbits of the fragments of such an explosion would be of a great variety of sizes and shapes. The fragments having nearly circular orbits will not be significantly affected by Jupiter's perturbations and continue to revolve as asteroids. The other fragments would be diffused by Jupiter into very large orbits by the expulsion process. The pieces which were not permanently ejected from the solar system form the comet cloud.

Some Important Comets

Halley's comet. It was first noted in 240 B.C. but was identified as a comet by Halley in 1682. Its period is about 76 years. It was last seen in 1910.

Brook's comet. This has a period of 29 years, but in 1866, it came within the orbits of the inner satellites of Jupiter. Therefore, its period of revolution about the sun was reduced to seven years. From the fact that it did not change the motion of the satellites, it is inferred that its mass is less than $\frac{1}{10,000}$th of the mass of the earth.

Ikeya-Seki Comet: The fascinating sight which the Ikeya-Seki Comet presented in the sky is still fresh in our minds. The comet was first observed by two amateur Japanese astronomers Ikeya and Seki and is named after them. It came nearest to the sun on October 21, 1965 and had a grazing collision with it. During the hairpin turn round the sun it split into two pieces. The comet attained about five times the brightness of the moon, and hence it is regarded as one of the brightest comet of the century. Its tail was about 20 million miles in length. Spectroscopic studies have revealed the presence of sodium, iron, nickel, copper, potassium and ionized calcium. The period of this comet has not been determined as yet, but it is surmised that it may reappear in our view some 500 to 1000 years later.

CHAPTER XII

Theories of the Origin of the Solar System

Regularities in the Solar System

CONSIDERING only the major planets and the satellites, the solar system exhibits the following regularities in its dynamical and physical properties which any successful theory of the origin of the solar system *must* explain:

Orbital Regularities. All the planets and satellites with the exception of the outer satellites of Jupiter and Saturn have a common direction of orbital motion. The eccentricities of the orbits are small and the orbital planes are practically coincident with the ecliptic.

The Titius-Bode Law. The mean distances of the planets from the sun very closely obey the Titius-Bode law which can be mathematically put as

$$r_n = a + b.2^n,$$

where r_n is the mean distance in A.U. of the nth planet from the sun, $a=0.4$ A.U. and $b=0.3$ A.U., provided the group of asteroids is counted as a planet. We may check that this formula gives reasonably accurate distances of the planets enlisted in the Table 2 of Chapter XI on taking $n=-\infty, 0, 1, 2, 4, 5, 6, 7, 8$. The planet corresponding to $n=3$ is absent. This place is occupied by asteroids. In fact, the absence of a planet corresponding to $n=3$, as predicted by Bode's law, led to the discovery of the asteroids. Are there planets corresponding to the values of n higher than 8 ? It is difficult to answer this question, for even if there are, they would be so faint in the reflected light of the sun that they will never be observed directly. One thing is certain that at such distances the gravitational pull of the sun will be too weak to hold them in the solar system.

The mean distances of satellites from their planets also obey similar laws.

Division of Planets. The inner planets, namely, Mercury, Venus, Earth

and Mars, have small masses, high specific densities, low rotational velocities and few satellites, while the outer planets, namely, Jupiter, Saturn, Uranus and Neptune, have large masses, low specific densities, relatively higher rotational velocities and a large number of satellites. Pluto is an exception.

We note another significant fact which any theory about the origin of the solar system *must* explain:

Distribution of Angular Momentum. The sun, although it has more than 98 per cent of the total mass of the solar system, possesses only 2 per cent of the angular momentum of the solar system.

Monistic and Dualistic Theories

In general, the theories about the origin of the solar system may be divided into two groups: (*i*) Monistic, and (*ii*) Dualistic. The propounders of the monistic theories deal with a closed system and assume that external celestial bodies have nothing to do with the formation of the solar system. On the other hand, dualistic theories attribute the formation of the solar system to the interaction of other celestial bodies to lesser or greater degree and thus they deal with an open system. The theories of Descartes, Kant, Laplace, Birkeland, Berlage, Kolmogorov, Weizsacker, Alfven, Hoyle and McCrea are monistic. The theories of Buffon, Moulton and Chamberlin, Jeans and Jeffreys, and Lyttleton, etc., are dualistic. We record that the distribution of angular momentum in the solar system proved to be the stumbling block for most of the earlier theories.

Important Attempts to Explain the Origin of the Solar System

We shall briefly discuss some of the important theories about the origin of the solar system.

Laplace's Nebular Hypothesis. In his nebular hypothesis, Laplace (1796) starts with a rotating nebula that cools and contracts and in doing so throws off successive rings of material that condenses into planets. The central residue issupposed to form the sun.

The fundamental difficulty with this hypothesis is that such a process will

not be able to explain the low angular momentum of the sun. It is also lacking in the finer details of the mechanism of condensation of the rings into planets.

Tidal Theories. The main exponents of the tidal theories are Buffon, Jeans, Jeffreys, Chamberlin, Moulton and Lyttleton. In all these theories it is assumed that the material which formed the planetary system came from the sun, being ejected out of it either under the tidal action of a star passing nearby or by bodily colliding with it.

It has been conclusively shown by Spitzer in 1939 that the matter ejected by the tidal action of an intruding star will not have any tendency to condense to form the planets. Instead, it will dissipate into space under the action of the attractive forces of the intruding star and on account of its high temperature. More or less simultaneously, from general dynamical discussion of the collision mechanism between the stars, the author of this book showed that no existing tidal theory can satisfactorily explain the origin of solar system.

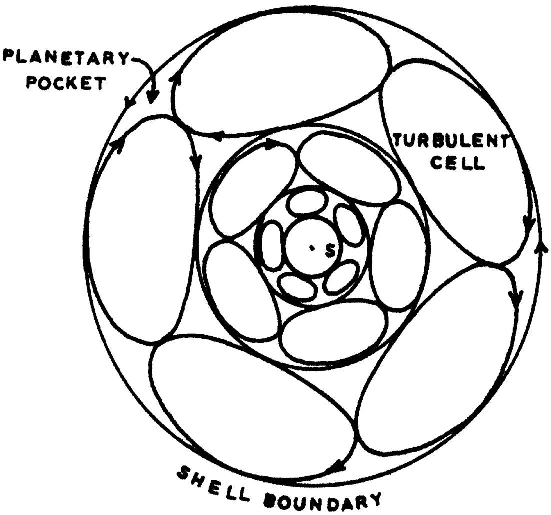

FIG. 12.1 *Eddy formation in Weizsacker's theory of the origin of solar system*

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medium has a non-zero angular momentum about its own centre of mass. If such a portion contracts upon itself, it tends to spin faster in accordance with the principle of conservation of angular momentum. However, if the conductivity is large enough, the magnetic lines of force that originally traversed this portion and the surrounding medium remain attached to both. Thus they behave like elastic strings tied to the rotating portion and its surroundings. The lines tend to get wound round the former and at the same time they exert a torque upon the latter. In this way angular momentum is transferred from the rotating portion to the surroundings.

Hoyle has applied these ideas to the origin of solar nebula. He supposes that this sort of magnetic braking operates first on a portion of material of many solar masses, which has started to contract under its own gravitation. Owing to the increasing density and consequently decreasing ionization, there comes a stage when the material can slip across the lines of force due to reduced electrical conductivity. A fragmentation of the stellar mass now takes place. With further contraction, a fragment heats up and again becomes sufficiently conducting for the magnetic braking to operate. At this stage, the solar nebula is supposed to be formed in the plane of rotation in the form of a disc and it is assumed to possess 10 times the present angular momentum of the solar system. After a time, magnetic coupling between the condensation and the disc results in the transfer of angular momentum to the disc and the cessation of the rotational instability of condensation. The latter then contracts gravitationally to form the sun. The disc also moves outwards on account of its increased angular momentum. The disc is supposed to be at the required position for the formation of the planets. Hoyle shows that hydrogen which is not incorporated into planetes evaporates from the periphery of the system and the escaping hydrogen takes away the surplus angular momentum.

Hoyle's theory is fascinating and explains many aspects but there is an uncertainty about the existence of the required initial magnetic field everywhere in the galaxy. Besides, the process by which the cloud breaks into condensation is not fully understood.

McCrea's Theory (1960). McCrea's theory is quite different from the theories we have discussed so far. It starts from two fairly well-established results about star-formation: (*i*) stars are formed in clusters of several hundred members, and (*ii*) the interstellar matter out of which they are formed is normally

and Mars, have small masses, high specific densities, low rotational velocities and few satellites, while the outer planets, namely, Jupiter, Saturn, Uranus and Neptune, have large masses, low specific densities, relatively higher rotational velocities and a large number of satellites. Pluto is an exception.

We note another significant fact which any theory about the origin of the solar system *must* explain:

Distribution of Angular Momentum. The sun, although it has more than 98 per cent of the total mass of the solar system, possesses only 2 per cent of the angular momentum of the solar system.

Monistic and Dualistic Theories

In general, the theories about the origin of the solar system may be divided into two groups: (*i*) Monistic, and (*ii*) Dualistic. The propounders of the monistic theories deal with a closed system and assume that external celestial bodies have nothing to do with the formation of the solar system. On the other hand, dualistic theories attribute the formation of the solar system to the interaction of other celestial bodies to lesser or greater degree and thus they deal with an open system. The theories of Descartes, Kant, Laplace, Birkeland, Berlage, Kolmogorov, Weizsacker, Alfven, Hoyle and McCrea are monistic. The theories of Buffon, Moulton and Chamberlin, Jeans and Jeffreys, and Lyttleton, etc., are dualistic. We record that the distribution of angular momentum in the solar system proved to be the stumbling block for most of the earlier theories.

Important Attempts to Explain the Origin of the Solar System

We shall briefly discuss some of the important theories about the origin of the solar system.

Laplace's Nebular Hypothesis. In his nebular hypothesis, Laplace (1796) starts with a rotating nebula that cools and contracts and in doing so throws off successive rings of material that condenses into planets. The central residue issupposed to form the sun.

The fundamental difficulty with this hypothesis is that such a process will

decreasing area and due to the depletion of the supply of material. These condensations become planets.

McCrea's theory does not deal with satellite formation and does not attempt to explain Titius-Bode's law. The treatment of supersonic turbulence in the medium is highly idealized and constitutes the main uncertainty.

We can conclude this discussion on the note that the problem of the origin of the solar system is still open.

Plurality of Planetary Systems

The question whether planetary systems other than the solar system exist in the universe can only be answered when the problem of the origin of the solar system is settled. For example, if the planetary system has come into existence due to the tidal action of an intruding star, it can safely be inferred that the occurrence of the planetary systems must be rare, as the encounter between the stars is very rare. On the other hand, if the mechanism of the formation of the solar system is of the type proposed by Hoyle and McCrea, then the occurrence of planetary systems must be more frequent. Even a conservative estimate suggests that about 5 per cent of the stars in our own galaxy and presumably the same percentage of stars in the other galaxies have planetary systems. This amounts to saying that there are millions of planetary systems in the universe. So far the following two stars in our own galaxy have been observed to possess planets: (*i*) Cygni 60, and (*ii*) Ophuchi 71.

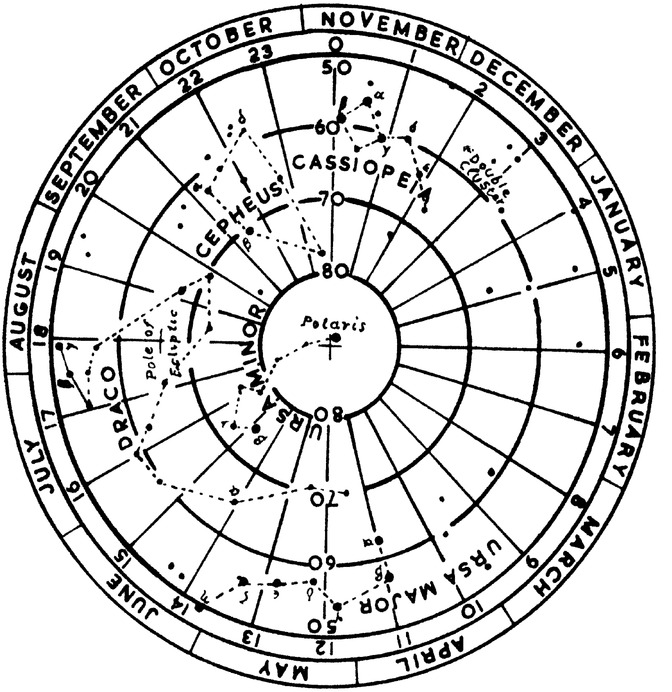
Possibility of Life on Other Planets

We next come to the question of life. This question is more biological than astronomical. The materials on which the living organism is built are carbon and hydrogen, and both of them are found in profusion in the universe. Until recently, it was believed that the complex organic molecules of which such organism are formed can only evolve in association with living matter. However, recently Calvin and Vaughn and other American scientists have discovered that in some meteors there exist complex organic molecules which form the basis of nucleic acids. Nobody can say with certainty that these are vestiges of what were once a living organism or are contaminations from the earth's atmosphere. Whatever it may be, this discovery removes the difficulty of formation of the complex molecules essential for the support of life.

Another great discovery which needs mentioning in this context is due to Miller who, at the suggestion of Pauling, performed the following experiments. He put methane, ammonia, water and hydrogen in a glass sphere and passed an electric discharge through it. He found that about 20 amino acids were formed, out of which the following are the most stable: glycine, α-alamine, β-alamine and α-amino-n-butyric acid. These conclusions have been verified by the Russian scientists, Pavlovskya and Pasynskii, and the German scientists, Heyus, Walten and Meyer. We remind the reader that, in the atmosphere of the planets, methane, ammonia, etc., are present and that the amino acids are the basic ingredients of organic matter.

As regards the observation of life on planetary systems other than ours, it is clear that when we are not sure of the existence of life on a nearby planet like Mars, where conditions are favourable for its existence, it is impossible to directly observe the organic matter in other planetary systems. Perhaps in the near future with the help of space ships we might be able to settle the question whether life exists on Mars and other planets of the solar system.

In our own lifetime, science has achieved miracles in the form of atomic energy, space ships, gigantic electronic brains, wonder drugs, and so on, and has consequently bestowed immense power on human beings. Let us wait and see what other miracles it brings about and what further mysteries it unfolds.



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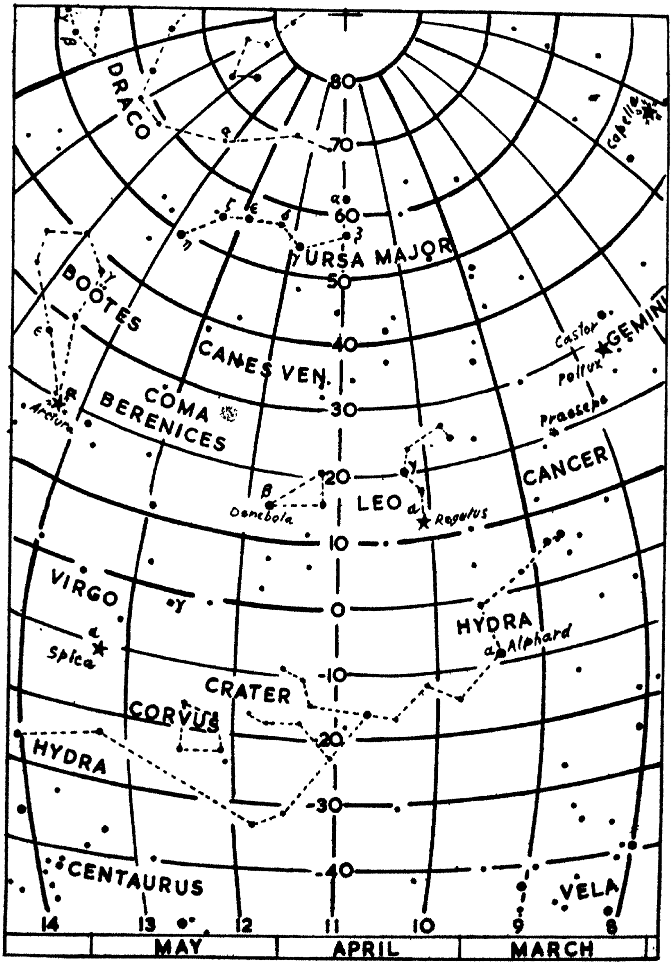
CASSIOPEIA
CEPHEUS
URSA MINOR
DRACO
URSA MAJOR
Polaris
Pole of Ecliptic
Double Cluster

CHART 1



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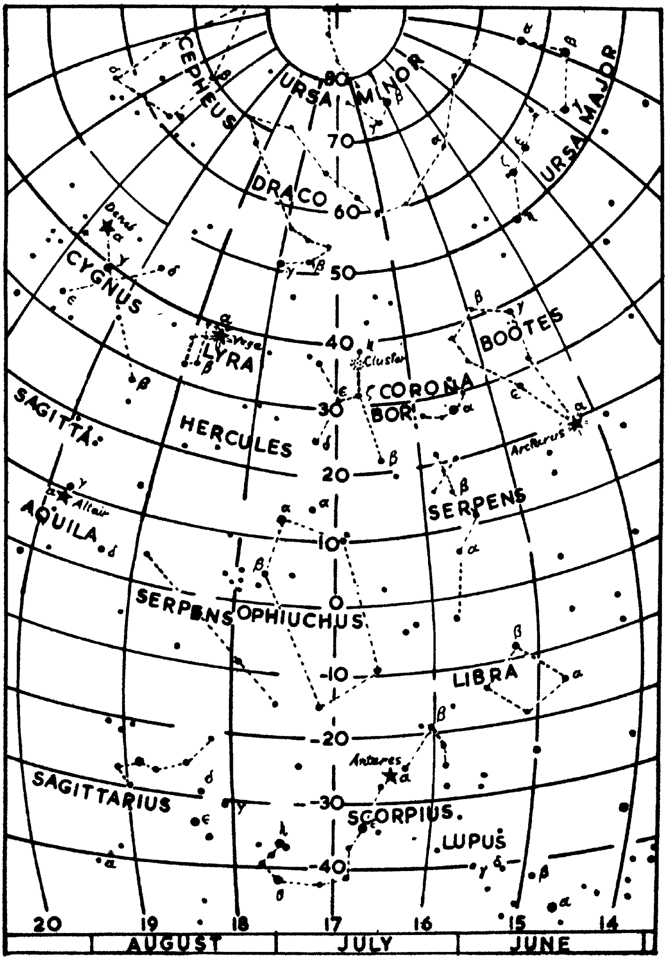
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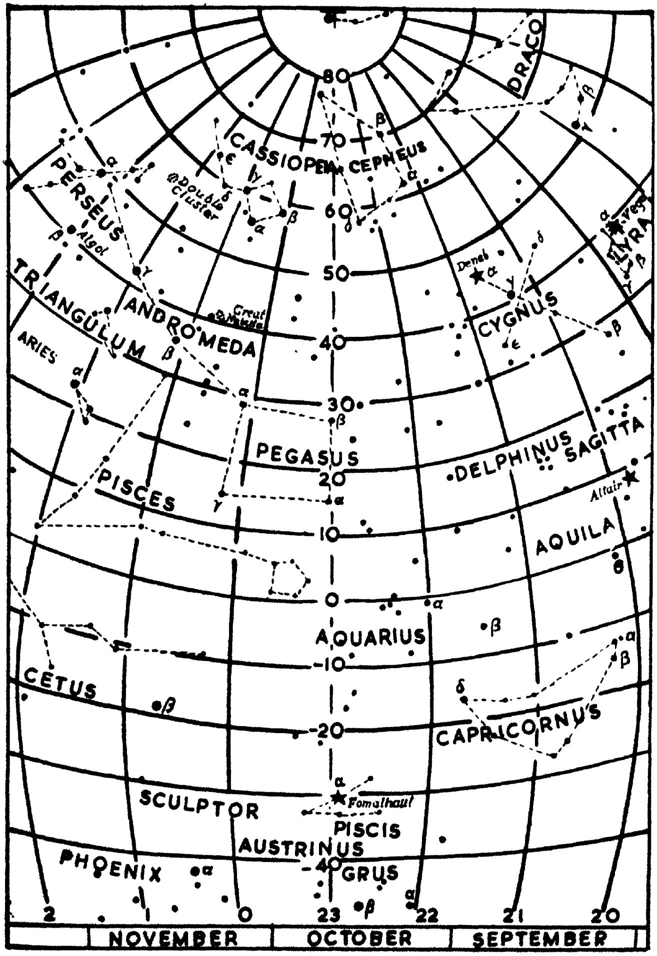
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ARIES
PEGASUS
DELPHINUS
SAGITTA
PISCES
Altair
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CETUS
CAPRICORNUS
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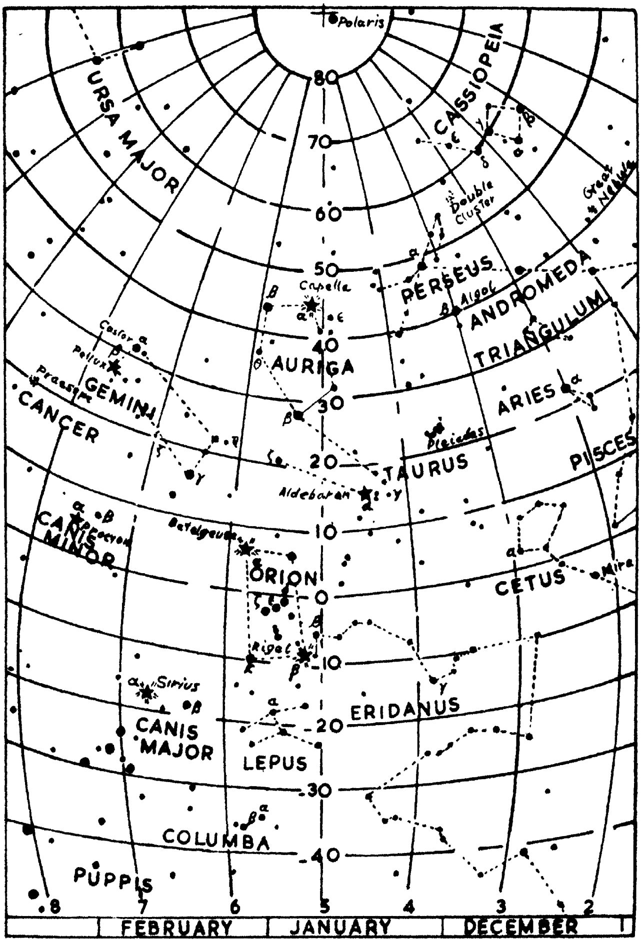
Polaris
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Pollux
Praesepe
GEMINI
CANCER
ARIES
Pleiades
TAURUS
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Aldebaran
Procyon
CANIS MINOR
Betelgeuse
ORION
CETUS
Mira
Rigel
ERIDANUS
Sirius
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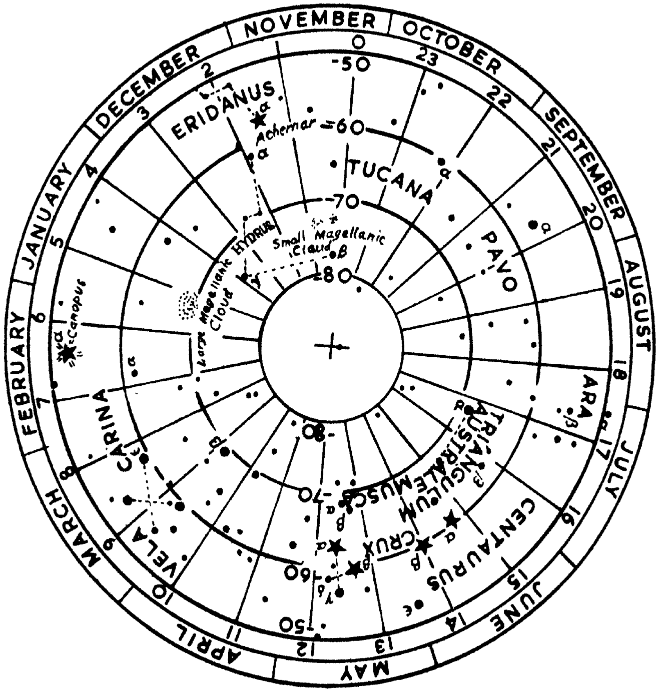
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PAVO
Large Magellanic Cloud
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TRIANGULUM AUSTRALE
MUSCA
CRUX
CENTAURUS
VELA

CHATR 6