RADIO ASTRONOMY J. H. PIDDINGTON

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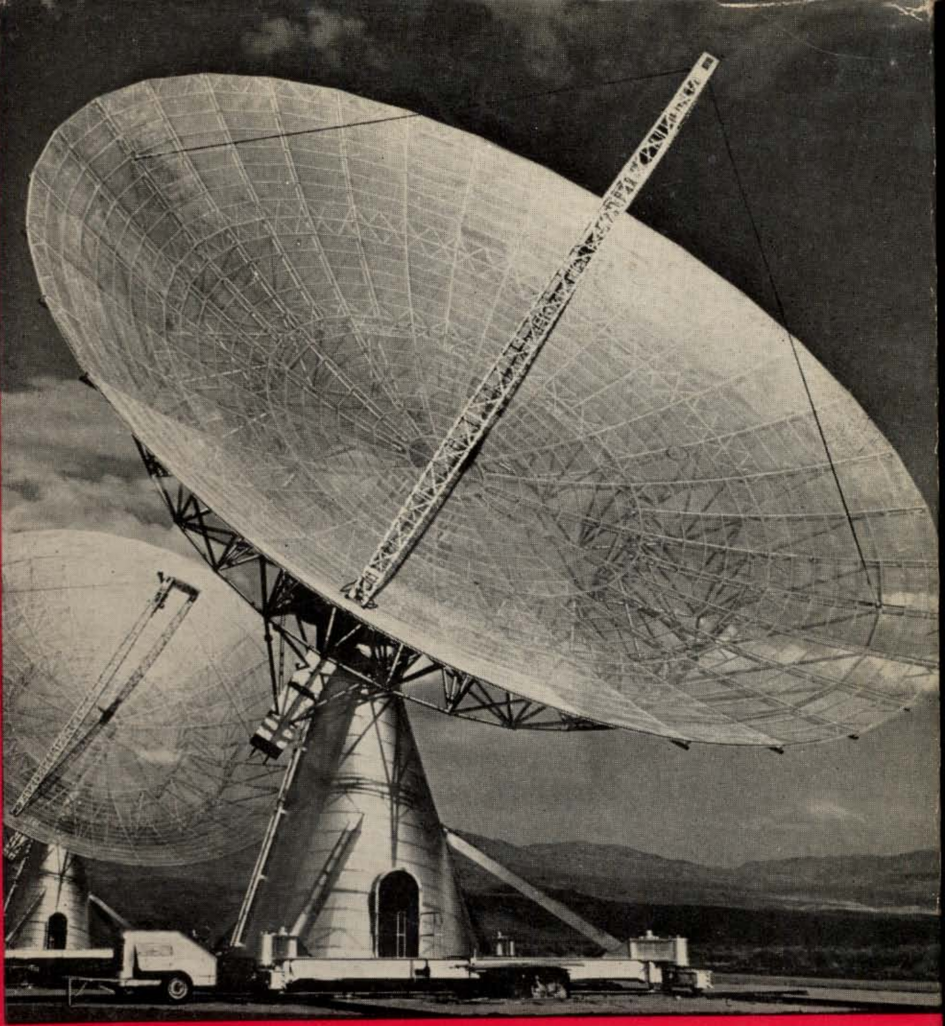

RADIO ASTRONOMY

J. H. PIDDINGTON

This book is an authoritative introduction to all the techniques and applications of radio astronomy, including radar astronomy and radio waves from the moon, planets, rockets and satellites. It will be useful to scientists working in many fields, while, by keeping the mathematical processes to a minimum and simplifying descriptions, the author has produced a work of great interest and value to the reader with little scientific training.

The introductory chapter contains not only an account of the history of radio astronomy and outstanding radio techniques in existence, but also an intriguing insight into future developments, including the specification of the world's largest steerable telescope, now being built for the U.S. Navy.

This work was written in the radiophysics laboratory of the Commonwealth Scientific and Industrial Research Organization, Sydney, Australia, whose policy of research made the book possible.

The photograph on the jacket shows the Owens Valley (California) radio telescope. Two 90-foot diameter steerable reflectors mounted on railway tracks form a variable-spacing interferometer.

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About the author

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* *Titles in preparation*

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Preface

In this book I have tried to give a complete but not detailed account of the science of radio astronomy which may be useful as an introduction to this subject for scientists working in other fields. At the same time, by minimizing mathematical processes and trying to simplify the descriptions of physical principles involved I have tried to make it informative to readers with little scientific training. If the chapters on radio techniques (Chapter 2) and wave propagation (Chapter 3) prove too technical, their omission need not detract greatly from an appreciation of the descriptive aspects of the subject given in the other chapters.

This book was written in the Radiophysics Laboratory of the Commonwealth Scientific and Industrial Research Organization whose policy of research and publication made the book possible. I am grateful to Dr J. L. Pawsey for reading Chapter 1, Prof. W. N. Christiansen for reading Chapter 2, Prof. G. R. A. Ellis for reading Chapter 3, Dr B. Y. Mills for reading Chapter 4, Mr F. J. Kerr for reading Chapter 5, Mr J. P. Wild for reading Chapter 6 and Mr S. F. Smerd for reading Chapter 7.

Sydney, Australia J.H.P.
October 1960

1. Introduction

RADIO astronomy is a new science, most of whose advances have been made in the last two decades. In introducing this subject it is desirable first to indicate the limits of optical astronomy, upon which we relied, until recently, for almost all our knowledge of objects and conditions beyond the Earth. The relation of radio astronomy to the older science is then shown and some of the inherent advantages of radio waves over light waves are indicated. A brief early history of the radio observations is followed by a review of the outstanding radio telescopes in existence or being planned and this introductory chapter closes with a look into the future of the new science.

1.1 *The waves used by optical astronomers*

Until the middle of this century almost all of our knowledge of conditions beyond the Earth had been obtained by observing light waves from stars, from interstellar gas clouds, from galaxies* and other distant objects. Over the centuries this science of optical astronomy made great advances with the invention of the telescope, the spectroscope and photography. When we consider the remoteness of the objects being studied these advances are quite astonishing. Many of the complex nuclear reactions taking place in the interior of stars are understood and the speeds of galaxies distant hundreds of millions of light-years have been measured with some accuracy.

Light waves, like radio waves, are electromagnetic vibrations. The waves we see have lengths varying from about 4000 angstroms (4×10^{-5} cm.) for violet light to 8000 angstroms for red light. This range is only a tiny fraction of the electromagnetic spectrum which, as shown in Fig. 1, extends from wavelengths less than 10^{-10} cm. for gamma rays to beyond 10^{6} cm. for long radio waves. All these waves are fundamentally the same except for their wavelength, which varies over the whole spectrum by a factor greater than 10^{16} or more than 50 octaves. There is, of course, a corresponding range in the *frequency* of the oscillations.

The light waves cover only about one octave in the whole spectrum.

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*This and some other astronomical and radio terms are defined in the glossary.

However, the use of photography and other techniques enables optical astronomers to 'see' from wavelengths of about 3000 angstroms (ultra-violet radiation) to more than 100,000 angstroms (infra-red radiation).* This wavelength range is called the optical 'window' in our atmosphere, through which radiation from distant objects may be received. Outside the limits of this window the radiation is absorbed by our atmospheric gases. This is shown in Fig.1, hatching representing partial absorption and black areas full absorption. The useful optical window, using photographic and photoelectric techniques, is about 5 octaves.

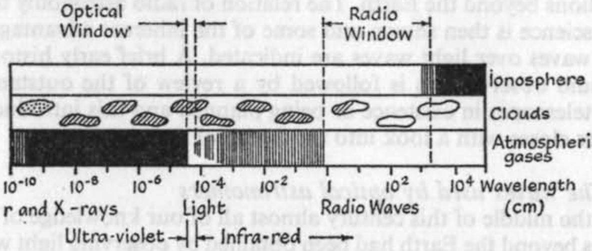

Fig. 1. The electromagnetic spectrum, its absorption and reflection by the Earth's atmosphere and the optical and radio windows through the atmosphere.

It is now known that many celestial objects emit ultra-violet and X-radiation as well as infra-red radiation in bands completely absorbed in our atmosphere. Much useful information will be provided by observations of these rays which will be made by instruments mounted in rockets and satellites. Already pictures of the Sun taken with X-rays have been obtained in this way.

1.2 *The radio window*

A second window, or region of transparency of the Earth's atmosphere, is provided in the radio part of the electromagnetic spectrum. As shown in Fig. 1, this extends from about 1 cm. (below which oxygen and water vapour absorb most of the radiation) to about 30 m. Above a few centimetres the *lower* atmosphere is completely transparent to all waves, even with lengths of hundreds or thousands of metres. However, above about 30 m. the *ionosphere* begins to reflect radiation arriving from distant objects. The combination of the two cut-offs results in a radio window of width about 12 octaves through which enters the radiation whose study is the science of radio astronomy.

Also shown in Fig. 1 are the effects of ordinary clouds in our atmosphere. These are opaque to visible light, so that optical astronomy requires fine, clear, weather. Radio waves on the other hand freely penetrate clouds, the reason being the great wavelength relative to the cloud particle size. Thus radio astronomy has the advantage that it may be carried on unhindered by weather conditions. Other more important advantages are discussed below.

The radio window was not utilized until relatively recently mainly because radio techniques had not been adequately developed. Great advances in this field were made during World War II and shortly thereafter the new science was making rapid strides. Through the radio window are received waves from many celestial objects – from the Moon, Venus, Mars, Jupiter and Saturn, from the Sun's gaseous atmosphere, from the vast clouds of ionized and non-ionized hydrogen within our Galaxy, from cosmic-ray electrons spiralling in the magnetic fields of our Galaxy, from numerous external galaxies and from other, mainly unidentified, objects popularly miscalled radio stars.

We are accustomed to thinking of radio waves as generated by electric currents flowing in aerial wires. The various mechanisms of radio emission from the above objects are now largely understood and they differ greatly from those used by man. First to be understood was thermal emission which, for a so-called 'black body', occurs according to the Planck formula, which applies at radio frequencies as it does in optics. This and other emission mechanisms are discussed in Chapter 3.

1.3 *Some advantages of radio waves*

Terrestrial clouds (of water droplets) are transparent to radio waves. Of far more fundamental importance is the fact that the vast clouds of interstellar dust, which hide most of our Galaxy from optical astronomers, are also transparent. Radio waves allow us to see right through these clouds and map the distant parts of the Galaxy.

While clouds of water droplets and interstellar dust are opaque to light waves and transparent to radio waves the *reverse* is often the case for clouds of electrical ions. Thus the outer atmosphere of the Sun is transparent to light waves and we see the photospheric disk which has an angular extent of about ½°. The outer atmosphere is opaque for some radio waves and the Sun we 'see' at these wave-

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*There are many absorption lines and bands above 8000 angstroms.

lengths is this extensive atmosphere of ionized gas. For example the angular extent of the Sun 'seen' at four metres wavelength would be more than 1°. Thus the solar atmosphere and other low-density ion clouds may be observed and studied effectively by their radio emissions.

With the discoveries of the different ways in which radio waves are generated in interstellar space, the science of radio astronomy has become more powerful. It is now known that most of the emission is provided by cosmic-ray electrons spiralling in the magnetic fields of our own or other galaxies. Thus radio measurements give information about cosmic rays and about interstellar magnetic fields. Other emission is provided by a tiny change in the internal energy of a neutral hydrogen atom. This provides an emission line which enables the distribution and velocity of neutral hydrogen to be studied.

Even in the decade or so since radio astronomy has been studied intensively it has appreciably increased our knowledge of the universe. Already the new science is largely responsible for our knowledge of the structure of our Galaxy, the vast conglomeration of stars, gas and dust visible as the Milky Way. Radio astronomers have shown that the disk-shaped visible Galaxy is surrounded by a more or less spherical 'corona' some 100,000 light years in diameter. This corona is invisible at any but radio wavelengths where it 'shines' brightly, the energy being emitted by cosmic-ray electrons moving under the influence of an extended galactic magnetic field.

The radio observations of this and other emissions have raised many fresh problems in cosmical electrodynamics, one of the most basic of which is the origin of magnetic fields in complex but ordered forms throughout and beyond the optical Galaxy.

1.4 *The early history of radio astronomy*

It seems that the history of radio astronomy commenced between 1894 and 1900 with attempts by Sir Oliver Lodge (1900, see references at end of chapter) and other physicists in Germany to detect centimetre wave radiation from the Sun. These attempts failed as did others during the next forty years, because of inadequate techniques available during that period.

Extraterrestrial radio waves or radio 'noise' was first identified in 1932 by K. G. Jansky in the U.S.A. (see Jansky 1935). He found radio waves with an essentially continuous spectrum (near a wavelength of 15 m.) coming from the direction the Milky Way, or central plane of our Galaxy. This discovery was made in the course of a series of observations of radio interference experienced by a radio communications link. It was correctly interpreted by Jansky in a series of papers which, unfortunately, were largely overlooked.

A systematic plot of galactic radiation at a much shorter wavelength (about 2 m.) was obtained by G. Reber (1944) in the U.S.A. using a metallic reflecting dish having the unusually large (in those days) diameter of 31 feet. He found several subsidiary maxima, one in the constellation of Cygnus, together with a band of radiation continuous along most of the Milky Way. Subsequent observations with more refined instruments have shown that radiation is received from the Galaxy from *all* directions, with a higher level from the direction of the Milky Way.

The next important discovery about radio waves from beyond the solar system was that of *discrete sources* of emission. Early in 1946, J. S. Hey, S. J. Parsons and J. W. Phillips (1946) in England found marked short-period irregular fluctuations in intensity at 5 m. of the radiation from the subsidiary maximum in Cygnus. They found that the fluctuating source subtended an angle less than 2°. The following year J. G. Bolton and G. J. Stanley (1948) in Australia reduced this limit to 8 minutes of arc. In the next decade many hundreds of discrete sources were listed and a score or so have been identified optically; these include normal galaxies and the remnants of supernovae. They also include highly unusual objects such as colliding galaxies. These objects are relatively much more efficient radiators in the radio than in the optical spectrum; for a given amount of light emission they radiate much more radio energy than say the Sun. For example the original Cygnus source has a radio to optical emission ratio about 10^{18} times that of the Sun.

Meanwhile radiation had been recognized from the object which had first interested radio astronomers – the Sun itself.

During the sunspot maximum around 1936 there were many observations of mysterious high hissing noises in radio receivers arising about the times of radio fadeouts; we know now that these were due to radio waves emitted by the Sun. However, the first documented recognition of the reception of radio waves from the Sun (solar noise) was made in 1942 by J. S. Hey (1946) in England and independently by G. C. Southworth (1945) in U.S.A. The publication of both of these results was delayed for reasons of military secrecy and was anticipated by G. Reber (1944) who also observed solar emission. The observations of Hey were at metre wavelengths and revealed an intense and very variable component associated with sunspots ('noise bursts'); those of Southworth were at centimetre wavelengths and showed the steady thermal emission which had been originally sought more than forty years previously.

All of the above discoveries were concerned with radio *continuum* emission as opposed to *line* emission (corresponding to an atomic transition). In optical astronomy great use is made of the numerous emission lines and H. C. van de Hulst (1945) in The Netherlands, suggested the possibility of detecting a spectral line from neutral hydrogen which fell in the radio spectrum. This was found by H. I. Ewen and E. M. Purcell (1951) in the U.S.A. and the discovery laid the foundations of a major branch of radio astronomy. It has made possible for the first time the direct observation of ground-state atomic hydrogen in interstellar space. This gas is a major constituent of the universe. Line observations also allow, through Doppler shift measurements, the determination of the velocity of the emitting (or absorbing) hydrogen gas.

Another basic discovery was made and another branch of radio astronomy took shape with the demonstration by J. S. Hey and G. S. Stewart (1947) in England that radio waves could be bounced off the ionized trails of meteors. This allowed meteors entering our atmosphere at any hour of the day and in any weather to be studied and led to the discovery of daylight showers of meteors. This branch is called *radar* astronomy meaning that emission from the object itself is not observed but rather reflections of radio waves transmitted by the observer. It has extended to observation of the Moon, the planets and other bodies within the solar system.

1.5 *The world's largest radio telescopes*

The complete equipment required to make observations of extra-terrestrial radio waves is called a radio telescope and is described in the next chapter. In the larger radio telescopes the most spectacular (and expensive) part is the *aerial system*. As the associated electronic equipment is reasonably standardized, only the aerial systems need be referred to in discussing the world's large radio telescopes.

Aerials have increased steadily in size and hence in performance, virtually the only limitation being the amount of money available. Since this is usually limited, a number of ingenious designs have been introduced to provide a given performance at a minimum cost. On the other hand the most popular design of aerial at the present time, the so-called *fully-steerable paraboloid*, has made no compromise with cost. The result, apart from the great expense, is extreme flexibility in use and often a spectacular appearance. The best known of these aerials is the 250-foot reflector at Jodrell Bank, England.

The reason why a *parabolic* reflecting surface is used in radio (as well as optical) telescopes is that an incident parallel beam of waves is focused at a point where it may be collected and fed to the receiver. The large cost of these instruments is due to their large size together with the fact that the surface must be accurate to better than a tenth of a wavelength. For 10 cm. waves this means that the surface must not deviate by more than about ⅜ inch over the whole area, more than an acre for a 250-foot reflector. This would not be so difficult if the aerial were fixed in position and shielded from wind, but a fully steerable reflector must be able to point to any part of the sky and so must suffer distortion due to changing gravitational forces and wind load.

Even a decade ago it was realized that while movable paraboloids of diameter not more than 100 feet were relatively simple to design and would cost only about one hundred thousand pounds, the cost would rise to about a million pounds for diameters near 250 feet. A diameter of 80–90 feet provides a very effective telescope, provided it can work at wavelengths near 10 cm., and so several such telescopes have been built in different countries. The first (1956) was that at Dwingeloo, Holland, and others are now in operation at Bonn, West Germany, in the U.S.S.R. and at four observatories in the U.S.A. Also deserving of mention here is the U.S. Naval Research Laboratory 50-foot telescope which, although somewhat smaller, was introduced in 1951 and has a more accurate surface, capable of efficient operation down to a wavelength of 1 cm. Meanwhile the 250-foot reflector at Jodrell Bank was put into operation (1957) with a lower limit of operation about 20 cm. This is the largest steerable paraboloid in the world and will remain so until the completion, perhaps in 1962, of the 600-foot reflector being built for the U.S. Navy.

Design studies for two further notable telescopes of the steerable-paraboloid type were started about 1956. The first of these is a 210-foot fully steerable reflector capable of working down to approximately 10 cm.; this will be completed in Parkes, Australia in 1961. The second is the 140-foot reflector of the U.S. National Radio Astronomy Observatory under construction in West Virginia.

The increased interest in space science, including radio astronomy, has led to the design of several telescopes in the 600- to 1000-foot range. Three of these are being built at present in the U.S.A.

The world's largest steerable telescope is being built for the U.S. Navy in West Virginia and may be completed by 1962. Nearly 700 feet tall, its parabolic reflector will be 600 feet in diameter or more than seven acres in area and the installation is expected to cost about $80 million. The structure will require 20,000 tons of steel, 600 tons of aluminium and 14,000 cubic yards of concrete. The reflecting paraboloid or 'dish' will be cradled in two structures resembling Ferris wheels which will tilt it to any angle of elevation from zero to 90 degrees. The entire structure will ride on four trucks on a circular railroad track nearly a third of a mile in length; this allows it to turn through a full 360 degrees so that the reflector may point in any required direction. An aluminium wire screen will provide the reflecting surface of the paraboloid. The screen will be divided into panels whose positions will be adjusted automatically by servomechanisms to compensate for distortions caused by powerful stress due to wind, gravity and temperature changes. In this way the surface will be maintained as a true paraboloid to within about $\frac{3}{4}$ inch which is the accuracy required to work with 21 cm. radio waves.

It is of interest to compare this colossus, the largest steerable radio telescope, with its optical counterpart, the 200-inch paraboloid at Mount Palomar. The latter weighs only 500 tons and cost less than one seventh that of the radio telescope and so is dwarfed physically. In one respect, however, it is far ahead of the radio telescope. The resolving power of any telescope (the narrowness of its beam) depends on the ratio of the reflector diameter to the wavelength used. The radio telescope will be thirty-six times larger in diameter but because of the very short wavelength of light, about 1-50,000th of an inch, the resolving power of the optical unit is 10,000 times better. This difficulty of poor resolving power plagues radio astronomers but is overcome to a large extent by the use of two separate aerials separated by distances up to several miles. The two aerials combine as an 'interferometer' providing a resolving power which depends on their distance apart rather than their individual dimensions (see section 2.5).

The fully steerable paraboloids are the aristocrats of telescopes, having made no compromise between requirements and cost. Great saving may be made by restricting or eliminating the reflector movement but of course this limits the usefulness of the instrument. Some reflectors have been mounted to tilt up and down in elevation, relying on the Earth's rotation to carry their beam across the sky. An example is a 120-foot paraboloid at the Heinrich Hertz Institute in East Berlin.

Some paraboloids have been constructed by excavating a hole in the ground, sometimes in the side of a hill. The surface is carefully shaped and covered with concrete and then wire mesh or metal spray. This provides a rigid reflector which is not subject to deformation as are the steerable dishes. Perhaps the most highly directive of these in existence is the 100-foot 3-cm. telescope in the Crimea which has a beam width of only 4 minutes of arc, which may be compared with about 10 minutes of arc for a 250-foot reflector working at 21 cm. The disadvantage of this type of aerial is that the beam may only be steered by moving the point where the radiation is collected, and the permitted movement is small.

The largest hole-in-the-ground telescope will be that of Cornell University, at present under construction in Puerto Rico. This has a 1000-foot *spherical* reflecting surface and will be used for radar studies of the planets (section 8.3). The point about a spherical rather than a parabolic surface is that the beam may be swung over a wider range of angles. On the other hand the collection of energy from such a reflecting surface presents special problems (section 2.3) because the energy is not focused at a point as for the paraboloid, but along a line. Another such telescope of imposing proportions is that being constructed for the University of Illinois. This comprises a 600-foot by 400-foot excavation in the side of a steep ravine. It is shaped as a *parabolic cylinder* so that the reflected waves are focused not at a point but along the focal line, where they are collected by 300 small dipole aerials supported by four 165-foot towers. Working at 50 cm. this telescope will have a beam-width of about 20 minutes of arc.

A paraboloid 720 feet in diameter working at a wavelength of 70 cm. has a beam-width of 16 minutes of arc. If we were to cut out a strip 70 feet wide through the centre of this aerial and use this piece as a radio telescope it would have a 'fan' beam 16 minutes of arc by 2 degrees. An aerial with a strip of paraboloid of just these dimensions is being constructed in Ohio, U.S.A. The strip is placed on the ground with its short side vertical and does not move, so that there is no trouble with distortion of its surface. Radiation from different parts of the sky is reflected on to it by a second reflector which is 700 feet long by 100 feet wide and has a flat surface which tilts about a horizontal axis. A similar, but larger and more accurate aerial is being constructed at Nançay in France. It will have a beam-width of 3 minutes by 20 minutes of arc at a wavelength of 20 cm. A modified version of the parabolic strip aerial is also in use at the Pulkovo Observatory, U.S.S.R. This has a 400 × 10-foot strip which is made up of numerous small flat plates. Each of these can be tilted separately so that in effect the whole 400-foot strip is tilted, thereby dispensing with the flat reflector.

In modified forms the strip type of aerial is in use in many countries. The use of two strips in the form of a cross and an ingenious switching arrangement (described in section 2.5) provide a single narrow beam. Two of these have been developed by the Radiophysics Laboratory, Sydney; having strip lengths of 1500 feet and 3300 feet. Yet a third is projected by the University of Sydney for completion about 1964; it will have arms about a mile in length and a correspondingly narrow beam.

Yet a further modification of the strip aerial is the strip with gaps in it; this may take the form of a row of parabolic reflectors spaced at regular intervals over a long straight baseline. Aerials of this type, analagous to the optical diffraction grating, were first developed near Sydney and are now found in many countries. The Sydney installation now takes the form of two strips, each comprising thirty-two paraboloids 19 feet in diameter stretching for 1200 feet; its mode of operation is described in section 2.5.

Two, three or four spaced aerials are sometimes combined as an interferometer (section 2.5) whose feature is the accurate location of 'radio stars'. Widely spaced aerials provide maximum resolution with a minimum aerial cross-sectional area. A rather photogenic example of an interferometer-type radio telescope is shown in Plate I; it is operated by the California Institute of Technology and is located in the isolated Owens Valley. It comprises two 90-foot diameter steerable paraboloids and illustrates one of the forms of construction and mounting used for these paraboloids or 'dishes'. The two paraboloids are mounted on railway tracks, one running north to south and the other east to west. This allows the pair to be combined as a variable-spacing interferometer with maximum flexibility. At present it is operating at a wavelength of 31 cm. but is capable of working at wavelengths as short as 3 cm. A similar but smaller prototype operates at Nançay, France.

A large, metre-wavelength interferometer of the variable-spacing type has been in operation for some years at the Mullard Radio Astronomy Observatory at Cambridge. Its parabolic cylinders are built up from wires since these are less expensive and provide the necessary accuracy at metre wavelengths. One element 3300 feet long and 40 feet wide is fixed while another smaller element may be moved on tracks. This arrangement allows brightness distributions to be plotted by a technique referred to as 'aperture synthesis'.

1.6 *The future of radio astronomy*

An official survey made in 1958 listed more than fifty radio astronomy observatories. At the time of writing the number is close to, if it does not exceed, 100 observatories in more than twenty countries. Most of the most notable telescopes, either in commission or being built, have been briefly described in the previous section. We may now consider some advances likely to result from the use of these instruments within the next five or ten years.

Some of the brightest 'radio stars' have already been identified with very distant galaxies of rare type and not previously known. These 'radio galaxies', although at distances of hundreds of millions of light-years, still provide radiation many times the limit of detection. It follows, therefore, that some of the thousands of sources near the limit of detection are also radio galaxies, their radiation being weak because they are situated at much greater distances. Indeed, these distances must far exceed the limit of optical visibility of galaxies of a few thousand million light-years. The radio waves from these galaxies must have originated many thousands of millions of years ago when, according to some cosmological theories, the universe was quite young. Observations of such sources will have far-reaching cosmological significance.

The largest telescopes, operating at the shortest possible wavelengths will resolve the detail in a few of the nearby galaxies and allow their structure to be studied. Our own Galaxy will be observed in much more detail and the mysteries of its nucleus and corona may be solved. These parts of the Galaxy are not visible optically so that they were only discovered recently. They appear to be the key parts of a vast dynamo which 'drives' the remainder of the system, creating fresh spiral arms, magnetic fields and cosmic rays. They may reveal the secret of the birth of galaxies and perhaps also their death.

Within the Galaxy are many isolated sources of radio emission. Some of these are supernovae – remnants of stars which exploded hundreds of years ago. Supernovae have been studied for many years but only recently was it realized that they are not merely debris of long past explosions, but regions of intense activity where cosmic rays and magnetic fields are created on a scale corresponding to thousands of times the *total* rate of power output of our Sun. These objects provide a combined study in electrodynamics, cosmic ray physics, nuclear physics and optical and radio astronomy.

Other radio sources within our Galaxy are clouds of hydrogen, several or many light-years in extent. Some of these are ionized by hot stars in their centres, which radiate thousands of times more strongly than the Sun. Radio measurements will tell us the density, temperature and extent of these regions and so, indirectly, allow the ionizing stars to be studied. Other gas clouds have no nearby bright star and are cold and dark and invisible optically. They can be observed by radio telescopes, however, and their densities and velocities may be determined and thus the dynamic structure of this component of our Galaxy may be deduced.

Moving nearer to home, it is hoped that soon we may observe radio emission from some of the nearer stars. The only star from which signals have been received as yet is the Sun which emits a rather weak but steady signal and, from time to time, much stronger and very irregular 'bursts'. These have reached a level of about ten thousand million times the strength necessary for detection on the Earth with the most modern equipment. This means that they would just be detectable if they came from a star one hundred thousand times the distance of the Sun.* The Sun is about 8 light-minutes away so the extreme limit of detection of a similar star would be 1½ light-years. The nearest star is 4·3 light-years away and there are 30 within about 12 light-years. In order to be detected these would have to do a little better than the Sun, but that is not unlikely because the Sun is not a particularly notable star. Alternatively, with an increase in radio sensitivity of one or two orders of magnitude, stars like the Sun might be detected at 5 to 15 light-years or so. The importance of observing stellar 'bursts' of radio emission is that these would originate in the outer atmosphere of the stars. These atmospheres are quite invisible optically but could be studied by their radio emission, just as the solar corona has been studied. At the time of writing, searches for stellar bursts are being conducted at Jodrell Bank (with the 250-foot reflector) and in Sydney.

A radio telescope directed at a nearby star would include in its field of view any planets which moved around that star and any civilizations which might have developed on those planets. It is not beyond the bounds of possibility that such a civilization might exist and might be attempting to communicate by radio with the Earth. Calculations show that communication should be possible provided our radio receivers were set to receive the narrow band of frequencies which could be radiated by a transmitter of limited power. The chances of satisfying all of these requirements are indeed remote but

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* The signal received decreases in strength as the square of the distance of the source.

the scientific rewards for success would be correspondingly great. Accordingly, observations were commenced in April 1959 at the Greenbank observatory in West Virginia. This project, called Project Ozma, was originally designed to provide periodic observations in the directions of the stars Tau Ceti and Epsilon Erindi, distant about 11 light-years. Up to the time of writing no positive results have been reported.

Studies of the solar system itself constitute three more-or-less distinct branches of radio astronomy, dealt with in the last three chapters. Already radio waves from the Sun have told us much about its outer atmosphere which is nearly transparent to light waves but opaque to, and so easily 'seen' by radio waves. It is hoped that further studies of the enormous explosions which occur in this atmosphere may lead to an understanding of their cause and their effects at the Earth, which include magnetic storms and communications black-outs.

Planets will be investigated both by observing the radiation from their surfaces and atmospheres and also by bouncing radio echoes from their surfaces (radar astronomy). There is no doubt that we will soon know much more about planetary temperatures, rates of rotation, surface natures and distances. In the case of the Moon the investigations will result in wide-band communications links, using radio waves bounced off its surface to communicate between any two points on the Earth.

There is no indication yet of limits of sensitivity of radio telescopes. In particular it should be possible to increase aerial size by amounts only limited by financial considerations. A sum of one thousand million pounds might pay for a steerable reflector of diameter 2500 feet, with one hundred times the resolving power* and power gain of the Jodrell Bank telescope.

Other radio astronomical advances will certainly be made by the use of radio telescopes carried above our atmosphere by rockets. This will allow the observation of waves of length greater than 30 m. and less than 1 cm., which at present cannot be observed because they are blocked by the Earth's atmosphere.

GENERAL REFERENCES

In spite of the great advances in radio astronomy most of our knowledge of the universe has been obtained from optical observations. Suitable

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* The 250-foot reflector has a beam ten times wider and covering one hundred times the area of sky.

texts describing these observations and their interpretation, which might be read in conjunction with the present work, include the following:

The History of Astronomy by G. Abetti (Sidgwick and Jackson, London, 1944); *Frontiers of Astronomy* by F. Hoyle (Heinemann, London, 1955); *Atoms, Stars and Nebulae* by L. Goldberg and L. H. Aller (Blackiston, Philadelphia, 1943); and *The Milky Way* by B. J. Bok and Priscilla Bok (Harvard University Press, 1957).

To these might be added some books on radio astronomy; those which have appeared since 1955 are as follows:

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2. The Techniques of Radio Astronomy

THE material of this chapter falls into three broad divisions. The first deals with the characteristics of the radio waves from extra-terrestrial sources. The second deals with the basic measuring components, aerials, receivers and recording systems used in radio astronomy; and the third deals with a number of complete equipments which have been developed for specific investigations. The technique of *radar* astronomy, involving transmitting as well as receiving systems, is discussed briefly in Chapter 8.

In this chapter we have attempted to cover all important developments without entering into any great detail. It was necessary to assume on the part of the reader some prior knowledge of electronics and those lacking such knowledge will find some difficulty in negotiating this chapter. However, an understanding of the equipment used is not necessary in order to appreciate the observational and theoretical results described in the later chapters, so that this chapter may, if necessary, be omitted.

2.1 *The radiation received*

The radio waves received from outer space may be described by their three qualities: spectrum, strength and polarization. The spectrum of radiation from a particular direction may be continuous, which means that the strength varies slowly (or not at all) with frequency. Most observed radiation has this form and the receivers used have band-widths narrow compared with the scale of spectral features. The main exception is the 1420 Mc/s line emission from atomic hydrogen; this is discussed in Chapter 5.

The strength of the radiation may be specified as the power incident on the Earth per unit area and per unit interval of frequency. In m.k.s. units, which are usually used for specifying radio astronomical power fluxes, the *flux density* S is in watts per square metre per cycle-per-second (watts $\mathrm{m}^{-2}(\mathrm{c/s})^{-1}$). If the angular extent of the source is small compared with the aerial beam-width then this flux density is sufficient to specify the strength. However, if the source of radiation is distributed over the sky, the strength must be specified for each direction; we then speak of the *brightness* b of a given area of the radiator, or the flux density per unit solid angle watts $\mathrm{m}^{-2}(\mathrm{c/s})^{-1}$ steradians^{-1}. The flux density S from a source of uniform brightness b, which subtends a solid angle Ω steradians at the point of observation, is then given by

$$S = b\,\Omega. \tag{1}$$

An alternative system of specification of wave strength is based on Planck's law relating the emission from a black body of electromagnetic energy of all frequencies, to the temperature of the body. In the radio spectrum a sufficiently accurate approximation to this law is given by the Rayleigh-Jeans approximation. This gives the brightness b in terms of the temperature T (degrees Kelvin) and the wavelength λ

$$b = \frac{2kT}{\lambda^2} \qquad (2)$$

where k is Boltzmann's constant ($1{\cdot}38 \times 10^{-23}$ in m.k.s. units). The brightness b may now clearly be specified in terms of an equivalent black-body temperature T which would give the observed value of b, according to equation (2). If we replace T by this *brightness* temperature T_b we then have

$$b = \frac{2kT_b}{\lambda^2} = 2{\cdot}77 \times 10^{-23}\,\frac{T_b}{\lambda^2}\ \text{watts}\ m^{-2}\,(c/s)^{-1}\ \textit{sterad}^{-1}. \qquad (3)$$

Similarly equation (1) allows the total flux density S to be specified in terms of a uniform brightness temperature and the solid angle subtended by the source at the observer

$$S = 2{\cdot}77 \times 10^{-23}\,\frac{T_b\Omega}{\lambda^2}\ \text{watts}\ m^{-2}\,(c/s)^{-1}. \qquad (4)$$

The specification of wave strength in terms of a temperature provides a simpler unit and is particularly convenient in discussing radiation of thermal origin.

The third and last characteristic of a radio wave which must be specified is its polarization, or the direction of its electric vector. A linearly polarized wave has its electric field always in one preferred direction. Aerial systems are usually designed to accept radiation having its electric field in a particular direction and so might accept all the energy of the plane polarized wave, if the polarizations of wave and aerial coincided, or no energy if the directions of polarization were orthogonal.

Alternatively, the radiation may be elliptically polarized or, as a special case circularly polarized, when the electric vector in the wavefront traces out approximate ellipses. The polarization is called right-handed if the field vector is a fixed plane perpendicular to the ray rotates clockwise when viewed in the direction of propagation. The opposite sense is called left-handed. When the vector traces out ellipses which change through all shapes and orientations, then the radiation is said to be randomly polarized.

An aerial which accepts energy polarized in one plane (the typical radio astronomy aerial) will accept only half of the energy flux of a randomly polarized wave. Since most extra-terrestrial radio waves are randomly polarized this fact must be remembered when estimating values of S and b; the formulae given above refer to the total flux and is twice that in any particular plane and twice that accepted by the aerial and measured.

2.2 *The basic measuring equipment*

The basic units required to observe solar or cosmic radio waves are shown assembled together to form a complete equipment in Fig. 2. Energy is intercepted by the aerial and flows to the receiver along a suitable feeder. Here it is amplified and rectified and the output transferred to a recording device. Three other sets of information must be simultaneously recorded: a time scale, a record of the direction in which the aerial was pointed, and calibration marks which allow the amplification or gain of the receiver to be determined.

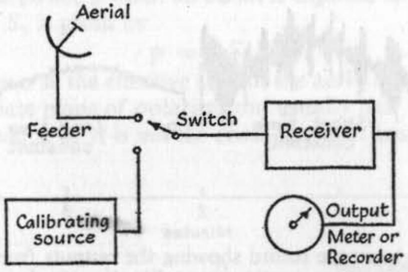

Fig. 2. The essential components of a radio telescope.

The whole equipment, when used for the recording of extra-terrestrial radio waves, is called a radiometer or *radio telescope*.

A typical record from a cm.-wave radio telescope is shown in Fig. 3. The large (left) and small (right) fluctuations correspond to two different receiver output filters (see section 2.4). Apart from these, the trace moves smoothly up and down corresponding to variations in intensity of the signal received from different parts of the sky. From time to time the receiver input is disconnected from the aerial and connected to a 'dummy load' or resistor of suitable value. The corresponding calibration marks are shown as P_1 along the record. When the dummy load is heated the calibration mark moves up to P_2 and the interval between P_1 and P_2 divided by the corresponding temperature change gives the sensitivity of the receiver and provides an absolute measurement of the power received from the aerial. When allowances are made for feeder and other losses, the power flux from the source may then be determined. As well as using a dummy load, the receiver is sometimes connected to a second aerial which remains pointing to a fixed, 'cold' part of the sky. This allows a direct comparison of sky brightness between the two regions without recourse to the dummy load. The cold sky level is shown as P_0.

The form taken by the dummy load varies greatly from cm.-wave radiometers to metre-wave radiometers. In the former case a useful design comprises a piece of wave-guide which may be connected in place of the aerial feeder. In the wave-guide is a long wedge-shaped piece of absorbing material which correctly terminates the wave-guide, so that the whole appears, electrically, as a resistance with temperature that of the wedge. The whole wave-guide is placed in an oven and heated over the required temperature range. At metre wavelengths the sky temperatures reach thousands of degrees and devices with large temperature ranges are desirable for calibration. One arrangement comprises two resistors, one at ambient temperature, the other much hotter. The receiver is switched from one to the other, each being carefully matched to the receiver. The hot resistor may be a tungsten filament lamp so that a temperature range as high as 2000 degrees may be realized. When yet higher temperatures are desired, diode noise generators may be used to provide temperature variations up to several hundreds of thousands of degrees.

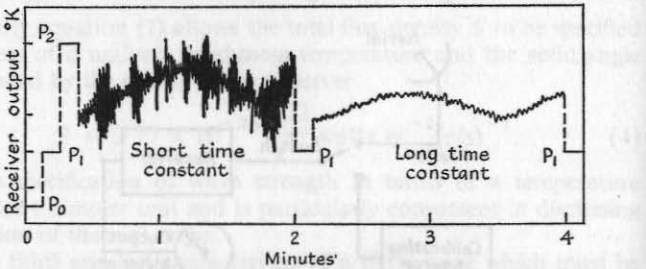

Fig. 3. A radio telescope record showing the outputs from receivers with short and long time constants; some calibration marks are also shown.

When the narrow-beam aerials now being built come into full use another piece of equipment will be added to the radio telescope. Such a vast amount of information will flow from the receiver that an electronic computer will be necessary to process it. Such processing includes the elimination of spurious receiver drifts by comparing different scans across the area of sky being analysed. It also includes the arrangement of data in forms most suitable for use by theoretical astrophysicists.

2.3 *Aerials*

The purpose of the aerial is to select waves arriving from a particular direction and pass them to the receiver. It must have two important qualities: a large enough area to collect sufficient power and also enough directivity to distinguish between the object being investigated and other nearby objects. On occasions an aerial might also be designed to accept a particular type of polarization and reject others. Finally the aerial characteristics must be known accurately so that the power and extent of the observed source may be computed.

The available power p when an aerial is exposed to a plane wave of flux density S_1 is given by

$$p = AS_1 \qquad (5)$$

where A is known as the effective area of the aerial and, S_1 is the flux in the appropriate plane of polarization, usually half the total flux. Generally the value of A is *not* the cross-sectional area of the aerial viewed from the direction of arrival of the wave. This is illustrated in Fig. 4 which shows an aerial beam with a maximum in the direction Ox. For this direction, the value of A for most modern radio astronomy aerials *is* roughly their cross-sectional area. However, as the direction of arrival of the wave moves away from Ox the value of A falls rapidly. When the angle of separation is 7½°, the value of A (and the available power p) has fallen to half its maximum while the area of interception has only fallen to cosine 7°·5 or 0·99 its maximum value.

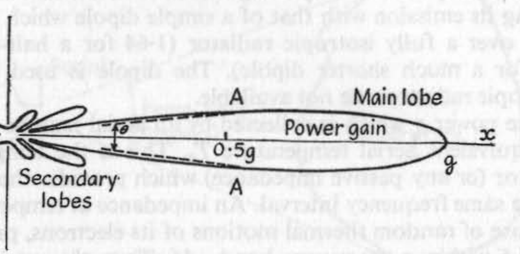

Fig. 4. An aerial beam pattern with a half-power width $\theta = 15°$.

Apart from its power-gathering capacity, which is the maximum of A, the important characteristic of an aerial is its beam-width between 'half-power points'. This is the angle θ which is about 15°

in the case shown in Fig. 4. For a circular aerial such as a paraboloid reflector θ is given in terms of the aerial diameter d and wavelength λ by

$$\theta = \frac{57\lambda}{d} \tag{6}$$

The beam-width shown of 15°, for a wavelength of say 21 cm, would require a reflector of diameter 80 cm. or less than 3 feet. By comparison, the present-day beams, ranging down to small fractions of one degree, are needle sharp.

The 'gain' g of an aerial (in any direction) may best be defined by considering the aerial used to transmit, rather than receive, power. The aerial may then be compared with a hypothetical isotropic radiator which transmits equally in all directions. The gain g in any direction is then given by the relative flux densities transmitted in that direction by the aerial being tested and the isotropic aerial. The maximum gain of an aerial, in the direction of the main lobe is one of the quantities which must be measured for a radio astronomy aerial. It may be found by using the aerial as a transmitter and comparing its emission with that of a simple dipole which has a known gain over a fully isotropic radiator (1·64 for a half-wave dipole, 1·5 for a much shorter dipole). The dipole is used because true isotropic radiators are not available.

The power p which is collected by an aerial may be converted to an equivalent aerial temperature T_a. This is the temperature of a resistor (or any passive impedance) which provides the same power in the same frequency interval. An impedance at temperature T will, because of random thermal motions of its electrons, provide power $kT\,\Delta f$ within a frequency band Δf. Thus the equivalent aerial temperature is given by

$$T_a = \frac{p}{k\Delta f}, \tag{7}$$

where p is in watts per unit frequency interval and k is Boltzmann's constant of $1{\cdot}38 \times 10^{-23}$ joules per degree.

By extending this concept of specifying noise level thermodynamically we may now derive a relationship between the effective receiving area of an aerial A and the gain g. To simplify the mathematical argument let us suppose we are dealing with an ideally simple aerial having gain g uniform over a solid angle Ω and zero elsewhere; from our definition of gain we then have $\Omega = \frac{4\pi}{g}$. In Fig. 5 an experiment is represented schematically, in which a resistor r at temperature T is connected to the aerial and radiates all the power given by equation (7) on to a black body which just fills the beam. The power received by the black body is

$$p_1 = kT\Delta f.$$

The power received by the aerial of area A is found from equations (1), (2) and (5), remembering that only half of the incident flux is accepted by the aerial because of its polarization and that $\Omega = \frac{4\pi}{g}$. The received power is then

$$p_2 = \frac{4\pi kTA\Delta f}{g\lambda^2}.$$

From thermodynamic considerations these two powers must be equal so that we have

$$A = \frac{g\lambda^2}{4\pi}. \tag{8}$$

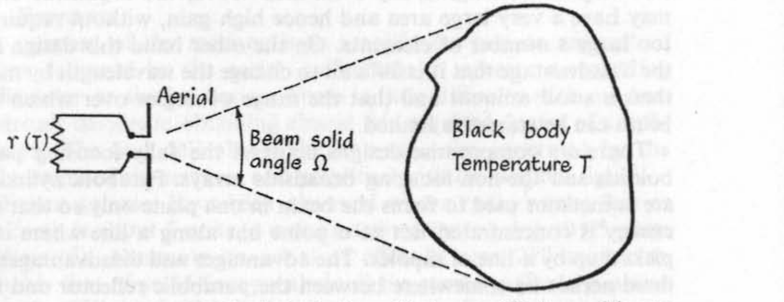

Fig. 5. An aerial and a black body in radiative equilibrium with one another.

This is a general property for all aerials and for any direction of emission. Having measured the maximum value of g the value of A may be found and then, from equation (5), the power gathered by the aerial.

For a parabolic type of aerial the value of A on the axis of the main beam is about half the physical area of the reflector. For the aerial whose beam ($\lambda = 21$ cm.) is shown in Fig. 4 the diameter is about 81 cm., the physical area 5150 square cm. and the gain, given by equation (8), about 74.

A wide variety of aerials are used by radio astronomers, the most popular being the parabolic reflector with a small aerial, usually one or two half-wave dipoles and a reflector plate, placed at the focus. This type of aerial presents outstanding advantages when the wavelength to be used is short and the gain required greatly exceeds 100. The wavelength is readily changed by replacing the small aerial at the focus and if the reflector itself cannot be moved to direct the beam, then movement of the small aerial allows a limited movement of the beam. The electrical design of the aerial is simple and flexible.

Second in popularity are broadside arrays of half-wave dipoles backed by a sheet reflector. This aerial does not reflect the beam but absorbs the power directly into the dipole elements. If the size of the array is not too great the dipoles and reflector may all be swung to direct the beam. In the case of large arrays the dipoles are mounted horizontally above the ground and remain fixed. The beam is moved by changing the phase between the dipoles. The effective area *A* of a broadside array approximates to the actual area so that the latter is used more efficiently than for the parabolic reflector. For larger wavelengths, say 3 m. and above, the broadside array may have a very large area and hence high gain, without requiring too large a number of elements. On the other hand this design has the disadvantage that it is difficult to change the wavelength by more than a small amount and that the range of angles over which the beam can be steered is limited.

There are compromise designs between the fully focusing paraboloids and the non-focusing broadside arrays. Parabolic cylinders are sometimes used to focus the beam in one plane only so that the energy is concentrated not at a point but along a line where it is picked up by a line of dipoles. The advantages and disadvantages of these aerials lie somewhere between the parabolic reflector and the broadside array. Another compromise design is the *hemispherical* reflector. Energy being focused by a paraboloid must be incident along its axis and so the reflector must always point in the direction of the source. A hemispherical reflector has no preferred axis and energy may be incident over a wide cone. In other words the value of *A* (equation 5) does not depend critically on the direction of the source as it does for most aerials. On the other hand, the energy is not focused at a point but along a *line*, through the centre of the hemisphere and parallel with the original beam. The difficulty is that the power-collecting device placed along this line must accept power which varies along its length both in phase and in its direction of arrival. Since the reflector itself need not be moved in order to point in different directions it may be built as a hole in the ground lined with reflecting wire mesh. A reflector of this design is being built at the time of writing in Puerto Rico. Its main objective is for obtaining radar echoes from the planets.

Other designs have replaced a large number of dipoles by a smaller number of Yagi (end-fire) elements, or helices, each of which has a small gain over a dipole so that a smaller number of elements are needed for a given overall gain. For observations of solar bursts at metre wavelengths even a single Yagi is sufficient. This design is mechanically light and simple and although its adjustment is rather critical it may be the best aerial for the amateur radio astronomer or for small student groups.

Two other types of aerial have been used but will not be discussed here. They are rhombic aerials and electromagnetic horns and have on occasions proved useful for special purposes.

Aerials with two or more widely-spaced elements are frequently used by radio astronomers as interferometers. Some of these special aerial systems are discussed in section 2.5.

2.4 *Receivers*

The purpose of the receiver is to amplify the minute amount of power delivered by the aerial, sufficiently to operate a recording milliameter or similar device. There is little difficulty with modern electronic devices in obtaining almost any required degree of amplification. The real difficulty is the internal noise generated by the early stages of the receiver and amplified with the wanted signal.

Distant galaxies have been observed whose radio power flux at the Earth is about 5 units (a unit as defined here, being 10^{-26} watts $m^{-2}(c/s)^{-1}$). Assuming an aerial of effective area 270 square m. (roughly that of an 85-foot paraboloid) the power gathered is about $3 \times 10^{-24} W(c/s)^{-1}$. This is the power output of an impedance at a temperature of about 0°·2 K. An impedance at normal room temperature (about 300° K) would generate 1500 times more noise power. This means that even with the receiver switched off, so as to minimize generated noise, its input circuit would generate 1500 times more noise power than the wanted power coming from the aerial. With the receiver switched on further noise would be generated in its electronic components. The total noise power is then increased by a factor *N*, called the receiver noise factor. A typical value of *N* in receivers used prior to 1959 was 10 so that the total receiver noise temperature was 3000° K.

Since *N* is mainly dependent on the receiver input stages these are the most critical parts of a receiver and have attracted the most attention. Prior to the introduction of the maser and parametric amplifiers, which are described below, it was usual to employ conventional signal frequency valve amplifiers in the first stage for wavelengths down to about 50 cm. At shorter wavelengths these devices became less efficient and no signal-frequency amplification was used, the signal being changed by a crystal diode frequency converter in a superheterodyne receiver. The best receiver noise temperature available were about 500° K at 1 m. and 2000° K at 3 cm.

It seems incredible that a signal corresponding to a temperature of 0°·2 K could be measured through a noise background of 2000° K yet this is done by an integration system which works as follows. If the receiver accepts a band of frequencies of widths Δf, then the detector output may be regarded as the sum of a large number of independent, random contributions. There will be Δf pulses per second with amplitude determined by the equivalent aerial temperature T_A. Now let us place a capacitance across the receiver output which reduces the response time from $(\Delta f)^{-1}$ to a much lower value, say τ. In the response period τ there will be $\tau\Delta f$ independent random contributions. Since these are random, they largely cancel one another leaving a root mean square output which is reduced by a factor $(\tau\Delta f)_{\frac{1}{2}}$. The effective aerial temperature is reduced by a similar factor. As an example, suppose the band-width were 5 Mc/s (megacycles per second) and the response time 1 second, the factor $(\tau\Delta f)^{\frac{1}{2}}$ is 2200 and the effective noise temperature falls from say 2000° K to 0°·9 K. The wanted signal corresponds to the variation in aerial temperature as the radio source drifts through the beam. If the time taken for this drift is say 20 seconds or more, then τ may be increased to 20 seconds without appreciably reducing the wanted signal. The effective noise temperature is then further reduced to a value of 0°·2 K and a signal of this same amplitude may just be distinguished. The effects of long and short time constants are seen in Fig. 3. The short time constant is one-tenth of a second and the receiver output, expressed as a temperature is 2·8° K. The long time constant is ten seconds and the noise output 0°·28 K. In each case the total variation in wanted signal is 2° K.

At first sight one might imagine that by increasing τ and Δf sufficiently the receiver sensitivity could be increased indefinitely. However, there are limits set to the value of each variable. In some cases the time constant τ is limited by the rapidity of change of the phenomenon being studied. For example, some solar bursts have durations much less than one second. When not limited in this way circuit time constants up to about one minute have been

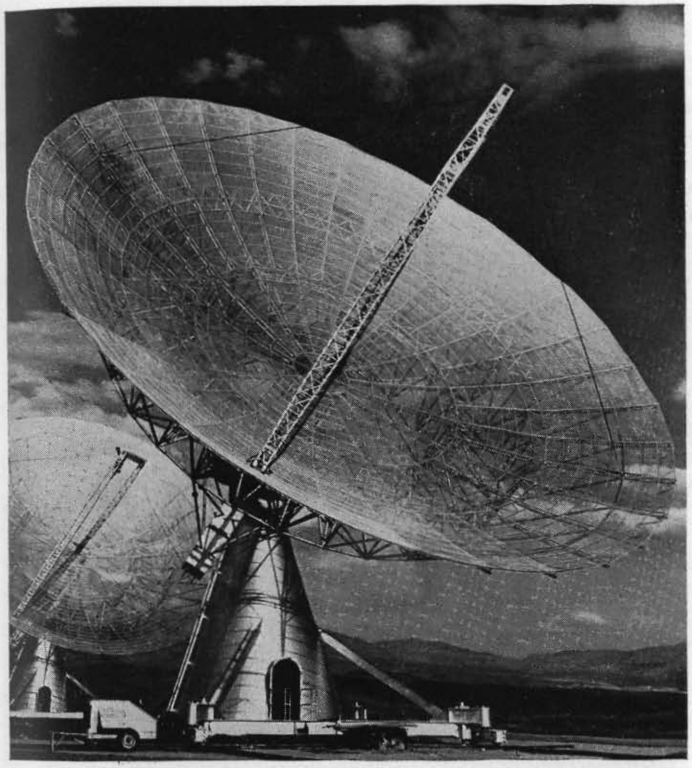

PLATE I. The Owens Valley (California) radio telescope. Two 90-foot diameter steerable reflectors mounted on railway tracks form a variable-spacing interferometer (*J. G. Bolton and the California Institute of Technology*).

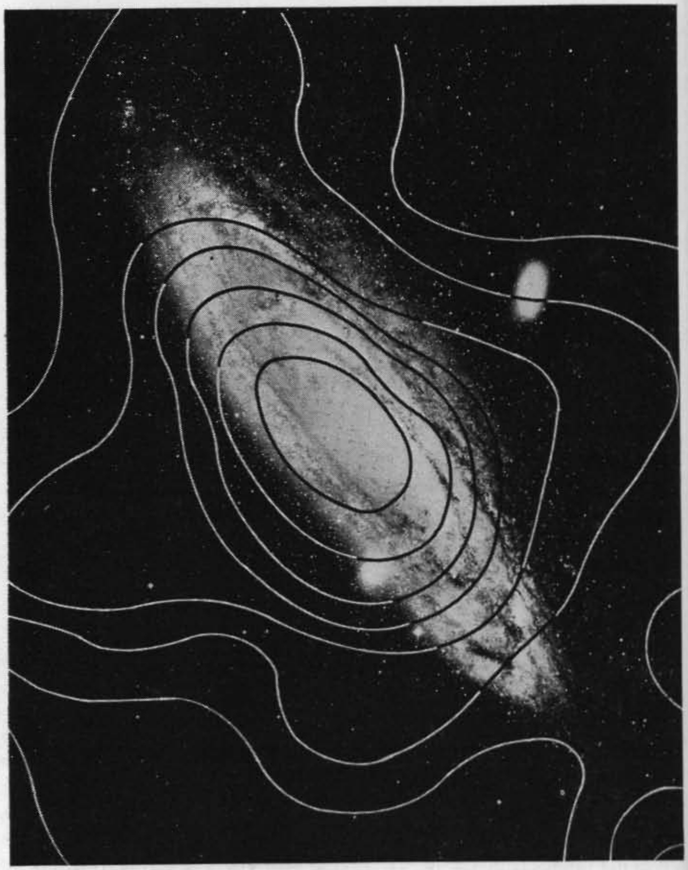

PLATE II. The Great Nebula in Andromeda (M31); a radio image is superimposed on the photograph (*Photograph by Mt. Wilson and Palomar Observatories. Radio image by Jodrell Bank Observatory*).

used frequently and up to five minutes on a few occasions. Beyond these limits random slow drifts in the receiver output limit any further increase in sensitivity.

The most serious output fluctuations occur in receivers operating from the mains. These may be minimized by using voltage stabilizers on both low- and high-tension supplies. Other drifts are due to changing characteristics of the circuit elements and may be reduced by thermostatically controlling the temperature of the apparatus. A widely used method of stabilization developed by R. H. Dicke in the U.S.A. switches the receiver input rapidly (e.g. thirty times per second) from the aerial to a resistor of the same impedance and at ambient temperature. The receiver output is also switched synchronously to *two* integrating circuits which are connected in opposition and fed to a centre-zero metre. The metre then indicates the difference between the aerial temperature and that of the resistor. Since the receiver noise does not contribute to the meter reading, the system is tolerant to changes in receiver gain. This system has the disadvantage that it doubles the inherent noise fluctuations; this is because the receiver is only connected to the aerial for half the time and so half of the integrating time is lost.

Increase in receiver sensitivity by increase in band-width Δf is also limited. In some cases this is because the received signal has a narrow band-width. Many solar bursts are restricted to bands of a few Mc/s and the hydrogen line emission to a few tens of kilocycles per second. When these limitations are not present, technical difficulties set a limit of about 10 or 20 Mc/s. Recently, however, receivers have been developed using 'travelling-wave tubes' which operate efficiently as amplifiers for wavelengths down to less than 4 cm. These devices have an enormous band-width, overall bands of 1000 Mc/s having been obtained which, with time constants of 300 seconds, have provided overall sensitivity of about 0°·01 K.

Yet more recently two entirely new types of receiver have been developed called the 'maser' (Microwave Amplification by the Stimulated Emission of Radiation) and the 'parametric amplifier' or 'mavar' (Mixed Amplification by Variable Reactance). Hitherto, power for receivers was supplied from a direct-current source. In the new receivers power is supplied by a radio-frequency source, usually higher in frequency than the signal. This RF source of power is usually referred to as the 'pump'. The two new amplifying devices depend on the application of distinct physical principles not previously used in amplifiers.

The maser is based on the behaviour of individual atoms and must be described in terms of quantum theory. Briefly, the amplification mechanism is as follows. The energy of an atom is restricted to a number of discrete levels E_1, E_2, etc., and when the level changes, a quantum of radiation (a photon) is absorbed or emitted. Radiation quanta, of energy E_2-E_1 falling on such material may be absorbed by those atoms whose level is E_1 to raise them to the E_2 level. On the other hand when the radiation falls on atoms in the E_2 state it may cause them to *emit* radiation, which is in phase with the original radiation, thereby increasing the strength of the original radiation (this is called 'stimulated emission'). Under equilibrium conditions the number of lower-energy atoms exceeds the number of higher-energy atoms, and so radiation traversing the material suffers net *absorption*. In the maser this situation is reversed by the 'pump' signal, which is radiation with energy quanta E_3-E_1, greater than those of the signal frequency, E_2-E_1. This is absorbed in the usual way and raises atoms to an energy level E_3, above E_2. Some atoms then spontaneously emit quanta of energy E_3-E_2 to fall to the E_2 level, where they are capable of increasing the energy of the signal so that radiation traversing the material experiences net *amplification*.

A suitable material for a maser is ruby which, when placed in a steady magnetic field of about 2000 gauss, provides suitable energy levels so that it acquires *negative absorption* (or becomes a signal amplifier) for 21 cm. waves. Masers have been built with noise temperatures of 60° K (cavity maser) and 10° K (travelling-wave maser). After reduction by the integration factor $(\tau\Delta f)^{\frac{1}{2}}$ overall sensitivities of 0°·03 K and 0°·001 K have resulted. An objection to the maser, however, is that the device must be immersed in liquid helium to reduce its temperature to about 3° K; this means a bulky and complex amplifier.

The action of the parametric amplifier may be explained by the analogue of a person on a swing who is increasing the amplitude of his motion by raising and lowering his centre of gravity. Each time he passes through the lowest point he raises himself in his seat and, since this does not change his horizontal velocity, his centre of gravity swings to a higher level than previously. While at rest at the end of the swing he again lowers himself in his seat and thereby starts the next half cycle with a large amplitude of swing. He expends energy by these movements at a frequency double that of the swing itself.

In the parametric amplifier the swing is replaced by a resonant electrical circuit comprising a capacitance C and inductance L.

Connected in parallel these resonate at a signal frequency $(LC)^{-\frac{1}{2}}$, the condenser alternately charging from and discharging into the inductance. The voltage across the condenser is analogous to the velocity of the person on the swing and the capacitance is analagous to the height of his centre of gravity above the seat of the swing.

Suppose that, when the voltage is a maximum, the capacitance of the condenser is suddenly reduced. This might be done by pulling the condenser plates apart, in which case mechanical work is done on the condenser to separate the electrical charges on the plates. The work so done increases the electrical energy of the system; in practice the capacity C is reduced electronically (e.g. by a variable-capacitance diode) but energy is still added to the system. Now when the condenser is discharged so that there is no voltage across it, the capacitance is restored to its original value; no work is required to perform this action and no energy goes into or out of the system. Thus by decreasing and then restoring the value of C, the signal energy has been increased. This sequence is repeated continually, the energy being supplied by a 'pump' signal.

Parametric amplifiers have been developed with noise temperatures between 260° K and 70° K and overall sensitivities of between 0°.4 K and 0°·03 K. These performances are not as good as those of the travelling-wave maser, but the latter is more cumbersome and less flexible in use.

2.5 *Advanced systems*

The first departure from the 'elementary' radio telescope of Fig. 2 was the use of two widely spaced aerials to form an interferometer system. A radio aerial of diameter say 100 feet operating at 1 m. has a beam of half-width of about 2° which is hopelessly inadequate for measuring the diameter of a radio star, say 0°·1. Even an aerial 2000 feet in diameter cannot resolve this radio star. However, consider the spaced-aerial interferometer shown schematically in Fig. 6 with two small aerials separated by a large distance D. Radiation entering the aerials from a direction perpendicular to the line joining them has the same phase in each aerial and gives a maximum combined signal. Radiation from a direction at an angle θ degrees is out of phase and gives no signal when

$$\theta = \frac{29n\lambda}{D}, \text{ where } n = 1, 3, 5, \text{ etc.} \qquad (9)$$

The signal from a point source therefore goes through a series of maximum and zero values as shown. The maxima are separated by angles $\theta = \frac{57\lambda}{D}$ which, for one metre waves and a separation of say 1000 metres is about 0°·03. Such an interferometer viewing a source of size about 0°·03 gives a reduced response as shown in Fig. 6. The reason is that part of the source is in the maximum of the aerial and part in the region of zero response, so that no zeros are recorded and the maxima are reduced. As the two aerials are brought closer together the response changes from the lower to the upper curve of Fig. 6. An interferometer using quite small aerials at spacings up to a few hundred metres will resolve sources as small as 0°·1, measuring their sizes and positions with accuracy.

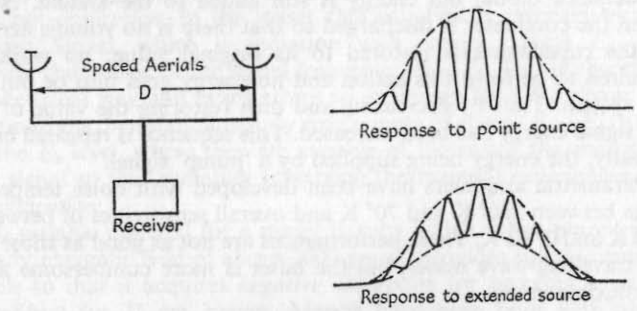

Fig. 6. The two-aerial interferometer and its response to a point source and an extended source.

Early examples of interferometers, as used in Australia by J. L. Pawsey and co-workers, used a single aerial on a cliff overlooking the sea. The place of the second aerial was taken by the mirror image of the first in the sea. This was a very simple arrangement but atmospheric refraction was likely to upset measurements at these low angles and most interferometers now use two or more aerials connected by cables and capable of accepting radiation from high angles of elevation.

The variable-spacing interferometer has been developed in Nançay and Cambridge, the aerials being mounted on two sets of railway tracks at right angles to one another. By adjusting the positions of each aerial, different interference patterns may be obtained from which the position, size and shape of the source may be deduced. A more recent example, operating at cm. wavelengths, is the Owens Valley telescope whose two 90-foot parabolic reflectors are shown in Plate 1.

In order to measure the size of distant radio sources the two aerials must be separated by very many wavelengths. The very distant sources, those likely to be of particular interest in cosmology, have angular sizes from a few seconds of arc to one minute of arc. An aerial spacing of about 3000 wavelengths is required to investigate these. The smallest sources then give interference patterns indistinguishable from that of a point source (upper trace of Fig. 6) while the largest give no interference pattern at all. The Owens Valley telescope operates at wavelengths near 30 cm. so that the maximum required separation is about 1 km. At larger wavelengths the flux density from the source is greater but the aerial separation must be increased. A three-aerial interferometer has been built near Sydney to operate at 3·5 m. with a spacing of 10·2 km. This distance is so great that a radio link between the two distant aerials is required to bring the two signals to a common point. The beam common to the two aerial systems is 3°·7 (north–south) by 0°·8 (east–west) and this is divided into fine 'fringes' running north–south. There is a third aerial situated 30 wavelengths south of the main array, this gives a coarse fringe pattern running east–west and allows more discrimination between sources. A radio link interferometer is also in operation at the Jodrell Bank Observatory. and another at St Michel in the South of France.

A novel form of interferometer, first developed by W. N. Christiansen in Sydney, consists of a row of many aerials all connected to a single receiver. He used thirty-two parabolic reflectors extending along a line 1000 wavelengths long; operating at 21 cm. this was 210 m. The optical analogue of this aerial is the diffraction grating. When white light falls on a grating a series of spectra are produced, the colours red to violet being spread out and then repeated in the second, third, etc., order spectra. If a single colour light falls on the grating it produces a number of narrow illuminated bands separated by dark regions. This is the aerial diagram of the multi-element interferometer: a series of long narrow bands (3-minutes of arc wide) separated by regions of zero response (1°·7 wide). This device was used to scan the Sun whose disk is only 0°·5 wide so that it was only in one interference fringe at any particular time. As the Earth rotated, the Sun moved through each of the maxima and produced a record of the brightness in a narrow strip running north–south across its disk. Grating type interferometers in this and more elaborate forms have been built in France, Canada and Japan.

An aerial system which bridges the gap between large 'pencil beam' aerials and interferometers has been developed in Australia by B. Y. Mills. It depends on the fact that when two different aerials are combined, interference is possible for radiation *common to both beams*. The principle of the device is shown in Fig. 7. Two conventional line-source aerials *NS* and *EW* of considerable length are set up on the ground. The aerial *NS* receives radiation from the narrow strip of the sky marked *NS* in the aerial pattern diagrams.

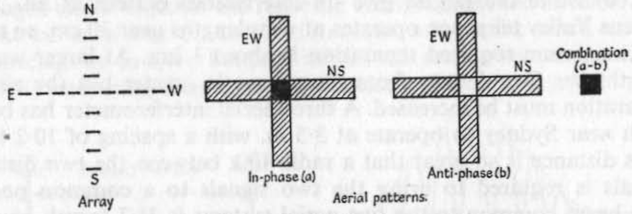

Fig. 7. Explaining the Mills-Cross radiometer.

The aerial *EW* receives radiation from the strip *EW*. If the outputs of the two aerials are simply added they give a diagram in the form of the whole cross *NS* and *EW*, the response from the central region (blackened) is greater because it is common to both aerials. If the aerials are connected in anti-phase then the response of the arms is not affected but that of the centre is reduced to zero. If the aerials are connected through a phase switch which periodically reverses the phasing* then a source in the central region will give an alternating signal, while that from the arms will give none. In effect the response of the aerial is that of the small central region only; this pencil beam may be steered north–south by adjusting the phasing between the aerial elements. It is carried east–west by the Earth's rotation. Two such crosses have been built near Sydney, one at 3·5 m. with an arm length of 1500 feet and a beam width of 0°·8; the other works at 15 m., has an arm length of 3500 feet and a beam-width of 1°·4.

The cross principle has been combined with the grating principle to provide an array working at 20 cm., used to scan the Sun with a pencil beam only 3 minutes of arc wide. The aerial system, built near Sydney, consists of sixty-four 19-foot diameter paraboloids arranged in the form of a cross, each arm consisting of thirty-two reflectors equally spaced on a line 1200 feet long. Each arm produces a set of knife-edge beams, some lying north–south, some east–west, and when combined these give a set of pencil beams only 3 minutes of arc in width separated by 1°. With this separation only one beam falls on the Sun at once. A similar system working at 10 cm. has been built in California.

Solar bursts of radio emission have notable spectral features which may only be studied by a radiometer which can receive and analyse signals over a wide range of frequencies. Such solar radio spectrographs have been developed in Australia and the U.S.A. So rapidly do some spectral features change that the Australian spectrograph was built to record a complete spectrum in an interval of ½ second. Broad-band rhombic aerials are used which are capable of operating without adjustment over a frequency range of about 2 to 1. Using four such aerials the range from 25–210 Mc/s (12 m. to 1·4 m. wavelength) is covered; the aerials are mechanically driven to follow the Sun across the sky. Each aerial is connected to a swept-frequency receiver which is mechanically tuned across its range in ⅛ second. The receiver outputs are combined in a time-sharing 'sequence switch' which allows them to be displayed in sequence on a cathode-ray tube. The spectrum is displayed as an intensity-modulated line; this is photographed on film which is moved slowly and continuously in a direction perpendicular to the line. The film then plots signal strength (degree of exposure) against frequency in one direction and time in the other. Examples of such *dynamic* spectra are given in Chapter 6.

The radio spectrographs in the U.S.A. use steerable paraboloids in place of the rhombic aerials. A single paraboloid with four separated feed systems mounted around its focal point has been developed to cover the required frequency band.

3. The Generation and Propagation of Radio Waves

In this chapter a fairly comprehensive, although brief, outline is given of the processes of generation and propagation of extra-terrestrial radio waves. Although the discussion is kept as simple as possible, parts may prove difficult to the reader with no prior knowledge of electromagnetic wave theory. This should detract little from an understanding of the contents of the later chapters.

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* The principle of phase switching was first introduced in Cambridge where it was used on *spaced* aerials to provide an interference pattern.

Most extra-terrestrial radio waves originate in highly rarified *ionized gas*. One exception is the 21-cm. line radiation emitted by cold neutral hydrogen gas; the generation of this line radiation is discussed in Chapter 5. Its propagation follows the same laws as that for all other radio waves and so does not need further special mention. Another exception is the radiation from solar and terrestrial satellites, which is dealt with in Chapter 7. For the present we will confine our attention to emission from ionized gas.

Most of the matter in the universe is hydrogen and when this is hot enough, as in the solar corona and parts of interstellar space, it breaks up into equal numbers of protons and electrons which may be referred to generally as ions. If an ion is accelerated, that is, if it is speeded up, slowed down or made to change its direction of motion, it emits an electromagnetic wave. Because they are much lighter (by a factor of 1840) the electrons may be accelerated more easily and so are much more efficient radiators. Thus, effectively all cosmic radio noise results from the *disturbed motion of electrons*.

The role of the electrons in radio astronomy does not finish with the creation of an element or quantum of radiation. The radiation must travel from its source to the Earth and its propagation may be affected by other electrons along its path. Since any emission process may work in reverse as an absorption process, the intervening electrons may reabsorb the radiation. Certain distributions of electrons may deflect the radiation from its normally straight path (refraction) or even reflect it entirely. Finally the intervening electrons may change the polarization of the original radiation. The foundation of a theory of propagation was laid down by Lorentz and extended by Appleton and others for the more complex situation when a magnetic field is present. The theory, often called the magneto-ionic theory, has proved most successful in predicting the behaviour of radio waves in the ionosphere and appears equally well applicable to the more distant regions with which we are concerned.

In the following section this theory of propagation is first discussed and then the processes of generation of radio waves. This may seem like putting the cart before the horse but, as will be seen, some of the processes of generation may only be understood from a prior knowledge of propagation.

3.1 *The theory of propagation*

In free space, all electromagnetic waves, irrespective of their frequency or polarization, travel with the velocity of light, about 300,000 km./sec. A wave of frequency f completes one oscillation in a period of $^1/f$ sec. during which it has travelled a distance c/f cm. where c is the velocity of light in cm. per second. Thus the wavelength is given by

$$\lambda = c/f. \tag{1}$$

For example a wave of frequency 1420 Mc/s has a wavelength approximately 21 cm.; this is the wavelength of neutral-hydrogen line emission.

When a radio wave travels through a region occupied by free electrons these vibrate with the wave and cause the wavelength (for a given frequency) to change. The positive ions also vibrate but being very much heavier their effects may be neglected. As in the theory of light, it is convenient to introduce a quantity called the refractive index of the medium n, being the ratio of the wavelength in free space to the wavelength in the medium. The value of n depends on the electron density which defines the 'plasma frequency' or resonance frequency f_0 of the medium according to the equation

$$f_0^2 = \frac{Ne^2}{\pi m} \tag{2}$$

where N, e and m are the electron density, electric charge and mass* respectively. The refractive index is then given by

$$n^2 = 1 - f_0^2/f^2. \tag{3}$$

As f_0 increases from zero the refractive index decreases from unity and becomes zero when $f_0 = f$, below which n is an imaginary quantity. This mathematical convention implies that the wave is *reflected*, a process well understood in our dealings with the ionosphere. As an example consider a medium of density one million electrons per cubic centimetre. The value of f_0 is then 9 Mc/s which means that waves of higher frequency pass freely through the plasma but waves of lower frequency are completely reflected. The waves which pass have enhanced wavelength and phase velocity, the latter exceeding the velocity of light. The frequency range which cannot propagate in a plasma is called a 'stop' band as opposed to a 'pass' band.

A wave vertically incident on a boundary of a plasma is reflected when $f = f_0$. At other angles of incidence the wave is reflected for lower values of f_0. Suppose we have a series of plane parallel strata of gradually increasing electron density and so of decreasing refractive index. Let i_0 be the angle of incidence† of a wave on the outer-

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* C.G.S. and electrostatic units are used throughout this chapter.

† The angle between the direction of propagation of the wave and the perpendicular to the plane strata.

most stratum where $n \sim 1$. This wave is gradually deflected and finally completely reflected at a level where n and i_0 are related by Snell's law

$$n = \sin i_0. \tag{4}$$

Combining equations (2), (3) and (4) gives the electron density N at the level of reflection. The problems of reflection from a spherical, rather than plane, system of increasing electron density is more complicated but it is not difficult to see that the ray which is directed towards the centre of the sphere reaches the lowest level before being reflected. Other parallel rays whose original directions would not take them through the centre of the sphere are reflected from higher and higher levels.

While not sufficiently dense to fully reflect a radio wave, a cloud of electrons may nevertheless refract it through a small angle. The Earth's ionosphere is often full of such clouds and the rays from a 'radio star' are bent accordingly. This means that on the ground the signal from the 'star' has an irregular and changing pattern, resembling the pattern of light on the bottom of a dish containing agitated water. A radio telescope records a signal which varies irregularly or 'scintillates'. The effect is much the same as the twinkling of real stars which is due to refraction of their light, not in the ionosphere, but in the lower atmosphere. The study of radio 'star' scintillations has formed a branch of radio astronomy, but since the results are mainly concerned with our own atmosphere they appear to be more of a *geophysical* problem and are not discussed further here.

So far we have considered reflection from stationary plasmas; individual ions move but the whole cloud of ions remains at rest. An important effect occurs if the cloud moves, say with velocity v in the direction of the observer. The familiar effect of a Doppler frequency increase occurs; if a signal of frequency f is sent by the observer and reflected back by the cloud then the frequency measured after reflection is $f(1 + \frac{2}{c}v)$. When the radiation *originates* in the moving cloud, rather than being reflected from it, the frequency observed is $f(1 + \frac{v}{c})$. The Doppler effect is of great importance in connexion with observations of the hydrogen line and radar echoes from planets and other bodies.

With the introduction of a magnetic field into the plasma some further interesting effects are noted. In the first place the original wave divides its energy into two different waves having different polarizations and different velocities of propagation. The medium is *doubly refracting*, a phenomenon well known in optics according to which it has simultaneously two different values of n. These values depend on f_0 and on a new parameter $f_H = \frac{He}{2\pi mc}$, called the gyro-frequency, being the frequency at which electrons gyrate around the magnetic lines of force. A field of strength 1 gauss has a gyro-frequency of 2·8 Mc/s. The values of n also depend on the *direction* of the magnetic field relative to the directions of propagation so that the medium is no longer isotropic.

Roughly speaking the way in which the magnetic field affects the wave is as follows: suppose the electric field of a plane polarized wave is vertically up from the paper and that the magnetic field has a component in the plane of the paper. The electric field will tend to make the electrons oscillate up and down but when they start to execute this motion the magnetic field forces them to move also *in* the plane of the paper. The wave thereby gains an electric field component in this plane and becomes elliptically polarized. The wide variety of different wave configuration possible allows two to occur simultaneously (for a given frequency of oscillation) having different wavelengths and velocities. This is the double refraction effect and the two waves are usually referred to as the ordinary (O) wave and the extraordinary (E) wave.

Some of the properties of the O and E waves may be understood by study of the relatively simple case of propagation along the magnetic field. Both waves are then circularly polarized, one clockwise and one anti-clockwise and the equation for the two values of refractive index changes from equation (3) to the form

$$n^2 = 1 - f_o^2(f^2 \pm ff_H)^{-1}. \tag{5}$$

The upper sign refers to the O wave and the lower to the E wave. The equation for the O wave is much the same as equation (3) except that f^2 is replaced by $(f^2 + ff_H)$; there is a *pass* band where $f^2 + ff_H > f_0^2$ and a *stop* band for lower frequencies. The E wave shows more complicated behaviour, having two distinct stop regions.

The pass and stop (shaded) bands of the O and E waves are illustrated in Fig. 8. Any point on either diagram corresponds to particular values of the two variables f_0^2/f^2 and f_H/f. The diagrams are drawn for an angle of 30° between the field and the direction of propagation. However, their essential features do not vary over almost the whole range of angles of propagation so that they lead to quite general conclusions, of value to radio astronomers. For example, suppose the point P on the diagrams corresponded to the values of f_H/f and $f^2{}_0/f^2$ at a particular point in the solar atmosphere. Radiation leaving this point and moving out of the solar atmosphere must traverse regions of successively lower magnetic field strengths and lower plasma densities. To reach free space and so propagate to the Earth its track must reach the origin, where $f_H = f_0 = O$. It is obvious that neither O nor E waves may reach the Earth from levels where $f_0 > f$. The E waves are even more drastically imprisoned, being unable to escape from regions where $\frac{f_0{}^2}{f^2} + \frac{f_H}{f} > 1$. The waves *can*, however, escape from the points marked P^1, which is in the region where $\frac{f_0{}^2}{f^2} + \frac{f_H}{f} \leqslant 1$.

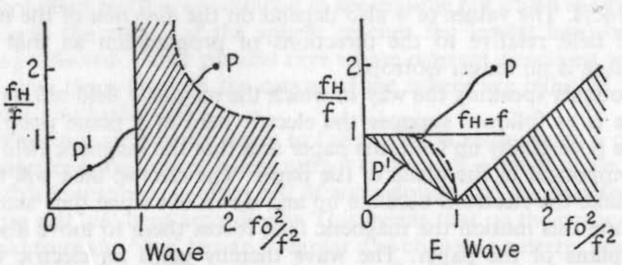

Fig. 8. Pass and stop (shaded) regions for the 'ordinary' (0) and 'extraordinary' (E) magneto-ionic waves.

We will not dwell further on the O and E waves except to mention the Faraday effect which has some importance in radio astronomy. Consider equation (5) in the limiting case where f_H is very small compared with f. If the effect of f_H is vanishingly small then we have two circularly polarized waves travelling with the same velocity. It is easy to show that the combination of a right- and a left-handed rotating vector gives a fixed vector which corresponds to a plane-polarized wave. However, f_H will have a slight effect, causing the two waves to travel with slightly different speeds. The result is that the plane polarized (combination) wave rotates its plane of polarization slowly as it travels forward.

3.2 *Thermal emission from hot plasma*

By Kirchoff's law, ionized gas may only emit radio waves provided it is also able to absorb them. In the preceding section the propagation of waves in a plasma was considered without reference to any absorbing process, but such processes must now be introduced in order to understand emission. The electrons of the plasma are accelerated by the electric field of the wave and so share the energy of the wave. If the electrons do not collide with other particles this energy is not dissipated but is handed back to the wave so that it leaves the plasma as strong as it entered. This is the case whether the wave passes through the plasma (a pass-band frequency) or is reflected (a stop-band frequency). If the electrons suffer collisions, however, the energy given them by the wave is dissipated and must be replenished at the expense of the wave, which is weakened.

The emission of energy is also provided by these same collisions in the following manner. The electrons have their own store of thermal energy which is simply their kinetic energy of *random* motion. When an electron passes near a heavy ion the electric field due to the electric charge on the ion causes the electron to be deflected. During this deflection, or acceleration, the electron emits radio waves, the energy source being the thermal energy of the electrons. It may seem curious that the collision process may result in either absorption or emission of radiation. Nevertheless, at the moment it receives its kick, the electron is in a position either to accept radiation (if there is strong enough radiation present) or to emit radiation.

If the number of collisions per second suffered by an electron is ν then the rate at which a wave is absorbed is proportional to ν and also depends in a complicated manner on the various magneto-ionic parameters discussed above. For our purposes it is sufficient to quote the absorption coefficient for a simple plasma with a magnetic field and for regions away from the stop regions of Fig. 8. These conditions hold generally in interstellar gas clouds and in the Sun's atmosphere (except near sunspots). The absorption coefficient is then approximately

$$\kappa = \frac{\nu f_0^2}{cf^2}. \qquad (6)$$

This means that the energy in a radio wave decreases exponentially as $\exp(-\kappa s)$, where s is the distance travelled in the medium.

In fully ionized hydrogen, in the regions generally of interest to radio astronomers, ν is given by a complicated expression in N and T, the gas temperature. The approximate value of κ reduces to

$$\kappa = \frac{0{\cdot}1\,N^2}{f^2T^{3/2}}. \qquad (7)$$

After travelling a distance s a wave retains a fraction $\exp(-\kappa s)$ of its power and so has lost a fraction $\{1-\exp(-\kappa s)\}$. This latter fraction is a measure of the opacity of a sheet of plasma of thickness s and when raised to temperature T it has a *brightness temperature* which is the product of its true temperature and its opacity:

$$T_b = T\{1-\exp(-\kappa s)\}. \tag{8}$$

Its *brightness* b is given by equation (3) of Chapter 2 and so we have

$$b = \frac{2kT}{\lambda^2}\{1-\exp(-\kappa s)\}. \tag{9}$$

When κs is much greater than unity the cloud is completely opaque and emits as a black body, the expression within the curly brackets being unity. When κs is much less than unity we have approximately

$$b = \frac{2kT_\kappa s}{\lambda^2},$$

and substituting from equation (7) above and remembering that $f\lambda = c$,

$$b = \frac{0{\cdot}2\,kN^2 s}{c^2 T^{\frac{1}{2}}}. \tag{10}$$

This expression is independent of wave frequency and length and corresponds to the horizontal part of curve (a) Fig. 9. The straight-sloped part is the black-body emission region where b is inversely proportional to λ^2. The whole curve is a radio spectrum of a typical ionized gas cloud, actual examples of which are discussed in the following chapter.

3.3 *Magnetic acceleration emission*

An electron moving with any (non-relativistic) velocity in a magnetic field of strength H, moves in a circle at a rate $f_H = \frac{He}{2\pi mc}$ revolutions per second. Since the electron is being accelerated it should be emitting radio waves and this is the case, the process being called 'gyro-emission'.

Gyro emission may be better understood by a study of the complementary process of gyro-absorption of a wave propagating in a medium where the value of f_H equals that of the wave, f. For the simple case of propagation along the field the refractive index is given by equation (5) and it is at once evident that for the extraordinary (E) wave, corresponding to the lower (–) sign, that n goes to infinity. This means that the wave has no velocity at all and feeds all its energy into the electrons. The energy absorption process is highly efficient because the electrons rotate exactly in phase with the wave and continually absorb the wave energy, thereby increasing their kinetic energy.

In a reverse process, when the wave is absent, the electrons rapidly radiate away their thermal energy. In the early days of radio astronomy it was thought that gyro-radiation might account for much of the solar emission. This cannot be so, however, as may be seen by studying Fig. 8. The wave concerned is the E wave and the region concerned is somewhere along the horizontal line marked $f_H = f$ (since this is the condition for gyro radiation). It is evident that the radiation from anywhere along this line (except where $f_0 = 0$) is prevented from leaving the solar atmosphere by the stop band which separates it from the origin.

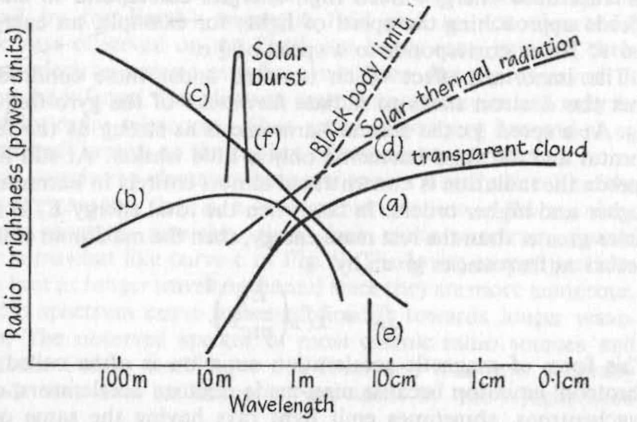

Fig. 9. Some radio spectra: (a) Thermal radiation due to electron collisions, showing the black-body limit and the 'nearly transparent' parts of the curve. (b) Synchrotron radiation from a single electron of energy 2.4 million electron volts in a field of one gauss. (c) Synchrontron radiation from a distribution of cosmic-ray electrons. (d) The spectrum of the quiet Sun. (e) The hydrogen emission line. (f) The spectrum of a burst of solar radiation.

Gyro radiation is emitted by electrons with speeds much less than that of light. As the electrons are speeded up, some curious effects are noted; in the first place, according to Einstein's theory of relativity their mass increases. According to this theory there is a universal equivalence between mass and energy, whatever the form of the energy. This may be written

$$E = mc^2, \tag{11}$$

where E is the energy, m the mass of the electron (or any other object for that matter) and c the velocity of light. The mass of an electron is $9{\cdot}1 \times 10^{-28}$ gram so that its energy when at rest is $8{\cdot}2 \times 10^{-7}$ ergs or $5{\cdot}1 \times 10^{5}$ electron volts (ev). If an electron is given kinetic energy of $5{\cdot}1 \times 10^{5}$ ev, then its total energy E_T is double its 'rest mass energy'. Such high energies correspond to electron speeds approaching the speed of light; for example, an energy of $2{\cdot}6 \times 10^{5}$ ev corresponds to a speed of $\frac{3}{4}$ c.

The important effect which is noted under these conditions is that the electron starts to radiate *harmonics* of the gyro-frequency f_H. At a speed $\frac{3}{4}$ c the second harmonic is as strong as the fundamental and the third harmonic only a little weaker. At still higher speeds the radiation is concentrated almost entirely in harmonics of higher and higher orders. In fact when the total energy E_T is many times greater than the rest mass energy, then the maximum emission occurs at frequencies given by

$$f_m = \tfrac{1}{2} f_H \left(\frac{E_T}{mc^2}\right)^2. \tag{12}$$

This form of magnetic-acceleration emission is often called 'synchrotron' emission because man-made electron accelerators, called synchrotrons, sometimes emit light rays having the same origin. Probably the most important theoretical advance in radio astronomy was to show that synchrotron or magnetic-acceleration emission was responsible for most of the observed cosmic radiation.

In the spiral arms of the Galaxy, magnetic fields of strength about 10^{-5} gauss exist, so that electrons would have gyro frequencies of only 28 c/s (corresponding to a wavelength of 10,000 km.). Such waves are of no particular interest to radio astronomers, but when the electrons are speeded up the picture changes. If the electrons have energies of say one thousand million electron volts, then their maximum energy is emitted at a frequency, given by equation (12) as 54 Mc/s, the corresponding wavelength being 5·6 m. which is well in the radio astronomy band. A frequency of 54 Mc/s corresponds to a harmonic of order about $1{\cdot}9 \times 10^{6}$. Naturally a single harmonic is not emitted, but rather a whole sequence, separated by intervals of only 28 c/s. The result is virtually a smooth spectrum of emission with a maximum at 54 Mc/s. Such a spectrum is shown in Fig. 9 as curve (b). It falls off quickly towards the shorter wavelengths and more slowly towards the longer wavelengths; over a 10 to 1 wavelength range near the maximum it only varies by a factor of about 1·4 to 1. It was this feature of the spectrum which showed that most of the variable *solar* radio emission cannot be synchrotron emission because its spectra are too narrow.

It is well known that the Earth is always under bombardment by ions travelling at speeds near that of light. These 'cosmic rays' have energies up to 10^{18} ev or more, but they become steadily more numerous as the energy decreases to 10^{9} ev below which they are deflected by the Earth's magnetic field and so not observed.* Cosmic rays observed on the Earth are heavy ions, most of them protons; electron cosmic rays have not been directly observed. It can now be inferred that electron cosmic rays do exist and may be studied by radio telescopes. Thus radio astronomy has added an observational branch to the subject of cosmic-ray physics.

If the cosmic-ray electrons have an energy distribution like the cosmic-ray protons, that is, a fairly rapid decrease in the numbers of more energetic particles, then their radio spectrum should appear somewhat like curve c of Fig. 9. The lower-energy particles radiate best at longer wavelengths and since they are more numerous, the radio spectrum curve increases steadily towards longer wavelengths. The observed spectra of most cosmic radio sources and that of the Galaxy itself have this form and it is now generally accepted that the radiation is provided by the synchrotron process.

3.4 *The two forms of Cerenkov emission*

As we saw above, when an electron has a close collision with an ion it may emit a radio wave; either the ordinary O or extraordinary E waves may be emitted if a magnetic field is present. There is another emission process, not entirely different in its nature, which may occur when a fast-moving ion (electron or heavy ion) passes through a plasma. As it passes each electron, although no actual collision occurs, the electron is pushed aside slightly and so tends to radiate. Usually no wave is emitted because all the elementary waves from the different electrons cancel one another out. This situation changes, however, when the original ion is moving with a velocity higher than that of the radio wave in the medium. Then, instead of exciting a standing wave which cannot escape, it excites a shock wave in the same way that an aircraft excites a shock sound

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* Except near the geomagnetic poles and, more recently, by instruments in satellites and space probes.

wave when it exceeds the velocity of ordinary (elastic) sound waves in air.

The essential point in this Cerenkov emission process is that the ion velocity exceeds the wave velocity. The refractive index of the medium n is the ratio of the velocities of light and of the wave and if n is less than unity then the wave velocity exceeds c. No ion can travel with such a velocity and so no emission occurs; this is the case for a plasma without a magnetic field (equation (3)), n always being less than unity. However, when a magnetic field is present the E wave may assume velocities less than c (equation (5), lower sign) and so the E wave may be generated by the Cerenkov process. A whole spectrum of waves is generated all moving away from the source in different directions. The direction in which a wave of a particular frequency is emitted depends on its phase velocity and on the velocity of the exciting particle: the component of the latter in the direction of propagation of the wave must be exactly equal to the phase velocity.

There are not, at the time of writing, any extra-terrestrial radio waves whose origin may be demonstrated as the Cerenkov process. Such waves *must* be generated in the solar atmosphere but being E waves they cannot escape for the reason given in section 3.1: they are blocked by a 'stop' region between their point of origin and the outer limits of the corona. However, as seen in Chapter 6, these E waves may, directly or indirectly, transfer their energy to O waves, which can escape.

The Cerenkov process will generate *any* wave which has a phase velocity lower than the ion velocity. In addition to the O and E radio waves a third type of wave may propagate in an ionized gas.* This is an *electric space-charge wave*, caused by the electrons alternatively bunching together and being pushed apart by the mutual repulsion of their electric charges. It is rather like a sound wave propagating only in the electron gas, which moves independently from the proton-gas. These space-charge waves may have phase velocities much lower than the velocity of light and so must be generated by sufficiently fast-moving ions. The Cerenkov process is thus capable of generating two entirely different types of wave: the E radio wave and the space-charge wave.

The space-charge wave cannot leave the plasma in which it is generated because only radio waves may propagate in a vacuum.

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* There is a fourth type, which is a sound wave modified by any magnetic field present. This only occurs at frequencies much lower than the ones of interest here.

However, these space-charge waves are probably very important in generating radio waves in the solar atmosphere. They generate radio waves by colliding with one another in the manner discussed in section 3.6.

In the following section another theory of growing space-charge waves is discussed. At first sight this appears to be quite different to the Cerenkov process. In fact the latter is a three-dimensional version of the former; a fact which is not generally recognized.

3.5 *Electric space-charge waves and clouds*

The magneto-ionic theory has been developed without taking account of the random thermal movements of the electrons, which means that the electrons are considered as a perfectly cold gas. This gives a good enough approximation when considering the propagation of radio waves in the ionosphere. It introduces some errors for radio propagation in *very* hot gases, but most important it completely neglects the presence of a third possible wave, the electric space-charge or electron sound wave, discussed above.

The velocity of this wave in a simple plasma, free of magnetic field, is given by

$$V = v\left(1 - \frac{f_0^2}{f^2}\right)^{-\frac{1}{2}}, \tag{13}$$

where v is roughly the velocity of individual electrons and as before f_0 is the plasma frequency (equation (2)). As in the case of the radio wave there is a pass band and a stop band. Away from the stop band the wave velocity is approximately v and the waves may be considered as one or more concentrations or bunches of electrons moving with this velocity. When a magnetic field is present the space-charge waves, like the radio waves, behave in a more complex manner.

The formation of electron bunches or clouds depends on the presence of *two* electron gases, one of which streams through the other. Alternatively, an electron gas may stream through a proton gas, this constituting an electric current. We will consider the simplest case of two electron streams, each of density N, one moving to the left and one to the right with speeds v_s (which is much greater than the random thermal speed v). Two types of wave may propagate in this double-stream medium, one with velocity greater than v_s and one with velocity less than v_s. The high-speed wave resembles that in a single medium (equation (3)), having a pass and a stop band; below a certain critical frequency the wave cannot propagate but is reflected from the medium. The low-speed wave reveals an entirely new characteristic: it does not have a stop band in the sense that waves within a certain frequency range may not propagate. It *does* have a stop band in the sense that waves within a certain *wavelength* range may not propagate. Furthermore, these waves, of length greater than the critical length $\frac{v_s}{\sqrt{2}f_0}$, are not merely reflected from the medium but remain in the medium and steadily grow in strength. The concept of waves is useful in analysis but these stationary, growing waves need not really be considered as waves at all. In effect, any sufficiently extensive region having a slight excess of electron density acquires more electrons from outside its borders and so becomes a *growing electron cloud.*

Although the mechanism of the growing electron cloud was only understood recently, it is simple and straightforward. Consider an electron stream traversing a stationary electron gas containing a cloud of density slightly greater than the surroundings. The cloud will have an excess negative electric charge and will tend to repel the approaching electrons. However, if the excess charge is small, the stream may still traverse the cloud, but electrons approaching the cloud are slowed down, those leaving are given a push which speeds them up. Consider a group A of electrons which are slowed while traversing the cloud. They spend more time in the cloud than they would if it had zero space charge. By spending more time in the cloud they add to its space charge and cause the next group, B, of electrons to be slowed even more. Group B contributes more than group A to the electric field of the cloud and so further slows group C and so on. The cloud continually increases in density.

The effect is an instability in the medium, causing bunching of the electrons into space-charge clouds. The size of cloud which has the strongest tendency to form is about $\frac{v_s}{f_0}$. When the two ion streams have equal and opposite velocities the growing clouds are at rest. When one electron stream has much lower density than the other, the clouds travel with the less dense stream. The possible importance of growing electron clouds, or space charge waves in radio astronomy is shown in the next section.

It is not generally recognized that the above theory of growing plasma clouds may be regarded as a one-dimensional version of the Cerenkov effect. Instead of considering an electron moving through a plasma, consider the plasma streaming past one or more stationary electrons. According to the Cerenkov effect some of the moving electrons are slowed down to form a cone-shaped space-charge wave. This does not continue to grow in intensity as in the one-dimensional case because it can propagate away from its source. Nevertheless both theories describe the slowing of one electron stream in passing an irregularity in a second stream of electrons or heavy ions.

3.6 *Emission beyond the black-body limit*

Let us now compare and contrast the so-called 'thermal' emission process (section 3.2) with the gyro and synchrotron or magnetic acceleration processes (section 3.3). In each case emission occurs when an electron changes its direction of flight or of *thermal* motion. The thermal motion or thermal energy of the electrons is thus a prime requirement for emission; the amount of energy radiated depends on the temperature of the electron gas. From this point of view all of these emission processes might be grouped under the heading 'thermal radiation'.

However, in addition to being hot the ionized gas must possess a second quality before it can radiate – it must have some *opacity*. It must be capable of absorbing radio waves, otherwise, by Kirchoff's Law, it is incapable of emitting them no matter how hot it becomes. An example of this law in operation is seen when a sheet of glass is heated. It emits very little light because it is transparent to waves of this length; on the other hand it emits heat waves copiously because it is opaque to waves of this length. The quality of opacity in a gas is provided by a mechanism of electron acceleration: as we have seen this may be a direct collision with a heavy ion or by the Lorentz force resulting from the motion of the electron across a magnetic field. Only in the former case is the emission termed thermal.

However, Kirchoff's Law is quite general and implies that any emission process may operate with equal efficiency as an absorption process. It also sets a *black-body* limit on the amount of radiation from any body, depending on the thermal energy of the radiating ions, that is, on their temperature. This applies whether the emission process is by close collisions, by magnetic acceleration or by the Cerenkov process. Some of the cosmic-ray electrons responsible for the galactic radiation have energies of 10^8 electron volts which is the average energy of particles of a gas at a temperature of about 10^{12} °K. It is not surprising then, that they are capable of producing brightness temperatures of 10^8 °K or more.

However, the brightness temperature of active parts of the solar atmosphere often attain values of 10^{13} °K and, on one occasion at least, 10^{15} °K. The spectrum of this radiation and other factors precludes the possibility of emission by the magnetic acceleration mechanism and we are faced with the difficulty of explaining how the gas can radiate far above the black-body limit – for it is certain that the gas is not at that enormous temperature.

The answer is very simple. Suppose that during some emission process, it does not matter which at the moment, two electrons move side-by-side. Having twice the electric charge of one they create a radio wave of double the magnetic (and electric) field strength and hence four times the power. A (sufficiently small) group of N electrons will provide N^2 times the power and so each electron provides N times the power it would give if alone. The whole electron gas, if bunched into groups of N electrons, is capable of providing radiation of intensity N times the black body limit.

Now let us consider which of the various emission processes might permit this effect. In the magnetic acceleration processes the electrons move in fairly large circles around the magnetic lines of force, there would be no reason why a bunch of electrons could not execute a circuit in unison and in the previous section a reason was given why electrons should tend to bunch. Similarly in the Cerenkov process of emission of the radio E wave, bunching should be possible. However, in the close collision process the reverse is true: it is highly improbable that even two, let alone more electrons, would execute similar close collisions with a particular ion at the same instant.

The conclusions of the last two paragraphs may be reached by elaborate and complicated mathematical processes using quantum electrodynamics; the extra emission from each electron is then referred to as stimulated emission. Such an approach seems unnecessary as the answer is obtained quite simply by the above classical argument.

One example of radiation beyond the black-body limit is found in any radio transmitting aerial. *Groups* of electrons are forced in and out of the aerial so that it radiates at *equivalent temperatures* of perhaps billions of billions of degrees, while its *true temperature* is only a few hundred degrees.

Another example may explain some of the intense bursts of solar radiation. It depends on the growth of clouds of electrons of dimensions approximately

$$l = \frac{v_s}{f_0}, \qquad (13)$$

where v_s is the streaming velocity. In a turbulent medium numerous clouds must form and move with random velocities, somewhat analagous to the thermal motions of the individual ions. The random velocities will be of order v so that two clouds will 'collide' with one another during a period of order l/v_s and emit radio waves whose frequency is the inverse of this time, that is v_s/l. Substituting from equation (14) the radio-wave frequency is then given by

$$f = f_0, \qquad (15)$$

or the plasma frequency.

Since the kinetic energy of the clouds may be far greater than that of individual electrons, the emission may far exceed black-body emission.

4. The Continuous-Spectrum Cosmic Radiation

COSMIC radio emission is the radiation received from beyond the solar system. It is made up of the two components, *continuous-spectrum emission* and *hydrogen-line emission*. The former fills the whole radio window (see section 1.2) and no doubt extends far beyond these limits set for Earth-bound observers. It represents all but a tiny fraction of the total cosmic radio emission and is the topic of the present chapter.

Hydrogen-line emission is limited to wavelengths near 21 cm. and a very small amount of power. Nevertheless it has led to scientific discoveries of equal importance, which are discussed in Chapter 5.

Cosmic-continuum emission at a wavelength of 15 m. (20 Mc/s) was discovered by Jansky, in the U.S.A., who set the pattern for future investigations. Moving his aerial beam slowly across the sky he plotted the intensity of the radiation against the direction and produced a set of radio isophotes or lines of equal intensity. This map of cosmic brightness closely resembles an ordinary contour map whose lines show equal land levels. Jansky found that the highest levels of radio brightness were concentrated near the Milky Way and in particular near the galactic centre in the constellation of Sagittarius. A most surprising feature of these observations, and one which was not appreciated for many years, was the high intensity of the radiation which corresponded to that of a black body at a temperature of hundreds of thousands of degrees.

A decade later an amateur observer, using a 30-foot paraboloid erected in his back yard, carried out radio surveys at 1·9 m. and 62 cm. Reber's work is one of the few important amateur contributions to science in this generation.

The broad picture resulting from these and numerous subsequent surveys of cosmic radiation is of a great band of relatively bright sky along the Milky Way with bright spots, the discrete sources, dotted about both within and away from the Milky Way. So far this picture does not differ greatly from the optical picture, except that our eyes have much greater resolving power than the radio instruments. However, there are three great differences.

Firstly, relative to the Sun the cosmic radio intensities are surprisingly high. For example, at a wavelength of 15 m. the Sun has a brightness temperature of about a million degrees Absolute (or Kelvin). If the stars radiated equally well then we should expect the brightness temperature of the Milky Way to be only about one-hundredth of a degree because the stars occupy only one-hundred millionth of the total area of the sky. Instead, the radio brightness temperature of the Milky Way is also about a million degrees; one hundred million times larger than might have been expected. It is now known that the stars themselves are *not* responsible for any appreciable part of the cosmic radiation; this originates by the acceleration of electrons in the vast spaces between the stars. Two forms of accelerations are important, the first being the deflection of a low-speed electron during a collision with a heavy ion; this is called *thermal emission.* The second emission mechanism depends on the deflection of high-speed electrons (or cosmic-ray electrons) in the galactic magnetic field; this is called *synchrotron emission* or *magnetic acceleration emission* (Chapter 3).

The second way in which our radio and optical pictures differ is in the form of the Galaxy. There is general similarity in that the visible and radio 'Milky Ways' are the dominant features. However, there are two important radio features which are missing in the optical picture of the Galaxy. The radio brightness shows a marked concentration not only towards the plane of the Galaxy but also towards the central point of the Galaxy. The radio brightness also has a nearly uniform component over the whole sky. This is due to a galactic 'corona' which extends far beyond the visible Galaxy and provides a strong background of radio brightness. The existence of coronas around external galaxies has also been demonstrated. These are completely transparent to optical radiation and so their existence, of enormous significance in connexion with galactic structure, could only have been demonstrated by radio telescopes.

The radio picture has one more remarkable feature lacking in the optical picture. Away from the Milky Way most discrete radio sources are very distant galactic systems, far beyond the limits of our own Galaxy. A few of these, now called 'radio galaxies', emit radio waves as much as a million times stronger than the average galaxy. These galaxies, barely visible through large optical telescopes, appear as bright 'radio stars' even using the simplest of radiometers.

4.1 *The surveys of cosmic radiation*

The radiation from the Galaxy is extraordinarily intense at metre and decametre wavelengths. Thus if a modern sensitive receiver is connected to a simple dipole aerial at a wavelength of 10 m., almost all of the noise output originates in the Milky Way. This made observation of cosmic noise easy, but plotting its distribution over the sky was another matter. An aerial beam of width about 1° gives a satisfactory amount of galactic detail but to provide such a beam at a wavelength of 10 m., aerial dimensions of more than 2000 feet are required. The dimensions of aerials used for the early surveys were closer to 20 feet with the beam-width correspondingly increased to 100° at 10 m. or 10° at 1 m. or 1° at 10 cm. This situation favoured the use of centimetre waves but unfortunately the intensity of emission there is very much less and early surveys revealed only the brightest galactic features.

Early metre-wave surveys of cosmic radiation were made at 1·9 m. in the U.S.A., at 4·7 m. in England (see references in Chapter 1), and by C. W. Allen and C. S. Gum at 1·5 m. in Australia. Plots of the brightest areas were obtained at 25 cm. by J. H. Piddington and H. C. Minnett in Australia who also made some measurements at 10 cm. These early surveys all showed the most intense radiation coming from the general direction of the galactic centre. It is now known that this radiation does come from the centre of the Galaxy which is obscured optically by clouds of dust and gas. Thus radio astronomers were the first to survey this interesting region, although the rather broad beams used, ranging from 3°·4 to 25°, gave very poor resolution.

Another concentration of radiation in the constellation of Cygnus was resolved by the narrower beams of the cm. wave aerials into two sources which have proved of great interest. One, often called Cygnus X, is a *radio nebula* within the Galaxy and is discussed in section 4.3. The second source, called Cygnus A, was the first *discrete source* to be discovered and was responsible for the introduction of a new type of survey using the multiple aerial-beam techniques of interferometry.

For the time being we turn from the single-beam surveys which provide the best plots of distributed radiation and take up the story of the interferometer surveys which provide the best method of accurately locating the discrete sources or radio stars as they were called.

The survey at 4·7 m. provided some evidence of a small discrete source of radiation. It was realized that a simple broad-beam aerial was not a suitable instrument for separating such sources from the background. On the other hand the use of two widely-spaced aerials would give an interference pattern as shown in Fig. 6 and would allow weak sources to be observed and their positions and sizes to be measured. The original discrete source Cygnus A was soon shown to subtend less than 8 minutes of arc and a number of other discrete sources were also located.

It was not long before some of these sources were identified with optical objects, thereby enormously stimulating theoretical interest in radio astronomy. None of the sources so far identified is a star and so they should all be termed *radio nebulae*. They include a variety of objects and their story is told in sections 4.3 and 4.4.

Early interferometer surveys at Sydney and Cambridge were carried out at metre wavelengths and up to 1952 about 100 sources had been located ranging in strength down to about 50 units,* a unit being 10^{-26} watts $m.^{-2}(c/s)^{-1}$. A few of the stronger sources were located with positional accuracy of a few minutes of arc and this led to the identification of some of them with optical objects. The identification of more sources, particularly those lying at great distances is one of the major lines of endeavour today.

In the years following these early surveys more and more elaborate radio telescopes have been devised to observe the radio sources. It was realized that identifications with optical objects would be aided not only by locating the sources with greater accuracy but also by measuring their angular dimensions. As identifications were made, interest in possible emission processes of the radiation was stimulated. The first requirement was a knowledge of the emission spectrum – this led to the development of systems covering a wide range of wavelengths and to accurate methods of calibration of intensity.

One of the most elaborate interferometers is that at Cambridge University Radio Observatory. This installation has four aerials and operates at a wavelength of 1·9 m. The beam-width of each aerial is 1°·2 in the east–west direction and 7°·7 north–south and this primary beam contains two sets of interference fringes at right angles (see section 2.5). A total of 471 radio sources, predominantly in the northern sky, have been located with this equipment. The minimum strength detectable is 8 units, a considerable gain over that of the earlier equipment; possible errors in position are listed up to about 10 minutes of arc. The longer-wave predecessor of the present Cambridge interferometer met a difficulty due to confusion between two or more weak sources. Although the fringes of the interference pattern are narrow (about 10 minutes of arc in the above system) the primary beam is wide (2°·4 by 15° in the earlier 3·7 m. system) and two or more of the numerous weaker sources may be present in the beam at once. The interferometer may then 'see' these sources as a single blend in a position not occupied by any real source. The use of shorter waves and hence a narrower beam seems to have largely obviated this difficulty.

The disadvantage of observing sources at cm. wavelengths is their relative weakness. For example the Cygnus A source provides a flux density at 5 m. of 22,000 units and at 9 cm. of only 700 units. On the other hand narrow aerial beams are easier to obtain at cm. wavelengths and with the invention of the new low-noise receivers (see section 2.4) the trend has been to shorter wavelengths. The two-aerial interferometer in Owens Valley, California, operates at 31 cm. with two 90-foot paraboloids giving a primary beam of 0°·8. This instrument was designed to locate a large number of sources with sufficient accuracy to allow them to be optically identified.

Interferometer techniques are necessary to provide the ultimate accuracy in source position and size. However, for a general survey of the sources *and* the background radiation, a narrow single-beam aerial is preferable. A 'pencil' beam survey at 22 cm. and a 0°·6 beam has been made by G. Westerhout with the 85-foot telescope at Dwingeloo, Holland.

The results of this survey are shown in part in Fig. 10. The contour lines represent lines of equal radio brightness, the outermost corresponds to a brightness temperature of 3·25° K. Very strong radio sources appear as closely spaced concentric contours. The map is simplified from the original which contained more lines

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* The total power flux in the whole radio spectrum, corresponding to one unit is about 10^{-17} watts m^{-2}. Over the whole surface of the Earth, the incident power is about one-thousandth of a watt. Even the strongest source provides only a few watts, an amount emitted by a small portable radio transmitter. This small amount of incident energy is due to the remoteness of the sources, the *total* radio power emitted by some is enormous.

intermediate between those shown here; also the map shows only a small part of the sky along the Milky Way. The co-ordinates are galactic longitude (ordinates) and latitude (abscissae). The sources shown are discussed in the following sections. A survey at 3·5 m. has recently been completed in Australia by B. Y. Mills, E. R. Hill and O. B. Slee using the Cross aerial (see section 2.5). It is fortunate that this has a beam-width of 0°·8; this allows the two surveys which differ in wavelength by a factor of 16 to be compared directly without making much allowance for different degrees of blurring due to different beam-widths. By late 1960 the 3·5-m. survey had revealed some 2000 discrete sources with intensities down to the limit of 'visibility' at 7 units.

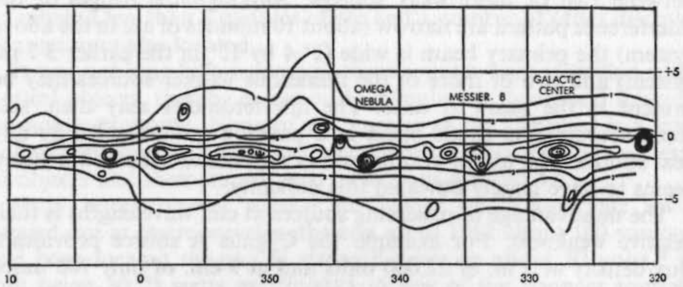

Fig. 10. A radio map of the Milky Way at a wavelength of 22 cm. (*Westerhout in Sci. Amer.*)

Two other partial surveys are providing interesting additional information on spectra of sources and background. The first is by C. A. Shain in Australia, using the 15 m. Cross aerial giving a beam of 1°·4. This is about the longest wavelength at which a reasonably detailed survey is likely to be available, at least until we can observe from above the Earth's ionized atmosphere. The results are shown in Fig. 11. The second partial survey is at an intermediate wavelength of 73 cm. using the 250-foot paraboloid at Jodrell Bank; the beam-width is about 0°·7.

With the completion in 1961 of the 210-foot aerial at Parkes, Australia, a survey may be undertaken at 10 cm. with a beam-width of 0°·1. This should reveal so much detail that a computing machine will be necessary to convert the information supplied by the telescope into forms which may be used by astrophysicists.

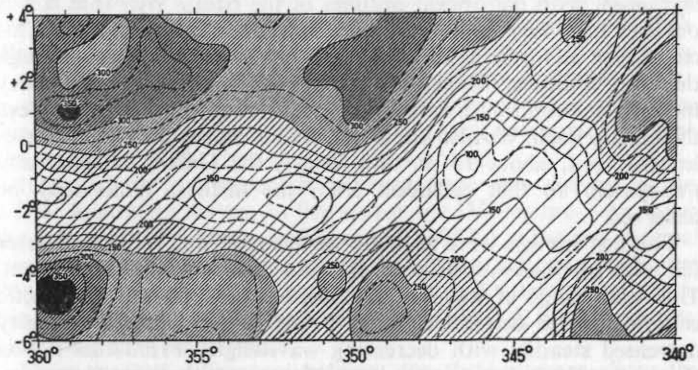

Fig. 11. A radio map of the Milky Way at a wavelength of 15m. (*Shain in Aust. J. Phys.*).

4.2 *The Galaxy*

The solar system lies in a vast conglomeration of stars, gas and dust called the Galaxy. The visible Galaxy is disk shaped, about 80,000 light-years in diameter, the Sun being situated about 30,000 light-years from the centre. The outlines of the Galaxy are dimly visible to us as the Milky Way, light from the stars and gas reaching us a few years after leaving the nearest stars and many thousands of years after leaving the more distant stars. Towards the edge of the Galaxy the stars thin out and give place to empty space. But farther away, at distances of the order of a million light-years we observe other great conglomerations of stars – the external galaxies. These are distributed irregularly in space, extending to the limits of our largest telescopes, a few thousand million light-years.

Observations of the structure of the Galaxy are difficult at optical wavelengths because most of it is obscured by clouds of dust. The structure of external galaxies can be seen more easily; these show diverse forms but the spiral structure of our Galaxy is reasonably reproduced in the Great Nebula in Andromeda. A photograph of this object, distant a million light-years, is reproduced in Plate II. The flattened disk of spiral arms surrounds a more or less spherical and brightly shining nucleus and the whole rotates about an axis normal to the disk. The lines drawn over and around the photograph are 73 cm. radio isophotes which provide a radio picture of the nebula.

The first crude surveys of the cosmic radiation showed such close agreement with the optical outlines of the Milky Way that it was obvious that most of the radiation originated in the Galaxy. This conclusion has been confirmed and it is now known that although there are countless discrete sources of radiation outside the Galaxy these do not contribute much to the main distribution, coming from the Galaxy itself. We also know now that except at the longest wavelengths used, about 15 m. and longer, the Galaxy is essentially transparent so that radiation from the farthest limits may be observed.

The first surveys were at metre wavelengths and these were later followed by observations at 62 cm. and then at 25 cm. and 10 cm. This wide range of wavelengths allowed the spectrum of galactic emission to be determined and it was found that the intensity decreased steadily with decreasing wavelength. From this it was shown that the radiation cannot arise from a purely thermal process. It is now known that at least two processes are operative, *thermal radiation* by the interstellar ionized gas and *non-thermal radiation* (so-called synchrotron radiation or magnetic acceleration radiation) by cosmic-ray electrons in the galactic magnetic field (see Chapter 3).

One of the first objectives of galactic radio astronomers was to separate the thermal and non-thermal components of emission. From our knowledge of thermal-emission theory the former component would then give a model of the ionized hydrogen in the Galaxy. This problem could not be solved until narrow-beam surveys were made over a wide range of wavelengths. Narrow-beam surveys were needed because the thermally emitting gas is confined to a narrow slab in the plane of the galactic disk; the early surveys with beams 10° or more in width could not resolve this narrow strip of radiation. The Dutch 22-cm. wavelength survey was completed in 1958 and the contours of radio brightness in the Milky Way region are shown in Fig. 10. The galactic centre is shown and several radio sources may be seen spread along the Milky Way. Most of these sources have been identified as large, bright clouds of ionized hydrogen, called HII regions. These sources stand out clearly and brightly from the weak non-thermal radiation at short wavelengths and many of the earlier identifications of thermal sources were made by the 50-foot telescope at the Naval Research Laboratories in Washington using waves of 10 cm. or less.

At the other end of the spectrum is the limited Australian survey at a wavelength of 15 m. the results of which are reproduced in Fig. 11. These contours are almost the reverse of the 22-cm. ones, bright regions on the former have become dark regions on the latter. The reason is that at 15 m. the non-thermal component provides brightness temperatures of more than half a million degrees Absolute. The HII clouds have brightness temperatures of only about ten thousand degrees and so their emission makes a negligible contribution. On the other hand they *absorb* non-thermal radiation coming from regions behind them. In other words they now appear as dark clouds on the bright (non-thermal) background.

Intermediate in wavelength between these two surveys is the 3·5-m. Australian survey. In this survey the HII regions have much the same radio brightness (still about 10,000° K) as the non-thermal component and do not show up clearly either in emission or absorption. They are neither bright blobs on a dark background (as in Fig. 10) nor dark on a bright background (Fig. 11), but simply grey blobs on a grey background.

These marked differences between the three surveys allow the thermally radiating HII regions to be recognized without difficulty. In Fig. 10 there are such regions at longitudes (bottom scale) 321, 328, 333, 338, 343, 346, 352, 359 and 5°. Some of these are also visible at optical wavelengths but most are obscured. The region near 328° is of particular interest because it probably represents emission from the galactic nucleus.

The ionized hydrogen distributed throughout the spiral arms of the galaxy may also be investigated by comparison of surveys at widely different frequencies. It is found that the total mass of ionized hydrogen in the Galaxy is less than sixty million solar masses. This may be compared with the total mass of unionized hydrogen of two thousand million solar masses and with that of the whole Galaxy (mainly due to the stars) of one hundred thousand million solar masses. The ionized hydrogen represents only a tiny part of the mass of the Galaxy but it is a very important part because it is the ionized gas which holds the galactic magnetic field in place. Without it there would be no magnetic field and no galactic radio continuum emission.

As early as 1951 it was shown that most of the background radiation had a non-thermal origin. The most popular theory of its origin was in a hypothetical star which emitted powerful radio waves as the Sun does occasionally, but a much smaller amount of light. Another feature noted in the early metre-wave surveys was substantial radiation from regions far from the Milky Way where very few stars are found. Thus the form of the Galaxy seen by a radio telescope was very different from that seen optically; the latter is concentrated almost entirely into a flat disk. Thus if radio stars were the source of cosmic radiation these would have to be much more widely spread than the visible stars.

The first clue to the origin of the non-thermal radiation was provided in 1950 by H. Alfvén and N. Herlofson in Sweden, who suggested that some of the sources might radiate by the synchrotron or magnetic acceleration process (section 3.3). The requirements for such a process are a magnetic field and electrons moving with speeds approaching the speed of light. There was independent evidence of widespread magnetic fields in the Galaxy and, although most cosmic rays which have been observed on the Earth are protons, it is likely that a proportion of cosmic-ray particles are electrons. The proof of this theory was provided by combined optical and radio measurements of the Crab Nebula as described in section 4.3. It is now agreed that almost all cosmic radio emission is by the synchrotron or magnetic acceleration process.

It remained to explain the second peculiarity of the cosmic radio surveys: the fact that strong radiation was received from directions other than the Milky Way. In 1952 I. S. Shklovsky in the U.S.S.R. separated the non-thermal radio-emission into two fairly distinct components: a strong disk component, more or less coincident with the Milky Way, and a weaker 'corona'. There could be no doubt that the disk component was galactic and the coronal component appeared to originate within a huge more or less spherical volume concentric with the Galaxy and perhaps one hundred thousand light-years in diameter. This corona is now an accepted part of our Galaxy and its radiation is certainly by the synchrotron process. It must contain a magnetic field of strength a few millionths of a gauss and it must also contain cosmic-ray electrons. It has been suggested that the cosmic rays which strike the Earth are speeded up in the corona by the vibrations of its magnetic field. This process of accelerating electrical particles was suggested by E. Fermi and may explain the origin of all cosmic rays, if not in the corona, then in the galactic nucleus or elsewhere. Since most of these regions are optically invisible, radio astronomy and cosmic-ray physics have merged in this field of investigation.

Our galactic corona is optically quite invisible and even its radio emission is not easily interpreted because we are inside the radiating object. However, radio coronas may be observed on external galaxies, notably that of our neighbour, the Great Nebula in Andromeda. Its well-known optical picture is reproduced in Plate II and superimposed are a few of the radio isophotes determined by a 73-cm. survey with the 250-foot telescope at Jodrell Bank. It will be seen

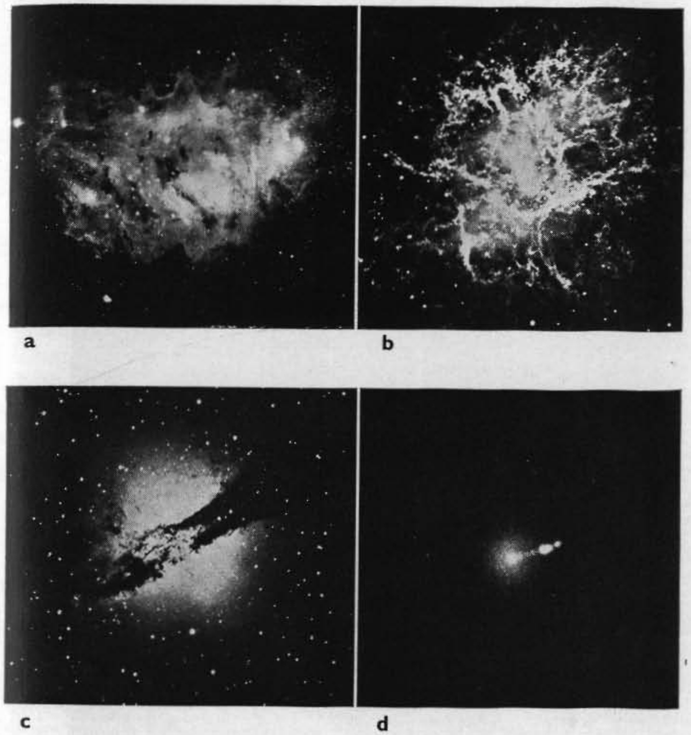

PLATE III(a). The Lagoon Nebula (M8); an example of a luminous cloud of ionized hydrogen in the Milky Way. Its radio picture is seen in Fig. 10.

PLATE III(b). The Crab Nebula (M1); the result of a supernova explosion on 4 July 1054 and now a strong radio source.

PLATE III(c). The closest 'radio galaxy', Centaurus A (NGC5128); perhaps two galaxies in collision, or one exploding.

PLATE III(d). The 'radio galaxy' Virgo A (NGC4486) with its unique jet extending from the nucleus.

(Photograph (a) by the Lick Observatory, others by Mt. Wilson and Palomar Observatories.)

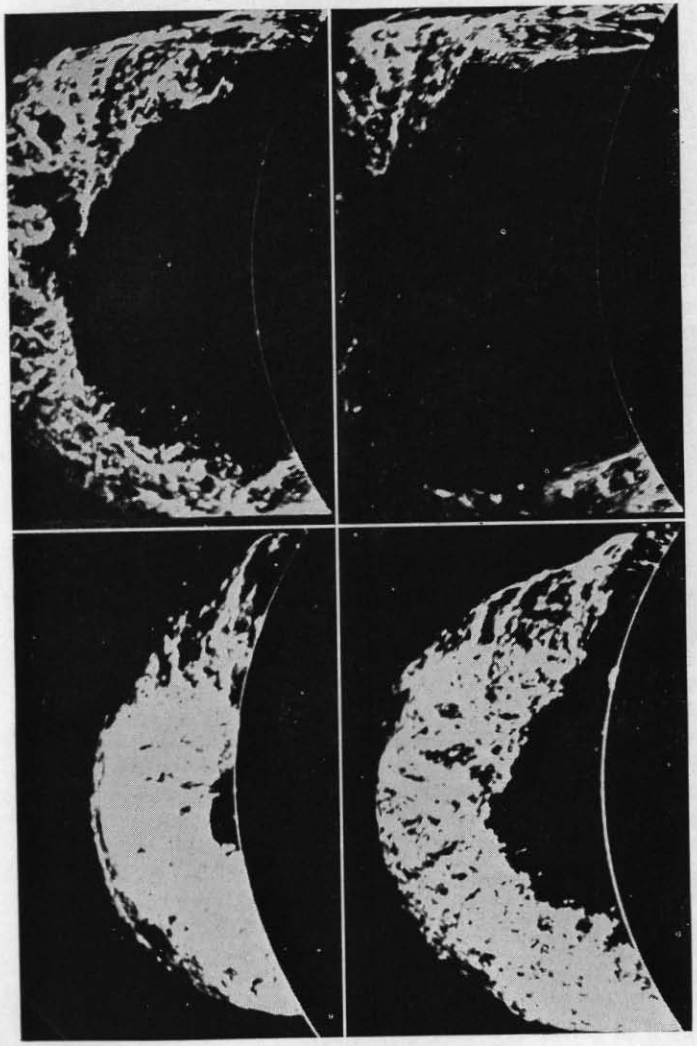

PLATE IV. Four stages in the ejection of a prominence from the Sun's atmosphere. The edge of the solar disk is seen near the bottom of each picture (*W. O. Roberts and the High Altitude Observatory*).

that the optically invisible corona (or halo as it has sometimes been called) extends far beyond the visible nebula. The brightness temperature at the outer isophote is about 2° K rising in steps of 2° K to 16° K near the centre of the galaxy.

The visible parts of the Andromeda Nebula and of our Galaxy are wrapped in spiral arms. This is also true of the radio disk components, being most clearly demonstrated by the hydrogen line radiation discussed in the following chapter. The 3·5-m. Sydney survey of the non-thermal continuum also is suggestive of a tightly wrapped spiral structure with arms about 1500 light-years in diameter and radiating in their central regions about ten times as strongly as the corona. However, because of the relatively small volume occupied by the arms, their total radiation is only about one-tenth that of the corona.

One other highly interesting galactic feature has been revealed by radio observations – the galactic nucleus. At cm. wavelength this shows up as a strongly emitting source as seen in Fig. 10 at longitude 328°. At 15 m. the same region is of low intensity indicating absorption. Finally the 3·5-m. Sydney survey indicates a bright strip 5° or 6° in length with a small decrease in brightness near 328°. These results may be explained in terms of a central cloud of ionized hydrogen (HII cloud) surrounded by a flattened spheroidal non-thermal source. At cm. wavelengths the radiation from the non-thermal source is small and the source seen is essentially the HII cloud. At 15-m. wavelength the non-thermal source is much the brighter and the main effect of the HII cloud is to absorb most of the radiation from the part of the non-thermal source lying behind it.

Additional evidence concerning the galactic nucleus has been provided by 21-cm. line observations and the story is taken up again in Chapter 5.

4.3 *Discrete sources within the Galaxy*

With the discovery of the first few discrete sources or radio stars as they were then miscalled, attempts were naturally made to identify them with visible objects. This was an exciting period in the history of radio astronomy as speculation on the nature of these objects ranged from hitherto unknown types of stars, to peculair nebulosities, even to comets. The only objects which were expected, on theoretical grounds, to give substantial emission were the clouds of ionized hydrogen or HII clouds. But none of these were identified with a radio object, the reason being that at the metre wavelengths used the HII clouds were too dim to detect with the early equipment, while the radio stars with their stronger radiation at these wavelengths, shone brightly.

In seeking identifications there have been three lines of approach. The first to succeed was used by J. G. Bolton in Sydney to identify the Crab Nebula and involved a search by radio astronomers for peculiar *catalogued* optical objects in the neighbourhood of strong radio sources. The second, exemplified by the Cassiopeia source (the strongest of all at metre wavelengths), involves a search by optical astronomers for peculiar, *uncatalogued* objects in the vicinity of radio sources. This method has resulted in the identification of many sources, both inside and outside the Galaxy, by W. Baade and R. Minkowski using the 200-inch Palomar telescope, and radio results from Sydney, Cambridge, Manchester and, more recently, from Owens Valley. The third method involves a search by radio astronomers for radiation from such outstanding optical objects as the Andromeda Nebula and other external galaxies; this method was used successfully at Jodrell Bank by R. Hanbury Brown and his co-workers.

The early observations were made at wavelengths near 3 m. but soon measurements at other wavelengths were made and it was found that the spectra of the sources differed, but none, except the Crab Nebula, had a form consistent with a thermal origin. In the case of the Crab Nebula the high *intensity* of radiation made a thermal origin very unlikely. With the introduction of cm. wave equipment and the narrow aerial beams available at these wavelengths, an interesting source, of substantial angular dimensions, was found in the constellation of Cygnus. This source, called Cygnus-X, was found to have a flat spectrum in the range 25 cm. to 3 m. Such a spectrum and the observed brightness temperature was consistent with a thermal origin in tenuous ionized gas. Other sources of finite size, called radio nebulae, were also located, notably that towards the centre of the Galaxy.

Prior to 1956 the aerial most suitable for locating the thermal sources was the 50-foot reflector at the U.S. Naval Research Laboratories, which could be used down to 3 cm., at which wavelength the non-thermal sources and background were very weak and the clouds of hot ionized hydrogen shone brightly as they do optically when unobscured. This reflector allowed radiation from a number of HII clouds to be measured. Later the larger Dutch telescope located some 35 gaseous nebulae a few of which, including the Omega Nebula and Messier 8 (the Lagoon Nebula) are shown in Fig. 10.

The galactic disk, as defined by the interstellar hydrogen (both ionized and neutral) has a lateral extent of more than 60,000 light-years but a thickness of only 600 light-years. Within this flat disk the gas is further concentrated into spiral arms and within these arms the gas is irregularly distributed in clouds of varying sizes up to a hundred light-years or so. This gas would all exist as dark, cold, neutral hydrogen were it not for the presence of bright, hot stars whose radiation ionizes the gas around them. These stars create a hot, ionized corona around themselves, shown by B. Strömgren to extend to 3 light-years for a relatively cool A_0 star and to 450 light-years for an exceptionally hot O_5 star. The gas within the 'Strömgren sphere' is at about 10,000° K and that outside is cold neutral hydrogen. It is these clouds (not really spheres because the gas density is not uniform) which comprise the numerous thermal Galactic radio sources.

One of these thermally radiating clouds of ionized gas is pictured in Plate III (a). It is the beautiful Lagoon Nebula (Messier 8), whose radio picture is shown in Fig. 10, taken at a wavelength of 22 cm. It has a radio flux of 260 units and, like all these HII sources, a flat radio spectrum in the cm. range. The nebula is at a distance of 3600 light-years, has an extent of 50 light-years and a total mass 2750 times that of the Sun.

Perhaps the most notable of the thermal sources, from the point of view of the radio astronomer, is Cygnus X which, unfortunately, is outside the limits of Fig. 10. With the use of narrow-beam telescopes this has already been resolved into three gas clouds and optical observations suggest a more complex structure, although most of the region is optically obscured by dust-clouds.

Since we can only see about one-twentieth part of our Galaxy by optical telescopes it is to be expected that many HII sources may only be observed by radio telescopes, which can see right through the obscuring clouds. However, even if the sources cannot be identified, their main properties may be determined by radio observations. Most difficult to determine is the distance of the source, but some estimate may be possible by measuring the obscuring effect of the HII source on the *non-thermal* radiation at metre wavelengths. Nearby sources will obscure more than distant ones so that it may be possible to provide an estimate of distance. The size, electron density (usually between 5 and 50 per cubic cm.) and total mass of the nebula may then be calculated.

All the non-thermal Galactic sources identified* are remnants of

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* The galactic nucleus is here regarded as part of the Galaxy itself rather than a discrete source.

supernovae, catastrophic explosions of stars during which a shell of gas is ejected from the remnant of the star. The shell may have a tenth or more of the mass of our Sun and the energy involved, about 10^{48} ergs, is more than that of 10^{31} tons of TNT or 10^{24} hydrogen bombs. Centuries after the explosion the shell has expanded to form a nebula, a few of which may be seen from the Earth; in some cases the original explosion was recorded as a new bright star which faded and disappeared again in a few months.

The first identification with a radio source was the Crab Nebula, the result of an explosion recorded by the Chinese astronomers on 4th July in the year 1054. Two other such identifications are with Tycho Brahe's supernova of 1572 and Kepler's supernova of 1604. These are the only identifications of radio sources with actual supernova explosions, the others are with objects which must be the remnants of supernovae, but explosions are not recorded. These three are also the only cases of what are called type I supernovae, which appear to take place among old stars and are less violent than type II.

There are six other identifications of galactic sources with optical objects, all of which appear to be remnants of more violent explosions (type II supernovae) of relatively young, very hot stars. Two of these, the Cygnus Loop and I.C. 443 are well-known optical objects whose origin was not known. However, the investigations with the 200-inch Palomar telescope shows that the structures of these nebulae correspond roughly to expanding shells. The spectrum lines in the radiation from different parts of the shells show different Doppler shifts indicating different velocities along the line of sight. All the fragments of a particular shell appear to originate at a single point in the sky, presumably the position of the exploding star and the fragments are still moving with speeds up to several thousand kilometres per second.

Perhaps the most interesting of the radio sources is the Crab Nebula. This had been studied for many years by optical astronomers and its picture is shown in Plate III (b). A surprising amount is now known about this distant (about 6000 light-years) object and at the same time it poses some of the most urgent questions in the field of astrophysics.

The light from the Crab Nebula differed from that of all other 'emission nebulae' or clouds of ionized gas illuminated by a bright central star. Such clouds are usually at temperatures of about 10,000° K, but to explain the light from the Crab Nebula in this manner the temperature would have to be hundreds of thousands of degrees. Furthermore it would require a fantastically bright central star and no unusual star was visible. The radio emission also differed from that of all other sources; its spectrum was almost flat, like that of thermally emitting sources, but its intensity was far too great to possibly have a thermal origin. In 1953 the Russian astronomer I. S. Shklovsky made the bold suggestion that both the optical and radio emissions were due to the spiralling motion of cosmic-ray electrons in a magnetic field – the synchrotron or magnetic acceleration process (section 3.3). As far as was known all light waves ever observed by optical astronomers were caused by ordinary thermal emission due to electrons and other particles colliding with one another. Here was a new process of emission requiring the presence of a rather strong magnetic field and also of very fast-moving electrons.

The difference between thermal and synchrotron emission is that the latter is plane polarized, because the electrons instead of being jostled in all directions are accelerated only in the plane perpendicular to the direction of the magnetic field. A crucial test of the theory then, was whether the light from the Crab Nebula was plane polarized and this was soon shown to be the case by Russian and Dutch astronomers. The synchrotron process also provides plane polarized radio waves but it does not follow that plane polarized waves will reach the Earth. The reason is the Faraday effect (section 3.1) which causes rotation of the plane of polarization as the waves traverse the ionized gas. Radiation from various depths in the nebula are rotated by different amounts and the polarization is blurred. Nevertheless Russian and United States observers have found traces of plane polarization.

With the synchrotron theory accepted it was possible to go further and estimate the strength of the magnetic field and the number and energy of the cosmic-ray electrons present. Two very interesting conclusions were reached. First there was so much magnetic flux present in the nebula that it could not possibly have existed in the original star before it exploded to cause the supernova. The reason for this is that a magnetic field tends to expand and if strong enough will explode the body containing it. For example, a field of strength one million gauss has approximately the power of the same volume of TNT. The field in the star would have been at least a hundred million times more powerful than TNT and would have burst the star long before the field attained the required strength. The magnetic field must, therefore, have been created in the vast expanse of the nebula itself which is now a few light-years across and still expanding with a velocity of 1100 km. per second. When the magnetic field is spread through such a volume its strength and the 'magnetic pressure' are both within reasonable limits. However, there remains the problem of its creation in the space between the remnant of the exploded star and the outer shell of the nebula. The energy necessary to create the existing field is thousands of times the *total* power output of our Sun during the 900 years since the nebula was born. The only source of energy of this magnitude is nuclear energy, probably the radioactive decay of isotopes formed during the original explosion.

The second interesting result of the theoretical analysis of the light and radio waves, was that the cosmic ray electrons responsible for the optical emission would radiate away most of their energy in a period of about 200 years. Since the nebula is 900 years old and the light emission is still visible we conclude that fresh cosmic rays have been created relatively recently, and may still be forming. The energy required to create enough of these cosmic rays is also thousands of times the total solar output and must also have an origin in nuclear reactions, perhaps the same as those responsible for the magnetic field.

4.4 *External galaxies*

Some scores of discrete radio sources are Galactic objects; as we have seen, the HII clouds are confined to a narrow strip near the plane of the Galaxy and the supernovae remnants are spread more widely but also largely confined to the galactic disk. By far the greater number of radio sources, however, have an isotropic distribution in space and, although most of these sources have not yet been identified with optical objects, it is probable that they all correspond to external galaxies.

The few dozen sources which *have* been identified with external galaxies may be divided into two basic types called 'normal galaxies' and 'radio galaxies'. The former, as the name implies, are average galaxies and emit roughly the same total radio power as the Milky Way and as the classical spiral galaxy in Andromeda (Plate II). It is probable that nearly all of the myriad external galaxies visible to the large telescopes emit a similar or smaller amount of radio power. Only a few of the closer of these, however, can be detected by their relatively weak radio emissions. While they are visible optically to distances of a thousand million light-years or more, their radio range is limited at the time of writing to perhaps ten million light-years. Nevertheless, radio studies of some of these galaxies have proved of great interest and a few are discussed in this section.

The other type of external radio source is the 'radio galaxy', which is a stronger radio emitter, providing up to about a million times the power of the normal galaxy. Such large increases in power render the radio galaxies visible at greatly increased ranges, perhaps at distances up to about ten thousand million light-years. The radio galaxies, although rare and interesting optical objects, do not emit appreciably more light and, prior to their radio detection, were never noticed among the much more numerous normal galaxies.

Summing up, the universe seen through a large optical telescope is made up almost entirely of normal galaxies which can be observed out to about one thousand million light-years. 'Viewed' through a radio telescope the universe appears as a dozen or so nearby normal galaxies and beyond them many hundreds of radio galaxies. These extend to ten times the optical limit and so encompass one thousand times the volume of the optically visible universe.

The Great Nebula in Andromeda (M31) was the first of the normal galaxies to be detected. At the same time (1950) the radio astronomers at Jodrell Bank were able to plot its radio brightness and show that emission occurred from regions far beyond the visible parts of the nebula. In Plate II a photograph of the galaxy is shown on which are superimposed contour lines of radio brightness; the latter were also obtained at Jodrell Bank (during 1959) using the 250-foot reflector, giving a beam-width of about 0°·6 for a wavelength of 73 cm. The central portion of the visible galaxy provides the strongest radio emission, but the radio isophotes are much less flattened than the optical contour and extend into a corona whose largest extent is several times that of the visible galaxy. This is a similar extension to that of our own Galaxy and presumably of other galaxies of the same spiral structure. The spectrum of radio waves from these galaxies is similar to curve (c) Fig. 9 and it is believed that the radiation is by cosmic-ray electrons spiralling in magnetic fields.

Another type of 'normal galaxy' which has been observed by radio telescopes is the irregular type of galaxy which includes our closest neighbours, the Magellanic Clouds. These galaxies have been studied in detail by their hydrogen line emission and their discussion is left to the following chapter.

More interesting than the normal galaxies are the rare 'radio galaxies' each of which is the result of a vast catastrophe of one form or another. The first discrete source discovered was Cygnus A, but its optical identification was a long and arduous task, requiring very accurate location, by F. G. Smith in Cambridge, and then photographs and spectra obtained with the 200-inch telescope at Mount Palomar. This source appears to be two galaxies in violent collision (or, alternatively, one very large galaxy exploding), debris flying in all directions with speeds up to 400 kilometres per second. The red-shift of this object shows that it is at a distance of about three hundred million light-years. As in the case of normal galaxies, the extent of the radio source is several times that of the optical source; also it is separated into two distinct blobs, possibly representing two separate galactic coronas. The Cygnus source is an enormously powerful radio transmitter, sending out radio energy at a rate of one hundred thousand million times the *total* energy radiated by our Sun. It is fortunate indeed that it is so distant or it would play havoc with radio communications. Even if it were at a distance of ten thousand million light-years it would still be visible to radio telescopes how being constructed.

The closest radio galaxy, distant only about two million light-years, is the Centaurus A source (the catalogued galaxy NGC 5128), a photograph of which is shown in Plate III (c). The galaxy is very bright and has a curious feature: the dark bar cutting right across the bright elliptical galaxy. Radio measurements at 31 cm. with a narrow beam show a radio object more than one hundred times the size of the optical object. The radio and optical objects are shown together for comparison in Fig. 12. The radio distribution shows three features which may be separated from one another; a small intense source seems to coincide with the optical source and two other wide distributions one above the other are separated by a region of low intensity. It seems that this source may have two partially separated coronas and this is made plausible by the optical evidence which suggests two galaxies in collision, the dark bar being a spiral-type galaxy seen edge-on in front of a bright elliptical galaxy. Alternatively, this may be another example of a single galaxy breaking up.

Another remarkable radio galaxy is the Virgo A radio source (NGC 4486) which has the anomalous optical feature of a very blue jet extending from its nucleus. A photograph of this distant (fifty million light-years) galaxy is shown in Plate III (d). The jet extends for 5 minutes of arc and the radio image has the form of an ellipse of much greater extent. The curious blue optical emission from the jet was not explicable in terms of ordinary thermal emission but is

now known to be synchrotron emission due to cosmic ray electrons spiralling in a magnetic field. This is the second case of observed *optical* emission by this process, which accounts for almost all radio emission. The other optical synchrotron radiation is given by the Crab Nebula (Plate III (b)). The Virgo jet represents a far greater catastrophe than the Crab Nebula supernova explosion. The exploding star had roughly the mass of the Sun while the jet has some million times the mass of the Sun.

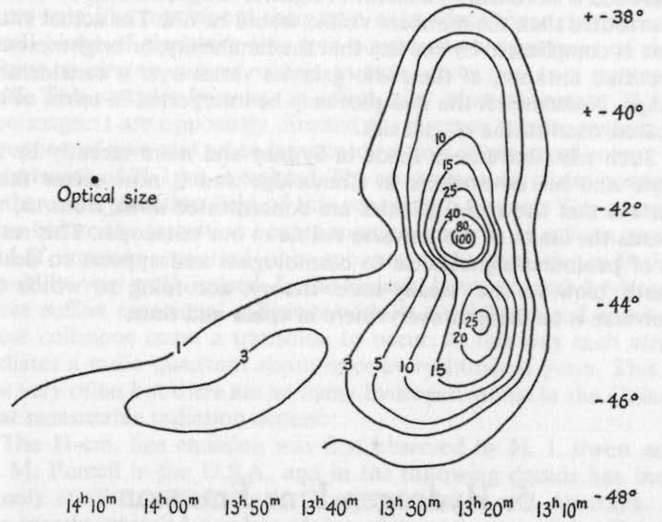

Fig. 12. The Galaxy NGC5128 as seen with a 31-cm. radio telescope; contours are in units of 1° K. The optical size of the galaxy is shown for comparison.

Another identification of particular interest has been made with the Owens Valley telescope (Plate I) and the 200-inch Palomar telescope. This is a radio galaxy distant six thousand million light-years, several times the distance of any object previously identified. The optical detection of this object was made possible by first locating it accurately with the radio interferometer. With its position known the optical telescope was then set to take a long exposure picture of that area of the sky.

Only about one hundred of the thousands of radio galaxies have been identified with optical objects. The remainder may only be studied statistically with a view to determining their distribution in space. For example, we should like to know whether they are more concentrated near our Galaxy or more concentrated at great distances from our Galaxy. Suppose that a number N of these galaxies is found having flux densities above a certain minimum value S_m. How many should we expect with flux densities above say $\frac{1}{4}S_m$? By reducing the minimum signal by a factor of four, galaxies are detectable to twice the original maximum distance and the volume searched is increased by a factor of eight. If the galaxies are uniformly distributed then the numbers visible would be $8N$. The actual situation is complicated by the fact that the luminosity, or brightness at a specified distance, of the radio galaxies varies over a considerable range. Nevertheless the N-S plot may be interpreted in terms of the spatial distribution of galaxies.

Such plots have been made in Sydney and more recently by M. Ryle and his co-workers in Cambridge and it now seems fairly certain that the radio galaxies are concentrated *away* from us, towards the limits of the universe visible to our telescopes. This result is of profound significance to cosmologists and appears to deal a death blow to the 'steady-state' theory, according to which the universe is unchanged everywhere in space and time.

5. Hydrogen Line Emission

DURING a colloquium of the Nederlands Astronomen Club, which was meeting in 1944 to discuss the pioneering work of Jansky and Reber (see Chapter 1), H. C. van de Hulst suggested that interstellar hydrogen would emit radiation at a wavelength of about 21 cm. and that this radiation might be strong enough to detect. The subsequent successful detection of this line opened a new astronomical vista with previously undreamed possibilities for extending our knowledge of the universe.

A hydrogen atom is made up of a heavy proton, around which gyrates a light electron. The electron may move in any one of a number of orbits at different distances from the proton. When it jumps from a more distant orbit to a closer orbit it emits a small packet or 'quantum' of radiation. This radiation has a wavelength much shorter than radio waves; it may be infra-red or light or ultraviolet radiation but does not concern us further here.

Radio wave quanta are much smaller packets of energy. For example, a wave of 21-cm. length comes in quanta of energy only about one-millionth those of blue light. Fortunately for radio astronomers there is another way in which the internal energy of a hydrogen atom may change and by such a small amount that it results in the emission of a *radio* quantum of energy. In addition to the above gyro motions both the proton and electron of a hydrogen atom spin like tops about their own axes. Since these particles are small blobs of electricity this spin constitutes a movement of electricity or *electric current* which, in turn, gives rise to a magnetic field. The particles become, in effect, tiny *electro-magnets*. If the two magnets are oppositely directed the electron tries to reverse its direction of spin and when it succeeds a tiny quantum of energy of wavelength of 21·1 cm. is emitted. The reverse process is also possible if there is a radiation field of this wavelength present. The average time before the transition occurs spontaneously is 11 million years, and if emission occurred only spontaneously then the radiation would be very weak indeed. In the Galaxy, however, each hydrogen atom suffers occasional collisions with its neighbours and some of these collisions cause a transition to occur. In this way each atom radiates a radio quantum about once every hundred years. This is not very often but there are so many hydrogen atoms in the Galaxy that measurable radiation occurs.

The 21-cm. line emission was first observed by H. I. Ewen and E. M. Purcell in the U.S.A. and in the following decade has been closely studied, principally in The Netherlands and Australia. It has greatly extended our knowledge of the structure of the Galaxy and of external galaxies, as well as that of smaller clouds of cold neutral hydrogen (HI clouds) which are optically invisible.

The feature of overwhelming importance about the line emission is that radiation from a cloud moving away from the observer gives a signal of longer wavelength (lower frequency) than that from a stationary cloud. Conversely a cloud approaching the observer gives a shorter wavelength signal. The reason for this is the well-known Doppler frequency shift which may be noted when a train with whistle blowing passes the observer: there is a sharp drop in the frequency of the whistle note (or increase in its wavelength). The frequency change is proportional to the velocity in the line of sight. A cloud moving with a velocity of, say, 30 km./sec. (one ten-thousandth the velocity of light) changes its wavelength by one ten-thousandth of 21·1 cm., or 0·0021 cm. The corresponding frequency change is 140 kc./sec.

It is evident then that 21-cm. radio signals allow us to measure not only the amount of hydrogen present but also its motion relative to the Earth. Furthermore, if two clouds of gas lie one behind the other it may be possible to observe both independently, their radiation being shifted in frequency by their relative motion. In this way the gas in the various spiral arms of the Galaxy, which move relative to one another, has been plotted and a model of the Galaxy developed.

It is of interest to calculate the total power incident on the Earth from all the hydrogen atoms in the Universe. The average brightness temperature of the whole sky is about 3° K over a frequency band of 100 kc./sec. Using the formulae of Chapter 2, the *total power incident over the whole surface of the Earth*, is about ½ watt. This important branch of science depends, therefore, on the reception over the whole Earth of the amount of power which might be radiated by a tiny wrist radio transmitter.

5.1 *Hydrogen line spectographs*

The line emission from a cloud of stationary hydrogen atoms lies in an extremely narrow band of frequencies centred at 1420·4 Mc/s. This spectrum line is shown as curve (*e*) in Fig. 9; a comparison with say, curve (*a*) emphasizes the difference between a spectrum *line* and a spectrum *curve*, or continuum emission. However, such narrow spectra are never observed because of Doppler shifts. The vast clouds of neutral hydrogen within the arms of the Galaxy are in turbulent motion, different parts having velocities spread over a range of about ± 6 km./sec. A line-of-sight velocity of 6 km./sec. results in a Doppler frequency shift of about 28 kc./sec. so that the spread of velocities over a range ± 6 km./sec. causes a frequency spread of double that amount or 56 kc./sec. Thus the hydrogen-line astronomer does not merely measure an intensity in each particular direction. He must measure a whole spectrum curve, each point on which corresponds to radiation from all the gas within the aerial beam and moving with a particular radial velocity. Such spectral curves are often called *line profiles*.

A radio receiver designed to receive radiation from such a cloud should have a band-width somewhat less than the spectrum to be observed, say 30 kc./sec. Narrower bands result in lower efficiency and wider bands blur the fine structure of the spectrum. There are other factors, however, which must be taken into account in the design of a hydrogen-line receiver and these we will now consider.

The spiral arms of the Galaxy rotate with different velocities and, because of this effect, individual clouds within the various arms have a spread of velocities over a range of ± 150 km./sec. Thus the receiver must be capable of tuning over a frequency range of about 1400 kc./sec. which is fifty times its band-width. Such a receiver could survey most of the Galaxy, but not the central region where the gas is spinning around at speeds up to 300 km./sec. The band-width required for this region is 2800 kc./sec. The plot of receiver output against frequency is a spectrum curve and the receiver is called a radio spectrograph. An example of such a spectrum curve or line profile is shown in Fig. 13. On the ordinate scale are shown both the frequency shift from the line frequency (1420 Mc/s) and the corresponding radial velocity in km./sec.

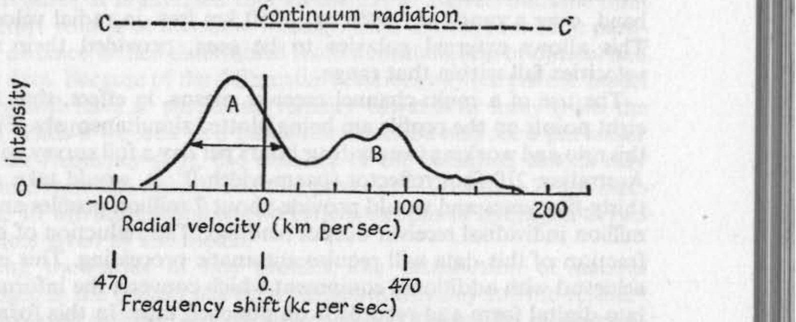

Fig. 13. A hydrogen-line profile showing concentrations of neutral hydrogen in two arms of the Galaxy.

There are two main maxima shown, corresponding to two big concentrations of hydrogen in two spiral arms. The area under each maximum is a measure of the amount of hydrogen within the aerial beam and within the particular arm. The width of the maximum gives the velocity spread, about ± 30 km./sec. for the maximum marked *A*. The velocity at the centre of the maximum is the mean velocity, about 20 km./sec. towards the observer for *A* and 75 km./sec. away from the observer for *B*.

For maximum receiver sensitivity, the time taken to plot each point on a line profile is a minute or two. As there are fifty points or more required to adequately outline the curve, a time of an hour is required for each spectrum curve. A sky survey with a 2° beam requires more than 70,000 spectra and this would take about ten years. With narrower beams the time becomes prohibitively long. To overcome this difficulty *multi-channel* spectrographs have been developed at the Carnegie Institute in Washington and at the Radiophysics Laboratory, Sydney. The Sydney instrument is essentially a double-conversion super-heterodyne receiver capable of accepting radiation simultaneously in forty-eight separate channels. Of these, forty-four are tuned to different frequencies at intervals of 33 kc./sec. These steps correspond to radial velocity steps of 7 km./sec. over a total range of ± 150 km./sec. The other four channels are wide-band ($\frac{1}{2}$ Mc/s) placed outside the line spectrum to obtain a reliable zero level of intensity. There is also provision for changing the centre frequency (normally 1420 Mc/s) and with it the whole reception band, over a range of —950 to +950 km./sec. in radial velocities. This allows external galaxies to be seen, provided their radial velocities fall within that range.

The use of a multi-channel receiver means, in effect, that forty-eight points on the profile are being plotted simultaneously. Even at this rate and working twenty-four hours per day a full survey with the Australian 210-foot reflector (beam-width 0°·2), would take about thirty-five years and would provide about 7 million profiles and 350 million individual receiver output readings. The reduction of even a fraction of this data will require automatic processing. This is now achieved with additional equipment which converts the information into digital form and records it on punched tape. In this form it is suitable for rapid analysis by an automatic computor.

5.2 *The structure of the Galaxy*

For more than a century astronomers have speculated on the possibility that the Galaxy has a spiral structure like that of some other galaxies such as the Andromeda Nebula (Plate II). Observations of star grouping provide some evidence of spiral arms, but as most of the Galaxy is obscured optically, its structure has only been recently revealed by radio observations.

The radio results fall into three categories as follows. At centimetre wavelengths thermal emission from ionized hydrogen may be clearly observed; this gas occupies a flat disk; it is distributed in the form of clouds such as the Lagoon Nebula (Plate III (a)) and its total mass is less than one-thousandth that of the whole Galaxy. At metre wavelengths a disk concentration is also evident, but its thickness is greater and it merges into a more or less spherical corona. The corona of the Andromeda Nebula is drawn in Plate II. The particles responsible for the metre-wave radiation are cosmic-ray

electrons and these, together with an equal number of protons (to preserve electrical neutrality) will weigh a quite negligible amount. However, their presence requires the existence of a magnetic field and perhaps of more substantial numbers of less energetic ions, so they do define an important part of the Galaxy.

It is the third category of radio observations, the hydrogen-line emission, that has brought about a revolution in the study of Galactic structure. Line profiles have been obtained for different parts of the sky and interpreted in terms of a simplified model of the Galaxy. In this model, as in the Galaxy itself, the innermost parts rotate fastest and the rate of rotation gradually falls off to the most distant parts. It is assumed that all the gas at a given distance from the centre rotates at the same velocity. This velocity, for each particular distance is then determined from a combination of optical and radio data. Because of the differential rotation, any part of the model galaxy will have a particular velocity towards or away from the Earth. Thus if we look in a particular direction and see a particular Doppler frequency-shift, the distance of the radiating clouds may be found from the model. The two peaks at —20 and +75 km./sec. in Fig. 13 will correspond to two concentrations of hydrogen at two distances given by the model.

Using thousands of line profiles, the distribution of neutral hydrogen in the Galaxy has been plotted in this way and the results* are displayed in Fig. 14. This plot combines the results of observations of the northern sky made in The Netherlands (the right-hand side) and observations of the southern sky made in Australia. The difficulties involved in preparing the plot are great and the inaccuracies may be considerable. First of all the Galaxy may not share the simple circular motion assumed in the model; again the gas temperature may not be constant as assumed in the model and this will lead to errors in the estimated amounts of gas present. Other difficulties are caused by the random motions of the gas clouds, which must be estimated and allowed for.

Nevertheless it is likely that Fig. 14 gives some idea of the large-scale structure of the galactic hydrogen. This gas is arranged in arms which show some spiral form and if we may assume that the stars, which are the main constituent of the Galaxy, are associated with the hydrogen, then the whole Galaxy has a spiral structure.

Most of the neutral hydrogen is confined to a flat disk of diameter about 80,000 light-years and thickness only about one-hundredth

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* More detail has been provided in a later chart, but this is too complex for reproduction here and the main features are given in Fig. 14.

that distance. Thus the spiral arms lie closely in one plane which we might designate the true galactic plane. This plane makes an angle of about 1°·5 with the old galactic plane, defined before the radio results were available. So accurate and comprehensive are the latter that the International Astronomical Union has recently changed the galactic co-ordinate system to fit the radio data.

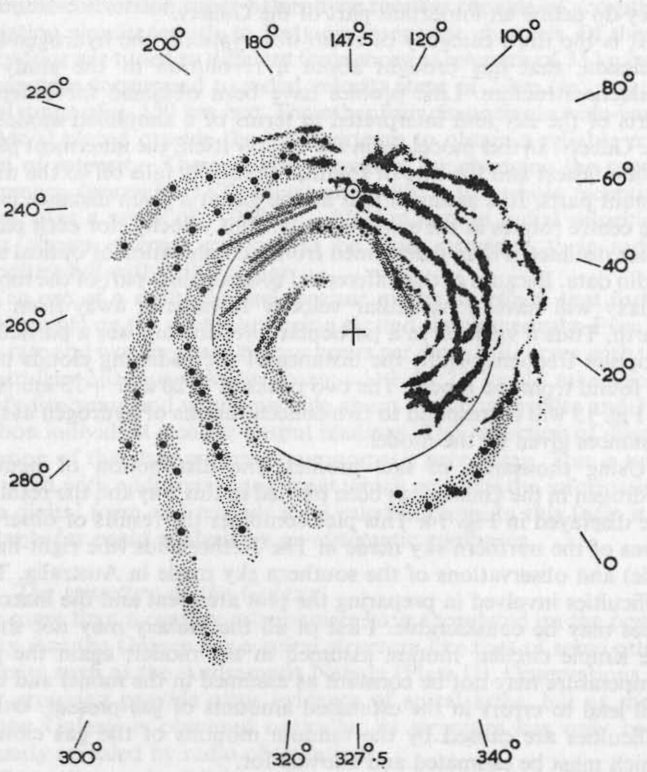

Fig. 14. A composite map of the spiral structure of the Galaxy. The Sydney pattern is to the left, the Leiden one to the right.

Within 20,000 light-years of its centre the spiral arms define a plane with the remarkable accuracy of 1 part in 1000. On the other hand the outermost parts of the galactic disk show a serious distortion; on one side the disk is twisted up from the plane, on the other side it is twisted down. This distortion is rather puzzling: it cannot be explained in terms of tidal effects due to near-by galaxies. An inter-galactic wind has been suggested, but a more likely origin is in electromagnetic forces associated with the vast magnetic field in the arms and in the corona.

While the galactic hydrogen is neatly arranged in a thin, flat (except near its edges) disk, its distribution within that disk is disordered, as seen in Fig. 14. It is rather disappointing that it is not yet possible to trace any complete spiral arm through the whole Galaxy. This is due partly to the blank region in the galactic centre. It will be remembered that the distances of hydrogen concentrations were derived from their observed radial velocities. In the direction of the centre all velocities (according to the model used) are transverse and since there is no radial velocity there is no distance scale.

The average density of hydrogen in the galactic plane appears to reach a maximum at a distance of 20,000 light-years from the centre (about half the total radius). Here it is about 1 atom per cubic cm., falling to 0·1 atom per cubic cm. at the edges. Everywhere the gas density is only a small fraction of the total mass density, except on the fringe of the Galaxy, more than 30,000 light-years from the centre.

The study of radio emission from near the centre of the Galaxy has shown some unexpected phenomena which may eventually explain the internal motions of the whole Galaxy. In the model discussed above, the motions were all assumed rotational, but observations of line emission within 9000 light-years of the centre show, in addition, radial outward motions. In the direction of the centre itself some gas is seen moving towards us with a velocity of about 50 km./sec. Most of this gas is in the form of a ring or spiral about 9000 light-years in radius, which rotates with a speed of about 200 km./sec. Outside this central ring or spiral formation the motion of the gas everywhere appears to be circular; only within the ring is there radial motion.

The Galactic nucleus poses a fascinating problem for astrophysicists. It seems that here are the forces responsible for the motions of the other parts of the Galaxy. Here also magnetic energy may be created as in the interior or supernova shells. One possible process, which may also operate in the interior of the Sun, is by stretching and winding up the magnetic lines of force of a weak field which was present when the Galaxy was formed some 5000 million years ago.

5.3 *Atomic hydrogen in other galaxies*

Atomic hydrogen emission from beyond the Galactic System was first observed by F. J. Kerr in Australia. The radiation from our nearest galactic neighbours, the Magellanic Clouds, was mapped and the velocities of their different parts relative to the Earth were determined. The total mass of neutral hydrogen in both the Large Cloud and the Small Cloud is about 5×10^8 solar masses or one-hundredth that of our Galaxy.

The shape of the line profiles from various parts of the Magellanic Clouds allowed estimates to be made of the velocities of rotation of different parts of the cloud. In each case the maximum velocity was about 20 km./sec. which might be compared with that of the Galaxy of about 300 km./sec. The random velocities of the cold hydrogen clouds within these galaxies was also found to be about 20 km./sec. From these results it was possible to estimate the total masses of the Clouds. Such an estimate is based on the fact that there must be a balance between the gravitational forces, which tend to make a galaxy collapse into a very dense mass of gas and stars, and the effects of cloud velocities, rotational and random, which tend to make the galaxies fly apart. The most probable total masses were 3×10^9 and $1{\cdot}3 \times 10^9$ solar masses for the Large and Small Clouds respectively. Thus the proportion of neutral hydrogen is 20 to 30 per cent as compared with 2 per cent for our Galactic System. The reason for this may be that the Clouds are much younger than the Galaxy and the hydrogen has not had so long to condense into stars.

Other results of these studies are the velocities with which the Magellanic Clouds are receding from us. In the case of the Large Cloud the speed is 300 km./sec.; for the Small Cloud it is 170 km./sec.

Radio astronomers at Harvard, using a 60-foot reflector, and in The Netherlands with an 85-foot reflector, have measured the radiation from a dozen or so additional galaxies. The most notable of these is M31, the Andromeda Nebula (Plate II), which resembles our Galaxy. This is at a distance of about a million and a half light-years and receding from us at a speed of about 300 km./sec. It has a total mass about three times that of the Galaxy and a hydrogen gas mass about 1·7 greater so that its proportion of hydrogen is a little smaller.

Radiation from a dozen or so other galaxies has been observed, ranging in distance to about eight million light-years (M81). The smallest of these (IC1613) has a mass only one two-thousandth that of the Galaxy.

Hydrogen-line observations have also been made of five clusters of galaxies and in all but one (M67, the oldest) it was detected; in general the older the cluster the smaller the proportion of hydrogen. These interesting observations may require repeating before we are sure that the observed signals came from the clusters and only the clusters. The reason is that the background of radiation from inside and outside the Galaxy is not uniform and it is difficult to be sure of the origin of any particular weak signal.

One cluster reported, in the constellation of Corona Borealis, was distant some 360 million light-years and had a velocity away from us of 21,000 km./sec. or about 0·07 the velocity of light. This result suggests the possibility of detecting clusters so distant that their velocities of recession approach the speed of light. Conventional optical measurements of this so-called 'red-shift' of distant galaxies have been made for shifts of 0·2 of the line frequency. More recently photoelectric techniques have raised this figure to about 0·5. With the introduction of 1000-foot diameter radio telescopes (section 1·5) and maser receivers (section 2·3) it appears that red-shifts of 0·7 the line frequency or more may be possible. This corresponds to a distance of over 5000 million light-years and the receiver, instead of being tuned to 1420 Mc/s, would be tuned to 425 Mc/s. These results will be of vital significance in deciding between the various theories of the shape of the universe.

A word of warning may be appropriate, about the great difficulties met in such red-shift measurements. This was evident in connexion with a reported red-shift of the Cygnus-A source, seen in absorption (see the following section for this technique). Subsequent observations failed to confirm this result and the claim has been withdrawn.

5.4 *Discrete galactic sources*

With aerial beams of width less than 1°, hydrogen-line emission from individual clouds of neutral hydrogen within the Galaxy may be studied. These clouds are invisible optically (being both transparent and cold), but their association with visible clouds of dust and of ionized gas may be assumed. The reason for this is that both dust and ionized gas are formed from the neutral HI gas; the ionized gas is found around hot stars and this in turn should be surrounded by neutral gas, situated beyond the reach of the star radiation.

The most outstanding optical object among the ionized gas clouds is the great Nebula in Orion. This cloud has been investigated by radio astronomers who hoped to find a surrounding neutral gas cloud. The reverse was found to be the case, the ionized hydrogen appears to be on the outside of a great cloud of neutral hydrogen expanding at a rate of 10 km./sec. The total mass of hydrogen in the cloud is about 110,000 solar masses. Other investigations have confirmed the expected association of neutral hydrogen and dust, the latter being detected optically because it obscures the more distant stars and ionized hydrogen gas.

Another way in which clouds of neutral hydrogen may be investigated is by their *absorption* of radiation from more distant radio sources. As we saw above a hydrogen atom may emit a tiny radio signal of wavelength 21·1 cm. Conversely, if such a radio wave is passing a hydrogen atom at the appropriate moment, it may be absorbed. Thus radiation from a distant radio source may suffer partial absorption while traversing neutral hydrogen clouds between the source and the Earth.

A spectrograph observing radiation from two concentrations of gas, having mean velocities of -20 and $+75$ km./sec. produces a line profile as shown in Fig. 13. If the same spectrograph were pointed at one of the *continuum sources*, such as Cygnus A (Chapter 4), the signal would be strong and steady over the whole of the tuning range. This is because a continuum source emits a signal which varies only slowly with frequency; its spectrum curve is shown as the dashed line *CC* of Fig. 13. However, when neutral hydrogen clouds lie between the source and the Earth an interesting effect is noted. The source radiation is partially *absorbed* in bands whose position depends on the velocity of each cloud. With the above two velocity values the absorption spectrum or profile has *CC* as a baseline and shows minima at *A* and *B* instead of maxima. It is rather like the original profile turned upside down.

This explanation is oversimplified because it neglects the effects of gas clouds which lie within the aerial beam but not in front of the continuum source. Nevertheless, it indicates the nature of absorption profiles and suggests how they may be used. The two spectral peaks *A* and *B* in Fig. 13 are interpreted as radiation from HI concentrations in two spiral arms having different radial velocities. If two similar *minima* are seen in an absorption profile, then it can be assumed that the source lies *beyond these two arms*. Since there is no third minimum it must lie in front of the third arm and so a fairly good distance measure is obtained for the source.

6. Radio Waves from the Sun

THE Sun is a very ordinary star, one of the 100,000 million making up our Galaxy, and having no marked peculiarities. It is a spherical ball of gas whose interior is highly compressed by the weight of overlying material and which, because of this compression, has become very hot. Near the centre the temperature is about 20 million degrees Kelvin, hot enough to cause the hydrogen to combine, forming helium – a thermo-nuclear reaction which releases enough nuclear energy to keep the star shining without collapsing any further.

The energy released in the central regions finds its way to the visible surface of the Sun, the photosphere, from which it is radiated into space. The diameter of the photosphere is about 1,400,000 km. and its temperature about 5000° K, just the correct value to maintain life comfortably on the Earth. The thickness of the radiating layer is only a few hundred kilometres, but above this thin opaque shell lies a vast atmosphere, too tenuous to be visible optically, except when special techniques are used. It is in this atmosphere that all the observed radio emission originates and so it is with this region we are mainly concerned. Nevertheless, visible effects on the photosphere are often associated with radio emission and must be studied in conjunction with it.

The atmosphere up to about 20,000 km. is called the *chromosphere* and from thereon to millions of kilometres it is called the *corona*. The gas temperature and density both vary irregularly throughout these regions but some idea of their averaged distribution is given by the dashed curves of Fig. 15. The derivation of these and the other curves of Fig. 15 is discussed below. Meanwhile it is sufficient to note that the temperature of the gas rises from a value of 10,000° K at a level of about 7,000 km. to a million degrees at a level of about 17,000 km., which is about the base of the corona. The coronal temperature then gradually falls off again as the corona merges into interstellar space.

If may strike the reader as peculiar that such a hot gas as the corona could exist between cold* outer space and the relatively

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* There is some evidence that *interplanetary* space is quite hot, perhaps 100,000° K in the vicinity of the Earth. On this view the interplanetary gas is an extension of the solar corona. However, regardless of how far the corona extends, it must eventually give way to true *interstellar* space at a temperature near absolute zero.

cold photosphere. The reason seems to be a type of very low-frequency electromagnetic wave emerging from the photosphere. These 'hydromagnetic' waves exist by virtue of magnetic fields in the ion plasma; they conduct energy up from below the photosphere and dissipate it in the higher atmosphere, thus causing heating.

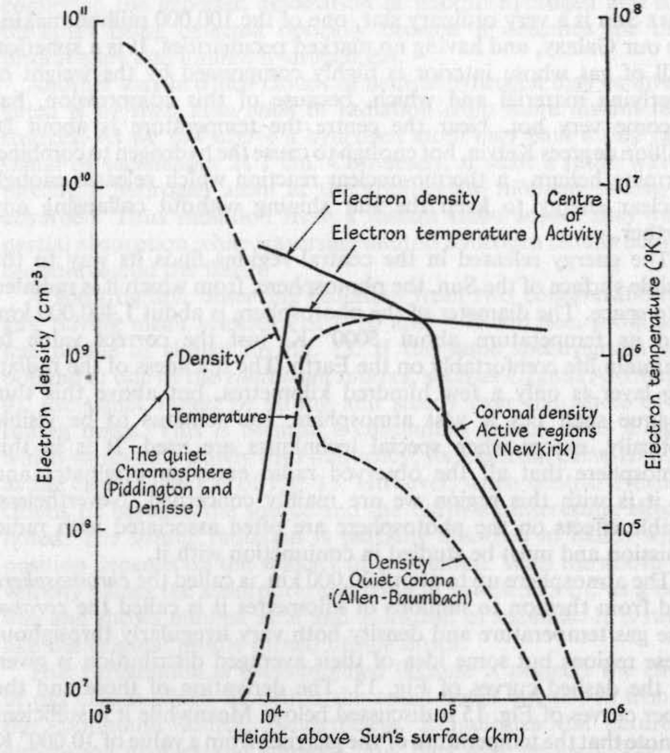

Fig. 15. The variation with height of electron density and temperature in the solar atmosphere. (a) Values for the 'quiet' Sun are shown by the two dashed curves marked 'quiet chromosphere' and 'quiet corona'. (b) Values for a 'Centre of Activity' are shown by the other curves. (*Christiansen et al. in Ann. Astrophys.*).

The above discussion applies to the 'quiet' Sun, away from sunspots and 'active' regions. The radio emission from these quiet regions has been studied since 1946 and, as we shall see, is fairly well understood.

In addition to the quiet regions there are disturbed regions, called 'Centres of Activity'. These are the most interesting parts of the Sun, in which a wide variety of phenomena are observed including the emission of various types of transient radio waves. Optically, the most obvious feature of a Centre of Activity is a sunspot, but CAs exist before and after the spot phase. Briefly, the life history of a CA is as follows.

During the *pre-spot phase* a bi-polar magnetic field develops as though a giant magnet, perhaps 50,000 km. in length, were lying horizontally below the surface of the Sun. No dark spots (sunspots) are present but wherever the magnetic field protrudes through the photosphere the overlying chromospheric gas glows by emitting bright spectrum lines. The gas is being heated by hydromagnetic waves travelling up the magnetic lines of force and the so-called *faculae* are the result. The disturbance extends into the corona, whose temperature is also increased.

The second or *spot phase* is the most important; the facular and magnetic field area increases in size and dark spots develop. These *sunspots* indicate the regions where the greatest concentration of magnetic field crosses the photosphere. They appear darker than their surroundings because the gas at the level of the photosphere is actually cooler than in the surrounding regions. Above the spots, however, the gas is hotter and denser and there is violent activity. A schematic representation of a Centre of Activity at this interesting stage is shown in Fig. 16. As well as the faculae there are glowing clouds of gas suspended high in the corona; these are called *prominences* and they are supported by the magnetic field. During the week or two duration of the spot phase the most significant of all the CA phenomena are observed – *flares* and their associated effects.

The flare itself is merely an increase in the intensity of line emission from some of the faculae. However, it is usually accompanied by a catastrophic explosion which causes a whole series of important effects. Chief of these is the ejection of a vast cloud of gas, weighing perhaps 10,000 million tons or more, with a speed of about 1000 km./sec. This gas cannot detach itself from the magnetic field and so drags this out with it, as shown in Fig. 16. The gas and its magnetic field reach the Earth a day or two later, causing magnetic storms and aurorae. As it is leaving the solar atmosphere it gives rise to powerful and irregular radio emission. At the same time X-rays are generated and cosmic rays are created; the former increase the ionization in our atmosphere, the latter sometimes reach the Earth also and have been recorded by cosmic-ray 'counters' on the Earth and in satellites.

Four pictures of an *eruptive prominence* moving up into the corona are shown in Plate IV. The outlines of the prominence at each of the four stages are clearly controlled by the magnetic field; also the forces necessary to initiate the motion are almost certainly electro-magnetic. Using a device called a coronagraph, moving pictures of the corona are now taken at several observatories around the world. These show that matter is ejected at various speeds up to about 1000 km./sec.; it takes various forms such as jets and blobs and when not ejected with sufficient velocity it falls back under the influence of the Sun's gravitational field. It is probably near the edges of these ejected clouds of gas that the most intense and most interesting solar radio emission has its origin. The generation of these radio *bursts* is discussed in section 6.4.

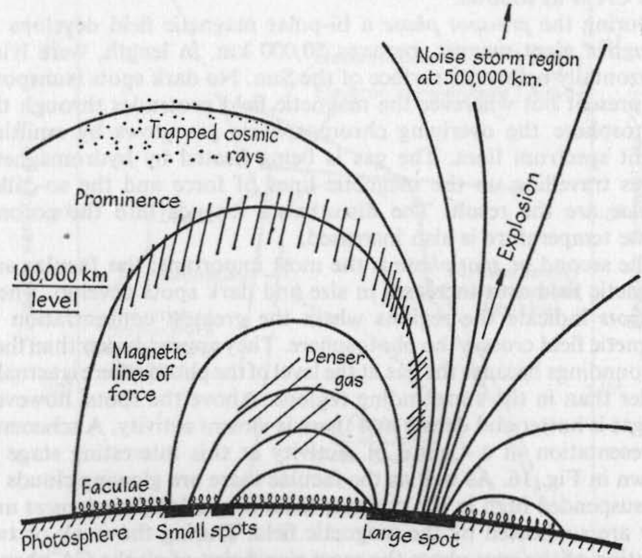

Fig. 16. A schematic diagram of a Centre of Activity in the Sun's atmosphere.

The final phase of a Centre of Activity is the *post-spot phase* which may linger on for many months. The spots, flares and all the associated effects have disappeared but the magnetic field is still present. It is weaker, however, and continues to spread, slowly becoming more diffuse. With the field remain the faculae and sometimes a quiescent filament, a cloud of cooler, denser gas shaped like a short length of thread.

Solar radio waves have two important properties; they originate in regions where optical observations may only be made with great difficulty and some of them originate by non-thermal processes (see Chapter 3) whereas, as far as we know, all optical emission has a thermal origin. Because of these properties the study of solar radio waves has greatly increased our knowledge of the solar atmosphere. Radiation away from Centres of Activity has been shown to have a thermal origin by a well understood mechanism; this radiation is discussed in the following section.

6.1 *The quiet Sun*

The possibility of detecting thermal radio waves from the Sun was considered more than half a century ago. Their detection was delayed for two reasons: first a lack of adequate receiver sensitivity and later a lack of knowledge of conditions in the solar atmosphere. The visible surface of the Sun has a temperature of about 5000° K and it was assumed that the atmosphere would be cooler. The angular extent of the Sun is about ½° so that its surface would occupy only about 1 part in 400 of a 10° aerial beam and, allowing for some losses, would provide an aerial temperature (section 2.2) of less than 10° K. Prior to about 1940 the noise generated by receivers themselves was equivalent to a temperature of about 5000° K so that there seemed little chance of detecting solar radiation.

The first observations of solar radiation at wavelengths of a few centimetres were made with radio equipment developed for war-time radar use. Narrow-beam aerials and more sensitive receivers had been developed and radiation corresponding to a solar temperature of a few thousand degrees was measured. This result was more or less as anticipated, but observations at metre wavelengths showed quite unexpected phenomena. Wildly fluctuating intensities were sometimes noted, the intensities corresponding to disk temperatures up to millions of millions of degrees. These so-called 'bursts' could not possibly have a thermal origin; their characteristics and possible origins are discussed in sections 6.3 and 6.4.

When the excitement about the unexpected 'burst' phenomenon had subsided it was noted that a steady base level of radiation was always present, corresponding to a disk temperature of about one million degrees Kelvin. This would also have come as a surprise had the result not been anticipated by strong optical evidence that the corona of the Sun is at just that temperature. The radio results and subsequent theoretical discussions proved conclusively that throughout the extensive solar corona, extending at least to several times the radius of the visible disk, the temperature is about 1,000,000° K.

Observations of the solar brightness temperature at intermediate wavelengths showed a gradual trend from about 10,000° K at 1¼ cm. wavelength, 55,000° K at 10 cm., 500,000° K at 50 cm. to 1,000,000° K at 1·5 m. The burst phenomena were also noted at the centimetre wavelengths, decreasing in strength to a negligible effect at 1 cm. At these wavelengths a third phenomenon was noted, in addition to the base level and bursts. This is generally referred to as the 'slowly varying component' and it is described in the following section.

The reason for the decrease in solar disk temperature with wavelength was provided independently by D. F. Martyn in Australia and V. L. Ginzburg in the U.S.S.R. First of all, the radiation has a thermal origin in the manner discussed in section 3.1. As seen there, a body may only *emit* thermal radiation if it is capable of *absorbing* similar radiation. Equations (1) and (7) together show that the absorption coefficient of an ionized gas, such as the solar corona, is proportional to the square of the wavelength. It was shown that the corona could absorb and therefore emit metre-wave radiation; the brightness temperature at this wavelength was therefore a million degrees – the temperature of the corona itself. Centimetre waves, on the other hand, would be only partially absorbed in the corona and partially in the cooler chromosphere. Very short waves, about 1 cm. in length, would be almost entirely absorbed in the middle chromosphere where the temperature is about 10,000° K. The apparent temperature of the Sun at this wavelength is therefore about 10,000° K.

Another result of the theory of thermal emission by the quiet Sun was a prediction of 'limb brightening' at centimetre wavelengths. A radio wave entering the solar atmosphere at an angle to the radius must pass through more absorbing gas to reach a given level. It is absorbed, therefore, at a higher level. Correspondingly, a wave emerging at an angle is emitted from a higher and therefore hotter level. This means that centimetre radiation from the edges, or limb of the Sun, is more intense than that from the centre of the disk. This limb brightening effect was later observed and a radio picture

of the quiet Sun at 20 cm. is shown in Fig. 17. The reason for the lack of symmetry is given below.

The above theory of thermal emission from the Sun was quantitatively inaccurate because the distribution of gas density and temperature in the chromosphere was not known. Optical observations of chromospheric radiation obtained during eclipses supplied a relationship between the electron density N and temperature T over a range of levels. They did not, however, allow N and T to be found independently. The determination of a radio spectrum from 1 cm. to 50 cm. made good this omission by providing a second relationship between N and T. By combining the two, J. H. Piddington, in Australia, was able to find N and T independently, thus providing a model of the quiet chromosphere. This is shown by two of the dashed curves in Fig. 15. It is now known that there are small-scale

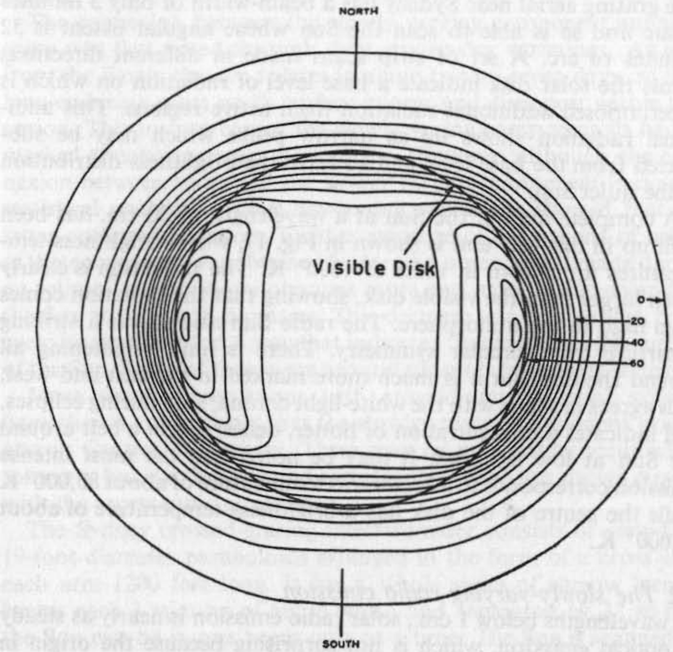

Fig. 17. A radio picture of the quiet Sun at a wavelength of 20 cm. (*Radiophysics Laboratory, C.S.I.R.O. Sydney*).

variations in *N* and *T* over the surface of the Sun. These are averaged out in the radio data and so the model of Fig. 15 must be regarded as *averaged* plots of both *N* and *T*, on which are superimposed small-scale irregularities.

The most effective aerial system for observing the quiet Sun is a row of spaced aerials acting as a diffraction grating (section 2.5). The grating aerial near Sydney has a beam-width of only 3 minutes of arc and so is able to scan the Sun whose angular extent is 32 minutes of arc. A set of strip scans made in different directions across the solar disk indicate a base level of radiation on which is superimposed additional radiation from active regions. This additional radiation shows up as narrow peaks which may be subtracted from the base level and so leave the brightness distribution of the quiet Sun.

A complete map of the Sun at a wavelength of 20 cm. has been built up in this way and is shown in Fig. 17, where brightness temperatures are shown in units of 1000° K. The radio Sun is clearly much larger than the visible disk, showing that the radiation comes from high in the atmosphere. The radio Sun also shows a striking departure from circular symmetry. There is limb brightening all around the disk but it is much more marked in the east and west. This agrees in shape with the white-light corona, seen during eclipses, and indicates a concentration of hotter, denser gas in a belt around the Sun at low latitudes. It may be noted that the most intense emission corresponds to a brightness temperature of about 80,000° K while the centre of the disk has a brightness temperature of about 50,000° K.

6.2 *The slowly-varying radio emission*

At wavelengths below 1 cm., solar radio emission is nearly as steady as optical emission, which is not surprising because the origin in each case is simply thermal emission. At these short wavelengths contributions from Centres of Activity are rarely significant.

At wavelengths just above 1 cm. the steady brightness temperature is about 10,000° K and superimposed on this are two new types of radiation. First there are small, irregular fluctuations lasting for seconds or minutes; these 'bursts' do not concern us as yet. Second, there are slow fluctuations of a few per cent which last for days or weeks. At 3 cm. this latter phenomenon is clearly marked, the amplitude of the fluctuations reaching 30 per cent or more. The amplitude increases towards sunspot maximum and varies from day to day with the number and size of sunspots seen on the disk. At longer wavelengths the slow variations become more marked, between 10 cm. and 50 cm. they may equal or exceed the steady base level. However, at metre wavelengths the effect dies away leaving the steady base level and the irregular bursts.

The slow fluctuation of intensity in the wavelength range about 1 cm. to 1 m. is generally referred to as the *slowly varying component*.

The connexion between the slowly varying component and sunspots was first noted through their day-to-day variations. As seen from the Earth, the sun rotates in about twenty-seven days, so that long-enduring spots on its surface appear and disappear within this period. This in turn causes the slowly varing component to have a marked twenty-seven-day periodicity. However, although the connexion between spots and the slowly varying component is close, a statistical analysis of their day-to-day variations showed that the latter outlasted the spots. Further evidence of the regions of origin of this component was obtained from radio observations made during an eclipse. As the Moon obscures more and more of the solar disk the flux at the Earth decreases. This decrease was not regular, however; its rate varied in a way that indicated 'hot spots' on the surface of the Sun. Some of these were around sunspots but others were not.

More recent observations with crossed-grating aerial systems have shown conclusively that the slowly varying component originates in Centres of Activity. These may or may not be occupied by sunspots, but it is the long-enduring faculae which are always present with the excess radio emission.

The Sydney crossed-grating interferometer consists of sixty-four 19-foot diameter paraboloids arranged in the form of a cross with each arm 1200 feet long. It has a whole series of narrow 'pencil' beams each 3 minutes of arc in width and separated by 1° so that the Sun can be in one beam only at a time. The Sun is scanned by these pencil beams and a radio picture synthesized in the manner of a television picture. Such a picture, taken on 21st January, 1958, is shown in Fig. 18, the units of brightness temperatures being 100,000° K. When compared with an optical view of the Sun, the regions of high intensity are seen to be Centres of Activity. It may be noted that the brightness temperatures of these Centres of Activity range from 400,000° K to 1,000,000° K, which may be compared with the brightness temperature over the disk of the quiet Sun of 50,000° K. to 80,000° K. Radio pictures of the Sun at 3·2 cm. have also been made in the U.S.S.R. using the large hole-in-the-ground paraboloid (section 1.5) which provides a 6 minutes of arc beam.

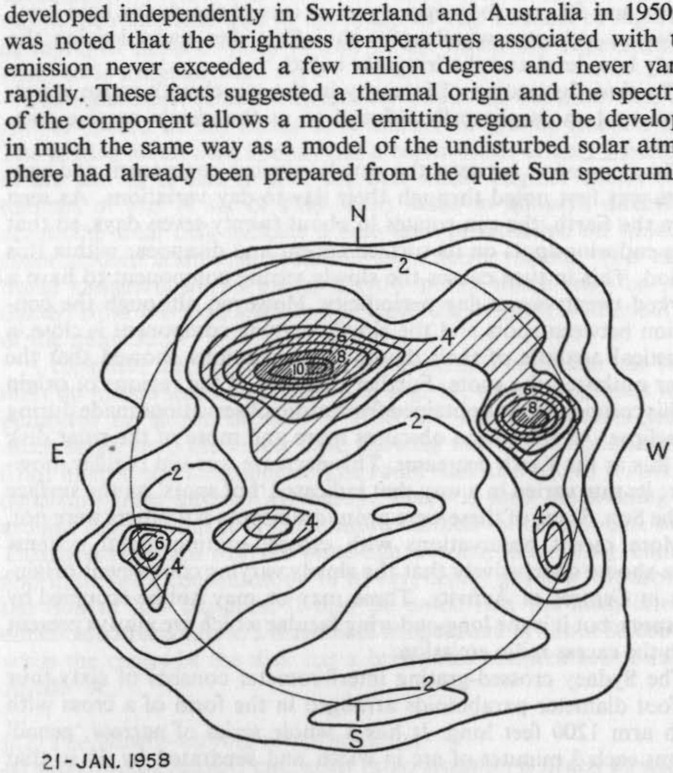

Fig. 18. A radio picture of the Sun with several Centres of Activity, taken on 21st January, 1958 (*Radiophysics Laboratory, C.S.I.R.O., Sydney*).

A theory of the origin of the slowly varying component was developed independently in Switzerland and Australia in 1950. It was noted that the brightness temperatures associated with this emission never exceeded a few million degrees and never varied rapidly. These facts suggested a thermal origin and the spectrum of the component allows a model emitting region to be developed in much the same way as a model of the undisturbed solar atmosphere had already been prepared from the quiet Sun spectrum. A radio wave of a given length is emitted mainly from a limited range of levels in the solar atmosphere. Radiation emitted from below that level is mainly reabsorbed before it can escape; radiation from above that level is weak because the atmosphere is nearly transparent and a transparent body can neither absorb nor emit thermally. Radiation of a shorter wavelength comes from a lower range of levels because it is more penetrating; it comes, therefore, from levels of higher density and lower temperature. This means that the apparent temperature of the Sun, as measured by the intensity of its radio emission, decreases with decreasing wavelength. In Centres of Activity the radio brightness increases for all wavelengths between about 1 cm. and 100 cm., which must be interpreted as an increase in temperature of a region of given density. Optical observations suggest that the temperature at a given level does not change greatly but rather that the density everywhere increases. This means that a region of given density is moved to a higher and hence hotter level.

More recent observations with grating-type interferometers have given better spectra of the slowly varying component. In particular, one Centre of Activity present on the Sun late in 1957 was viewed by telescopes in Japan (7·5 cm.), Australia (21 cm.), America (88 cm.) and France (176 cm.). The resultant spectrum showed a steep rise from 500,000° K at 21 cm., after which the brightness temperature decreased slightly. This spectrum allowed a model of the active region to be determined and this is shown by the full curves in Fig. 15.

Comparing these curves with those for the quiet Sun, it is evident that the main increase in electron density occurs between the levels 20,000 km. and 100,000 km.; within this range the density is greater by a factor of about 10. This region is the lower part of the corona and some increase is also noted at much greater heights, the factor being about 3 up to 300,000 km. Optical observations of coronal electron densities overlap the radio model and extend beyond a million km.; the two curves show good agreement.

The temperature distribution above a Centre of Activity may also be compared with that of the quiet Sun. In the corona, say above 20,000 km., the temperature in both cases is one or two million degrees Kelvin, being unaffected by the presence of the Centre of Activity. In a narrow region near 10,000 km., however, the temperature above a Centre of Activity is several times greater than that of the quiet Sun. In particular, the temperature in a region of given electron density is higher in the Active Regions. For example, the level where the electron density is 10^9 per cm.^{3} the temperature is about 10^5 ° K in the quiet Sun and above 10^6 ° K in an Active Region.

It is within or near this Active Region, where the most interesting and spectacular of solar radio events originate. These are termed 'bursts' and are discussed in the following sections.

6.3 *Radio bursts*

As we have seen, a solar flare is one manifestation of an 'explosion' in the chromosphere which causes intense heating, copious emission of ultra-violet and X-radiation and the ejection of clouds of ionized gas. Starting at the time of the flare and continuing for hours or even days, radio emission is observed over the whole spectrum from wavelengths of about 1 cm., where it is very weak, to wavelengths of 15 m. or more, where it is often very strong. This radiation differs from other extra terrestrial radiation in its spectral form; not only is the spectrum often narrow, but it is continually changing. Substantial changes may take hours or may occur within a fraction of a second. With one exception these transitory components are now referred to as *bursts*; the exception is the 'noise storm' which may last for a day or more which is too long to be aptly described by that term.

In Fig. 9, curves representing the spectra of various types of radio emission are shown. Most of these are broad band, the exceptions being the 21-cm. hydrogen line (*e*) and a typical solar burst (*f*). A second or a minute later the solar radiation may have changed from the form shown to a quite different form, spread over a different part of the spectrum. Early observations at one or a few fixed frequencies showed a puzzling complex of radiation which was difficult to interpret; certain patterns were noted, however. The most clearly defined event was a powerful burst lasting for a few minutes at each wavelength where observations were made, and progressing steadily towards longer wavelengths. These 'outbursts' as they were called followed large flares and provided brightness temperatures exceeding a million million degrees Kelvin.

These early observations indicated what type of radio telescope was required to reveal fully the characteristics of the bursts. It should be capable of tuning over a wide range of frequencies in a fraction of a second and recording the intensity of radiation at each frequency, that is, the spectrum of the burst. Since the burst spectra were continually changing, it was necessary to provide a continuous record of these changes – that is a *dynamic spectrum.*

The recording of rapidly changing spectra was not an easy matter. If the spectrograph were to produce curves such as those shown in Fig. 9, then some thousands would be required for each hour of observation. The interpetation of these results would be laborious to say the least. The difficulty was overcome by using a cathode-ray oscillograph (the picture tube of a television receiver) and a 35-mm. camera with continually moving film. As the receiver was tuned through its frequency range, say from 70 to 130 Mc/s, the oscillograph spot moved in unison across the screen. The key to the recording system was that the *brightness of the spot* was determined by the receiver output – a stronger signal meant a brighter spot just

as on a television screen. This system provided a complete spectrum in the form of a single intensity-modulated straight line. This line was photographed on film which moved very slowly in a direction perpendicular to the line being photographed. A fraction of a second later a second line was traced on the screen giving a slightly different spectrum; this and succeeding lines were photographed to provide a picture similar to that of Fig. 19. This shows a number of dynamic spectra, the spectrum at any instant being found by drawing a vertical line at the time concerned. Where the line crosses blacked-in or hatched areas there is a burst being recorded over the frequency range given at the left of the diagram. While Fig. 19 illustrates the recording principle, called 'intensity modulation', it is oversimplified because it does not show the gradual variation in brightness of the spot found in actual dynamic spectra. The blacked-in areas represent intense radiation, the hatched areas strong, steady radiation and the white areas no radiation.

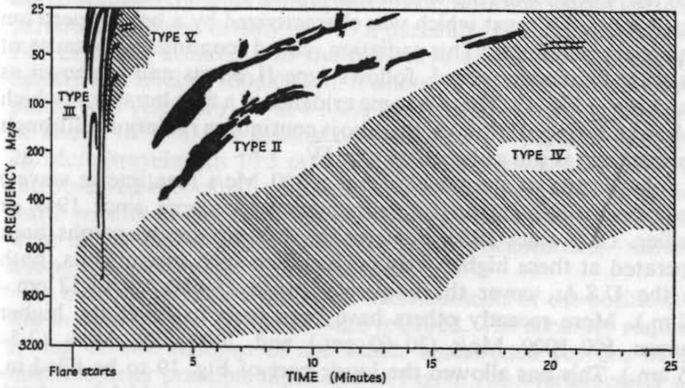

Fig. 19. The spectra of sola radio bursts, showing how they vary with time (dynamic spectra).

The first dynamic spectrograph was built near Sydney in 1949. Using a wide-band rhombic aerial, it operated in the range 70–130 Mc/s (2·3–4.3 m. wavelength). By 1952 the frequency range had been extended to 25–210 Mc/s (1·4–12 m.), requiring the use of three rhombic aerials, each covering a range of frequencies of approximately two to one. Using this equipment J. P. Wild and his associates recognized three typical burst types. Of these, type II is the most powerful and corresponds to what the earlier single-frequency observers called an outburst. Also powerful but less enduring are the type III bursts, some typical examples of which are illustrated in Fig. 19; these had previously been referred to as isolated bursts. Type I bursts do not usually follow closely after a flare, as do the types shown in Fig. 19. For this reason they are not shown in Fig. 19. This burst type, which accompanies 'noise storms' is discussed in section 6.6.

It should be remembered that all the above discussion concerns waves of length more than one metre or frequencies less than 300 Mc/s. Also working within this region, French observers recognized a type IV burst which was characterized by a broad spectrum and great steadiness. This radiation, called 'continuum' because of its wide frequency spread, follows type II bursts and is shown as hatching in Fig. 19. There is some evidence of a fifth burst type which follows after type III bursts; this also is continuum radiation, although its spectrum is not as broad as type IV.

Solar bursts at frequencies above 300 Mc/s (centimetre waves) have been observed on single-frequency telescopes since 1949 or earlier. Only since 1956, however, have radio spectrographs been operated at these higher frequencies. Two such instruments, both in the U.S.A., cover the frequency range 25–580 Mc/s (52 cm.–12 m.). More recently others have been built to cover the higher ranges 500–1000 Mc/s (30–60 cm.) and 2000–4000 Mc/s (7·5–15 cm.). This has allowed the lower part of Fig. 19 to be filled in, although, because of the relatively few observations which have been made, there is less certainty about the forms of dynamic spectra here. However, there appears to be continuum radiation starting about the time of start of the flare and continuing, with gradually decreasing frequency, over the whole period shown. The high frequency part of the dynamic spectrum may join on to the type IV radiation.

6.4 *Emission from streaming gas*

It will be seen that the events depicted in Fig. 19 all follow after a solar flare. In discussing the characteristics of the radio bursts, we should keep in mind their relationship to flares and to the 'explosion' know to accompany flares.

Near the maximum of the eleven-year solar sunspot cycle, flares, mostly small ones, occur at an average rate of several per hour. Even these small flares are often accompanied by the type III bursts whose spectral form is shown in Fig. 19. These bursts last only a few seconds but often occur in groups as shown. The individual burst appears as a sharp line, tilted from the vertical slightly towards the right. This means that as time progresses the frequency of the burst decreases from say 600 Mc/s (wavelength 50 cm.) to 25 Mc/s (12 m.) where the record stops.

Type III bursts were first recognized in Sydney and an interpretation was given in terms of the natural resonance or plasma frequency of the solar atmosphere f_0, given by equations (2) and (3) of Chapter 3. It was suggested that the observed frequency drift was due to a disturbance of some sort, perhaps a cloud of ions, travelling outwards through the solar atmosphere. At a particular height there is a particular electron density and so a particular resonance frequency. For example, according to the full curve of Fig. 15, the electron density at a level of 100,000 km. is about 10^9 per cm.^{3} which corresponds to a value of $f_0 = 284$ Mc/s (wavelength 1·05 m.). At a level of about 10^6 km. the density has fallen to 10^7 per cm.^{3} and f_0 to 28 Mc/s (wavelength 10·5 m.). If a model corona is assumed, then the observed rate of fall of frequency may be interpreted as an outward *velocity* of the disturbance. Velocities determined in this way were far in excess of any known optical phenomenon – namely, about one-quarter the velocity of light.

In order to test this hypothesis, measurements of the positions of the sources of type III bursts were required. The accuracy required is one or two minutes of arc which necessitated the use of the interferometer principle illustrated in Fig. 6. An interferometer was constructed near Sydney using two wide-band rhombic aerials and a receiver whose frequency swept twice per second through the range 40–70 Mc/s. The output is recorded as a function of frequency and time and gives the position of the source, east or west of the centre of the Sun at any given frequency and time. It was soon established that the sources of type III bursts did indeed move with velocities approaching that of light and also that at any given instant the source of lower-frequency radiation was farther from the Sun than that of higher-frequency radiation. All this is consistent with the 'resonance' hypothesis but still does not explain the actual origin of the radiation.

A few times per year flares of great magnitude are observed on the Sun; these frequently give rise to geomagnetic storms and aurorae a day or so later. They also provide the spectacular radio 'outbursts' or type II bursts shown in Fig. 19. This event follows the emission of type III bursts which often occur almost immediately after the start of the flare. Type II bursts are characterized by one or more narrow bands and other formations which drift slowly from high to low frequencies. They differ from type III bursts in several important ways. First of all their frequency drift is much slower, corresponding to an outward velocity of a disturbance of about 1000 km./sec. (only one three-hundredth the velocity of light). When two type II bursts occur together, as in Fig. 19, the features are duplicated with remarkable fidelity in two frequency ranges separated by a two-to-one interval. This indicates that the emitting source radiates at a fundamental frequency and at its second harmonic. This feature is occasionally observed in type III bursts but these also tend to occur in unconnected groups.

We have seen that radiation from the quiet Sun and also the 'slowly varying component' may be nicely explained in terms of ordinary thermal radiation from a hot body. This cannot be the case for types II and III bursts, however, because the observed intensity of the radiation exceeds any possible thermal emission by a factor of more than 10,000. Furthermore, the narrow and rapidly changing spectra of these bursts show that they are not generated by the synchrotron process (section 3.3). They must, therefore, result from the ordered motion of bunches of ions. In order to radiate efficiently these bunches must have dimensions less than a wavelength, that is, less than about 1 m. Emission above the black-body limit is then possible as shown in section 3.5. If there are N electrons in a bunch and that bunch is accelerated in any way, then the power radiated is N^2 times that of a single electron. This means that the power radiated by each electron in a bunch is increased by N times, a phenomenon called 'stimulated emission'.

The mechanism of electron bunching is well understood and has been discussed in sections 3.4 and 3.5. It may be described alternatively by the Cerenkov generation of shock space-charge waves, by the slowing of electrons approaching an existing bunch of electrons or by the trapping of electrons between two existing bunches. These mechanisms are all basically physically similar and simply amount to the fact that in a double-stream medium an existing bunch of electrons, however few in number, attracts other electrons simply by slowing them down. In this way the bunch grows continuously.

Both type II and III bursts are associated with fast-moving disturbances in the corona, and the leading edges of these disturbances must be regions of interpenetrating electron streams and hence of electron bunching. If v is the streaming velocity, then the minimum size of the bunches is about $\frac{v}{2f_0}$, where f_0 is again the plasma resonance frequency. The electron bunches will move about with velocity of order v and may generate radio waves, above the black-body limit of intensity, in any one of three different ways.

Two of these three emission mechanisms have been described: one is gyro-radiation (section 3.3) and the othe Cerenkov emission of the extraordinary radio wave (section 3.4). In neither case is the emission spectrum likely to peak at the plasma resonance frequency f_0. On the other hand all the experimental results point to notable peaking at f_0 and at its second harmonic $2f_0$, so that the above emission mechanisms are not responsible for type II or type III bursts.

The third possibility may now be considered; this is radiation by collision between bunches. Just as an electron will radiate as it is deflected in a close collision with a proton, so a bunch of electrons will radiate as it passes a second bunch of electrons or a bunch of protons. At the front of the fast-moving disturbance associated with types II and III bursts there will be turbulent inter-streaming regions. Here space-charge bunches or waves will be formed and move about in all directions with velocities typified by the streaming velocity v. The maximum radiation will be provided by collisions between two bunches of minimum dimensions $d = \frac{v}{2f_0}$ which pass one another at this minimum distance. The corresponding radio pulse has duration $\frac{2d}{v}$ or $^1/f_0$ and the maximum frequency emitted is the inverse of this duration – that is f_0. Lower frequency radiation will tend to be trapped in the manner shown in Chapter 3. Thus the emitted radiation will tend to have a narrow spectrum around the plasma frequency f_0.

The main characteristics of type II and III bursts seem to be explained by the above theory. The formation of bunches of N ions increases the radiation limit to N times the black-body limit. Even weak bunches give values of N of a million, so that the high intensities are explained. Stronger bunching is known to provide second harmonic radiation as observed, and finally, the radiation should show little or no polarization, as observed.

6.5 *Broad-band radio bursts and noise storms*

Referring again to Fig. 19 we notice three burst types which have a broad frequency band and which vary more slowly than the types II and III. Of these the type IV has been studied in most detail, principally in France by J. F. Denisse and his collaborators.

Type IV radiation has been studied at metre wavelengths and the present discussion does not include the radiation shown above a few hundred Megacycles (Fig. 19). The intensity of type IV radiation is high and remarkably steady; it appears to follow, and perhaps is associated with type II bursts. It may last for some minutes or a few hours and measurements made at Meudon show that it may be generated at heights in the corona of a few million kilometres. This is greater than the measured heights of any other disturbances.

Type IV bursts show brightness temperatures up to ten thousand million degrees Kelvin and so cannot have a thermal origin. The most likely mechanism for generating these waves is the synchrotron process. The following series of events are thought to follow a flare and 'explosion' in the chromosphere. The explosion causes a vast cloud of ionized gas to be ejected with speeds up to about 1500 km. per second. At the leading edge of this cloud type II bursts are generated perhaps in the manner described above. With the cloud is carried a magnetic field and in this field are trapped cosmic-ray electrons and protons. At great heights the protons escape and are observed an hour or so later in the vicinity of the Earth, being detected by instruments carried in rockets. Some of the fast electrons remain trapped in the coronal magnetic field (Fig. 16) and there they rotate about magnetic lines of force, radiating by the magnetic acceleration mechanism. The electrons gradually lose their energy by radiating it away or by an occasional collision with a slower particle; some escape into interplanetary space. These processes of dissipation take an hour or so, during which a high, steady level of radiation is maintained.

Perhaps the principal objection to the above theory of type IV radiation is the fact that it is sometimes partially circularly polarized, whereas synchrotron radiation is linearly or randomly polarized. The explanation may be that another type of radiation appears as type IV starts to wane. This is type I or noise-storm radiation, which is not shown in Fig. 19, but is described below.

In the same way that type IV continuum follows type II bursts, so type V continuum appears to follow type II bursts. This radiation has not been studied as long as type IV and its origin is doubtful. It may also be synchrotron radiation but its much narrower spectrum and faster variation raise some doubts.

The broad-band radiation at frequencies above about 1000 Mc/s (at the bottom of Fig. 19) has only recently been studied by the use of dynamic spectra. However, a clue to the origin of at least part of this emission is found in single-frequency records taken more than a decade ago. These results extend to frequencies up to 24,000 Mc/s (1·25 cm.), but are most numerous at 3000 Mc/s (10 cm.). At these frequencies the slowly varying component causes the main variation. Occasionally, however, a fairly rapid increase of a few per cent of the base level was observed with no subsequent decrease. It was not possible to identify these increases with any of the above types of burst, but they were easily explained in terms of thermal radiation from a *suddenly heated* region. Thus the radiation shown in the lower part of Fig. 19 may have a thermal origin like the slowly varying component being differentiated only by the unusually rapid heating of the plasma responsible.

There is one further type of solar radio emission whose origin provides a fascinating study in wave theory. This is the type of radiation which caused serious interference to British Army radar sets in 1942 and was later given the name 'noise storm'. Its most notable characteristic, one which differentiates it from all the other disturbances is its long duration; a typical noise storm lasts about one day. Noise storms occur only at metre wavelengths and cover a broad band of frequencies, say from 100–150 Mc/s or even from 50–300 Mc/s. This continuum radiation is called type I continuum. In addition there are narrow-band short-duration bursts; they have a band-width only about 1 per cent of their mid-frequency and last a few tenths of a second. These are called type I bursts.

Apart from their long duration, noise storms are notable among all other disturbances for their *strong circular polarization* and limitation to frequencies below about 300 Mc/s. They do not appear to be as closely associated with flares as the other burst types but this may result from another observed characteristic: noise storms originate above very large sunspots but are only observed when the spots are near the centre of the solar disk. This means that noise storm radiation is emitted *largely radially* from the Sun and not equally in all directions. Thus a noise storm might start shortly after a flare but not be observed on the Earth until the spot has moved close enough to the centre of the disk (by solar rotation). It is now thought that noise storms may be part of the pattern of Fig. 19, starting after, or even during the type IV phase and continuing long after all other emission has died away. In fact it may well be that noise-storm radiation overlapping type IV may account for the occasional partial polarization of type IV.

A powerful instrument for the study of noise storms is the large grating interferometer at Nançay, operating at 1·77 m. wavelength. This provides daily plots of their positions with an accuracy of about

4 minutes of arc east–west and 10 minutes of arc north–south. By noting the rate of movement as the Sun rotates, their heights above the visible disk of the Sun may be found; they lie between 300,000 km. and 700,000 km.

Noise-storm radiation cannot be thermal because of the very high observed intensity, nor can it be synchrotron because the spectrum is often too narrow (see Fig. 9 (*b*) for the synchrotron spectrum); also the polarization is not consistent with such an origin. We must conclude that noise-storm radiation, like types II and III bursts, is far above the black-body limit and is caused in some way by the ordered motion of groups or bunches of electrons; that is by stimulated emission. However, the actual mechanism of generation of radio waves by the bunches of electrons cannot be that described above for types II and III bursts. This process of emission by the collision of bunches of ions results in a restricted emission band near the plasma frequency f_0; also the radiation is not polarized. Noise storms on the other hand comprise a *broad continuum* on which are sometimes superimposed *very narrow band* bursts. Furthermore all this radiation is strongly *circularly polarized*, the direction of polarization corresponding to the so-called '*ordinary*' or *O* radio wave (section 3.1). Hence type I continuum and bursts must be due to a bunch-acceleration mechanism other than collision between bunches.

As seen in Chapter 3 there are two possible mechanisms, each depending on the magnetic field which is certainly present. In this field the motion of a bunch of electrons, like that of a single electron, is in a spiral path around a magnetic tube of force. Such motion must generate radio waves by two processes: the gyro process because the electrons are being accelerated by the field and the Cerenkov process because the electrons are moving faster than the 'extra-ordinary' or *E* radio wave. In the latter case a shock wave is formed. Unfortunately in both cases the *E* wave only is generated. As shown in Fig. 8, *E* waves cannot escape from the solar atmosphere. In any case, even if they could escape the observed radiation is known to correspond to the *O* wave.

There appear to be two possible ways around this difficulty. In the first the bunches of ions are regarded as plasma waves which may propagate more or less freely through the solar atmosphere. The speed of propagation will depend on the plasma density and on the strength and direction of the magnetic field. Under suitable conditions the speed of propagation may exceed that of light and may attain the speed of the *O* radio wave. Under these conditions the *O* radio wave may be generated by the plasma wave and may then escape from the solar atmosphere. This theory was first proposed in Australia in 1955.

A second theory starts with the generation of the *E* radio wave by electron bunches and the gyro and Cerenkov processes. These processes are very efficient and should quickly transfer most of the kinetic energy of the bunches to *E* radio waves. These waves cannot escape but they may move to regions where they generate *O* waves, either directly or by first creating plasma waves which in turn provide *O* waves. This theory, although more complex, may better explain the spectral features of noise storms. The *E* waves (and later *O* waves) generated by the Cerenkov process account for the continuum radiation; waves generated by the gyro process account for the narrow-band bursts.

7. Radio Waves from the Moon, the Planets, Rockets and Satellites

A large part of optical astronomy has been devoted to the study of our own satellite (the Moon) and the solar satellites or planets. A better understanding of these objects may lead to an acceptable theory of the origin of the solar system. This in turn will allow us to predict the chances that there are other planetary systems moving around some of the many million stars of our Galaxy. If it is found that many stars should have planetary systems, then it is likely that there will be life elsewhere in the Galaxy, perhaps even civilizations. However, optical studies of the local planetary system are not easy; some of the planets even have their surfaces permanently obscured by clouds. The addition of radio techniques are welcome, therefore, and have already added greatly to our knowledge in this field.

Practically all of the visible light from the Moon and the planets is reflected sunlight. However, the Moon is also seen to glow a dull copper-red during its eclipse by the Earth, when direct sunlight has been cut off. This effect is due to light which has been scattered in the Earth's atmosphere, having had most of the blue component removed in the process. Most of the energy emitted by the Sun is in the visible spectrum and while some is reflected by the various objects in the solar system, some is absorbed to heat them. In this way the Earth is maintained at an average temperature of about

300° K. (27° Centrigrade). Planets nearer the Sun are hotter and those farther away colder and the same general considerations will apply to man-made interplanetary objects.

When we observe the planets at wavelengths longer than those of visible light, that is at infra-red and longer wavelengths, a new phenomenon is observed. The strength of *reflected* solar radiation decreases and, more important, the strength of *emitted* planetary thermal radiation increases (section 2.1). This thermal emission originates at the object, the Moon or a planet, itself, and its study may tell us more about that object than the study of reflected light. At radio wavelengths the reflected radiation is negligible and we observe only emitted radiation.

The general nature of most of the lunar and planetary radiation should be predictable from theory. As seen in section 2.1 any object which is not absolutely cold (that is at 0° Kelvin or —273° Centigrade) should provide some thermal radio emission. The second requirement is that the object should not be a perfect transmitter or reflector of radio waves, that is that it should absorb some radiation incident upon its surface. Both of these requirements are met by rock, soil and other surface features of the Earth and also, presumably, of the Moon and planets. It follows that they should emit radio waves by a purely thermal process.

If the body concerned were a perfect absorber of radio waves (a 'black body'), its radio brightness would be given by equation (2) of section 2.1. The actual radiation will be somewhat less because the surfaces of the Moon and the planets, like that of the Earth, are partial reflectors. The actual radiation will be given by equation (3) where T_b is less than the true temperature of the surface layers and is called the brightness temperature.

Measurements of lunar and planetary radiation assume a new interest when we start to measure variations which occur as the angle between the radiating body and the Sun changes. As one would expect, the sunlit side of the body is hotter than the dark side and the variations in temperature tell us something about the cooling rate and so about the nature of the surface of the object.

One of the most interesting results of planetary radio observations is the discovery of an intense and very variable radiation from Jupiter. This cannot possibly be thermal radiation and its study provides a fascinating problem.

With the launching of the first Russian satellite in 1947 a new branch of radio astronomy was opened, one which may eventually outweigh all others. We have already considered the astronomy of naturally occurring radio signals. We now have a second technique available: a transmitter may be sent to, or beyond, the object to be investigated. The returning signals may tell us something about the object. Of course there is an extension of this technique to sending instruments other than a simple radio transmitter. For example, a device for measuring magnetic field strengths (a magnetometer) may be carried in the rocket and relay the information it obtains back to Earth by radio. This technique combines radio astronomy with other physical and later perhaps even biological, sciences.

7.1 *Radiation from the Moon*

As we have seen, the Moon is essentially an emitter (as opposed to a reflector) at infra-red wavelengths and many observations in this range have been made of the radiation emitted. At the time of a lunar eclipse the infra-red emission is seen to fall rapidly as the Earth's shadow spreads over the surface and the cooling rate inferred from these measurements has been interpreted in terms of possible surface characteristics. It was decided that solid rock was the probable main component.

Measurements of lunar *radio* emission were first made in 1946 and in 1949 a complete set of observations throughout the lunar cycle, at a wavelength of 1.25 cm., was reported from Australia. The point in making such a set of observations is that the Moon rotates about its axis once every lunar month and so presents a constantly changing hemisphere to the Sun. On the other hand the lunar hemisphere seen from the Earth is always the same, because the Moon moves around the Earth in the same period, rotating once on its own axis. The result is that the Sun rises and falls on the visible lunar hemisphere, which should be heated and cooled accordingly and should radiate more and less radio energy accordingly.

As expected, the radio brightness rose and fell throughout the lunar cycle, the apparent temperature varying between about 200° K and 280° K. The striking feature of the results was that the brightness was not a maximum at full Moon but about 3½ days later. On the other hand, the infra-red measurements showed a maximum at full Moon as expected, so that the radio emission did not keep pace with the infra-red emission. A further difference found was that the radio brightness temperature variation was smaller than the infra-red temperature by a factor of 0·39. A last difference was that the radio wave temperature variation was more nearly sinusoidal than the infra-red temperature, which flattened out during the lunar night.

The difference between the radio and infra-red results could only mean that these radiations came from two different places and on closer examination this proved to be the case. Infra-red radiation incident on rock or similar substances is absorbed in a very thin surface layer. Correspondingly, infra-red radiation emitted by hot rock emerges from a very thin surface layer. On the other hand, 1·25 cm. radio waves will penetrate several centimetres into most rocks and so will be emitted from well below the surface. As the Sun rises and falls on the lunar landscape, the thin surface layers are heated to temperatures ranging above that of boiling water and cooled to temperatures far below the freezing point of water. Below the surface, however, the temperature fluctuations are less violent and the maximum and minimum temperatures are delayed after the periods of full Moon and new Moon. The reason for this is that the heat waves take some time to penetrate to the lower levels and, while cooling, the heat waves take some time to emerge again, thus delaying cooling.

The most surprising result was yet to emerge from this investigation. After a careful mathematical analysis it was found that the amplitude of the temperature fluctuations and the delay in the peak temperature could not be accounted for in terms of any single lunar substance. They could, however, be accounted for in terms of two substances: solid rock overlaid by a thin layer of dust would provide the observed radiation.

Lunar radio emission at wavelengths between 0·8 cm. and 75 cm. has since beem measured. At wavelengths above a few centimetres no temperature variations are observed. This is presumably because this longer-wave radiation emerges from greater depths, where the temperature fluctuations are negligible. It would seem that when man does reach the Moon he need only excavate to a depth of a metre or less to reach a level where the temperature is uniform. Its value is somewhat below the freezing point of water near the lunar equator and decreases towards the poles.

7.2 *Thermal radiation from the planets*

Because of their much greater distances, thermal radiation from the planets is much weaker and ten years were to elapse after the detection of lunar radiation before thermal emission from the planets could be measured. However, during its closest approach to the Earth in 1956, Venus was observed by U.S. radio astronomers at wavelengths of 3·1 cm. and 9·4 cm. using the 50-foot diameter U.S. Navy paraboloid. The brightness temperature was unexpectedly high, about 560° K, and more accurate measurements over the following three years gave a steady value of 580° K, or more than 300° C. which is about the melting point of lead.

This was a surprisingly high level of radiation, particularly as it was the dark side of the planet which was observed. Later observations at a shorter wavelength of 0·86 cm. gave a rather uncertain value somewhere between 250° K and 570° K. The upper limit would be consistent with the earlier results but the lower limit, if it proves to be the correct value, would seem to indicate that these waves originated in a cooler region than the longer waves.

The brightness temperature of 580° K, about double that anticipated, may have several possible explanations. Some of the radiation may be non-thermal, but the general steadiness suggests a thermal origin in which case the temperature of the emitting region must be at least 580° K. On the simple theory of planetary heating and cooling this is not possible. Venus is closer to the Sun than the Earth, but not enough to raise its temperature to 580° K. However, there are other possible explanations, one of which is the so-called 'greenhouse effect' which causes the interior of a greenhouse to reach higher levels than the outside garden.

Solar radiation has its energy mainly in the visible spectrum and this passes freely through the glass of a greenhouse to heat the earth below. When this becomes hot enough it radiates an equal amount of energy (at much longer wavelengths) and if the glass were not present a balance would then be reached. However, the glass is opaque to the heat and infra-red rays radiated by the earth and these are prevented from escaping until the glass itself becomes hot and the interior yet hotter. Such a condition may occur in a planet, the planetary atmosphere taking the place of the greenhouse glass; radiation from the surface of the planet may be thus enhanced. Alternatively, if the planetary atmosphere were opaque to radio waves it would provide thermal radio emission. A planetary atmosphere might reach extremely high temperatures and so account for an unexpectedly high level of radio emission.

Radiation from the planet Mars was also detected in 1956, the brightness temperature being about 218° K. This is in fair accord with the infra-red temperature of 260° K, a little below the freezing temperature of water (273° K) and is entirely consistent with thermal radiation from the surface of the planet. A corresponding result was found for Jupiter at a wavelength of 3 cm. As seen in the next section, however, Jupiter also emits non-thermal radiation at longer wavelengths (10 cm. and above) and even bursts at metre wavelengths. Saturn is the fourth planet from which radiation has been detected and here again the intensity is consistent with a thermal origin in the warm surface layers.

7.3 *Non-thermal radiation from Jupiter*

Thermal radiation of radio waves from the warm surfaces (and perhaps the atmosphere) of planets was entirely predictable, although it is so weak that it could not be detected until 1956. The possibility had also been considered, of receiving radio emission from electrical storms in the atmosphere of the nearest planet, Venus. This was not thought likely, however, because of the enormous power needed in the lightning flashes to make them detectable at a distance of 41 million miles or more.

It came as a complete surprise, therefore, when U.S. observers announced in 1955 the detection of strong, rapidly fluctuating signals from the planet Jupiter at a wavelength of 13·6 m. This result stimulated fresh observations and also a search through old records in an effort to verify it. It was found that records of 18·4 m. cosmic radiation taken near Sydney during 1950–51 showed a series of bursts which may have come from Jupiter. These had previously been passed over as terrestrial interference but a detailed analysis showed that not only did they come from Jupiter but for one period of a few months they came from one particular part of the disk. When this part was obscured by rotation of the planets, no radiation was received. It was possible to determine the longitude of this source of radiation and at just that longitude a visually disturbed part of the Jovian atmosphere was visible. This comprised an oval-shaped dark blob surrounded by an optically bright 'corona'. Most of the radiation from Jupiter at that period was thought to come from this particular area.

Investigations at a number of wavelengths have shown that the Jupiter bursts have band-widths of about 10 Mc/s centred on 20 Mc/s; their wavelength range is, therefore, about 12 m. to 20 m. Individual bursts last for a minute or so and groups of bursts last about an hour. The energy involved in each burst is enormous, being the equivalent of several hydrogen bombs – we are indeed fortunate that no corresponding effect occurs frequently on the Earth. The only terrestrial phenomenon known to provide such energies are large volcanic explosions, such as Krakatoa. However, as Jupiter is some 390 times as massive as the Earth and as its surface is optically completely obscured by its atmosphere there may be phenomena quite unlike any on the Earth.

One possible phenomenon depends on the fact that the observed radio bursts are strongly polarized, showing that Jupiter has a magnetic field. It is also known that different parts of the atmosphere rotate with different angular speeds and this may twist up the magnetic field and store up magnetic energy. This energy may subsequently be rapidly released, as is thought to happen at the time of flares on the Sun. The result might be an 'explosion' as occurs at the time of flares, and the emission of radio waves by one of the mechanisms responsible for solar radio bursts (Chapter 6).

When radio telescopes were sensitive enough to detect the anticipated thermal emission from Jupiter, this was sought and probably found at a wavelength of 3 cm. At somewhat longer wavelengths, however, more unexpected results were obtained. The brightness temperature at 3 cm. was about 180° K which is consistent with a thermal origin. At 10 cm. it had risen to 600° K and at 21 cm. to 2000° K to 3000° K. Measurements at 31 cm. gave a value varying between 5000° K and 10,000° K and showed that the radiation was plane polarized, the electric vector lying approximately in the equatorial plane of Jupiter. It would seem that these results may be interpreted in terms of synchrotron radiation (section 3.3) by cosmic-ray electrons trapped in the magnetic field of Jupiter. Instruments carried in space probes and satellites have shown that high-speed electrons and protons are trapped in the Earth's magnetic field. These are confined to two vast 'radiation belts', one about 2000 miles above the surface of the Earth and the other at about 10,000 miles. These trapped particles could not provide radiation of comparable intensity to that coming from Jupiter. To explain the latter requires a very much larger number of particles. An alternative suggestion is that the radiation is by low-energy electrons which provide gyro-radiation (section 3.3) at the frequency 2·8H Mc/s, where H is strength of the magnetic field in gauss. This mechanism requires a field of at least 1200 gauss at the surface of the planet. A possible objection to this theory is the fact that gyro radiation is the 'extra-ordinary' component of radiation and this meets a stop band (section 3.1) before it can escape from the planetary atmosphere.

7.4 *Signals from rocket-launched transmitters*

From the date of launching, the two radio transmitters carried in the first Earth satellite provided information of scientific value and opened a new branch of radio astronomy. In the following three years the effort expended in 'space' research has increased enormously and during 1961 the U.S. Government may spend one thousand million dollars on this field of science. This sum does not include the much greater cost of developing the rockets needed; this is met from the military budgets. It will be spent on the various instruments, both in the rocket and on the ground, needed to collect scientific data and then to process this data. The scientific results extend into many fields apart from radio astronomy: geophysics, optical astronomy, cosmic ray, solar and plasma physics, not to mention the biological sciences. All of these will depend, to some extent, on the transmission of radio waves to and from the instrumented part of the rocket.

It seems appropriate to mention here two other indirect effects of space science on radio astronomy. First, the very rapid growth of the former has provided a great impetus to many of the earlier branches of radio astronomy; this is particularly so in the U.S.A. and perhaps also in the U.S.S.R. This is a logical development because these different branches will overlap with rocket radio astronomy as the rockets move farther into space. Already plans are afoot to use rockets to test the theory of dust on the Moon; as we saw in section 7.1 this theory was largely a result of radio observations. Later, rockets will reach the planets and perhaps venture far into the solar atmosphere to the regions where the powerful radio 'bursts' are generated.

The second way in which rapidly expanding space research in the U.S.A. has affected radio astronomy, as well as allied branches of physics, is to create a shortage of scientific manpower and cause a flow of manpower from the universities to business organizations. The latter play a major part in the new developments and seem able to double the financial inducement offered to scientists.

It was not surprising that radio telescopes which existed before the launching of the first satellites have proved useful in sending signals to and receiving them from satellites and space probes. The most notable contact of this nature up to the time of writing was that between the 250-foot Jodrell Bank telescope and the U.S.A. space probe Pioneer V. The latter was launched during March 1960 and at 70,000 miles per hour moved into an orbit around the Sun. Radio signals were sent daily to a receiver carried in this space probe where they were amplified and used to switch on a transmitter. The latter sent information back to the Earth concerning the strength of the magnetic field in interplanetary space and also the numbers and speeds of fast ions, including cosmic rays. Contact was maintained to a distance of 22·5 million miles at which time the solar batteries used on the space probe failed and contact was lost. With heavier batteries and more powerful transmitters it may be anticipated that radio contact at the distance of the Sun (93 million miles) or any of the planets will be easily maintained. However, contact at the distance of even the nearest star is another matter, requiring roughly a million million times the power to reach 22·5 million miles.

Radio transmission via satellites will have many uses, perhaps the most important of which will be a world-wide communication facility. This depends at present on ionospheric reflections which are limited in reliability and frequency range. It is safe to say that within the next decade we will witness a revolution in this art with the advent of two types of communication satellite.

The simplest is that of the 'passive reflector' satellite. This contains no receiver or transmitter but has a large reflecting surface (100 feet or more in diameter) which directly reflects signals received from one ground station back to a second station. This system requires large transmitter powers and a considerable number of satellites to give coverage over the whole Earth. Since it is essentially a radar system it is really more apt for inclusion in Chapter 8.

It seems likely that 'repeater' satellites will provide the world-wide radio links of the future. These need not be large but they are fitted with a receiving aerial and contain a receiver and transmitter which relays the signals. Three such satellites at an altitude of 22,300 miles and equally spaced around the Earth would give world-wide coverage. At this altitude they circle the Earth once in twenty-four hours and if they are in the equatorial plane, then each remains permanently above a particular spot on the Earth. This removes all tracking problems and allows aerials on the Earth to remain permanently directed at one or two satellites.

8. Radar Astronomy

RADAR is a form of two-way radio link. A signal is transmitted by a directive aerial on the Earth to the object being studied. The signal is there reflected in many directions and a tiny fraction arrives back at the same aerial to be amplified and compared with the original signal. This comparison provides information about the target body, its distance, speed of rotation, the 'roughness' of its surface and so on.

The radar principle was developed in 1926 to investigate the ionosphere and has proved of enormous value in exploring our upper atmosphere. Radar techniques were greatly improved before and during World War II, when radar sets were used extensively for detecting enemy aircraft, ships and other objects. It came to the attention of astronomers in 1946 when echoes were first obtained from the Moon 240,000 miles away. It was to be twelve years before echoes from the next closest object, Venus, were obtained. Meanwhile, radar meteor astronomy was founded when British Army radar operators observed echoes from meteor trails, the columns of ionized gas left in the wake of meteors burning in our atmosphere. Radar reflections have also been obtained from aurorae and these investigations are discussed in some books on radio astronomy. However, it is felt that this subject falls more within the sphere of geophysics and so is not included here.

The basic units of a radar system are shown in Fig. 20 and they operate as follows. With the switch in position 1 the transmitter sends a pulse of energy to the aerial and out towards the object being investigated. Some energy is reflected back towards the Earth and before it arrives the switch is moved to position 2 and the received signal is fed to the receiver. A timing device records the round-trip time and when this time is multiplied by the velocity of light we have the round-trip distance. It is usual to send a series of

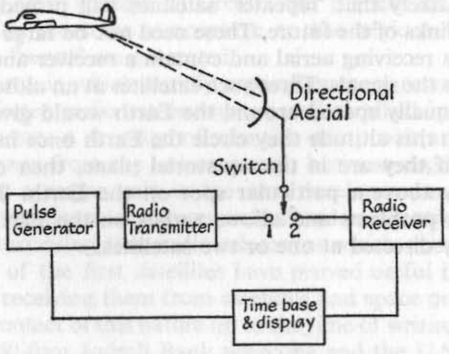

Fig. 20. The basic units of a radar system.

pulses; sometimes a number are sent out before the first returns to Earth.

The reason for the long delay in detecting Venus may now be understood. This planet is about 100 times as far away as the Moon so that a given radar set would provide a signal at Venus 10,000 times weaker than that at the Moon. The reflected signal is then similarly attenuated on its way back to Earth so that, although Venus provides about ten times the reflecting area of the Moon, the signal received back is 10,000,000 weaker than the lunar echo. Clearly a great improvement in techniques was required to overcome this large factor.

This improvement came with increases of transmitter power up to a million watts or more, with improved receivers using masers and parametric amplifiers (section 2.3), with larger aerial arrays (section 1.5) and with improved data processing techniques.

The future of radar astronomy lies in two distinct directions. The first is the investigation of solid bodies, the Moon, the planets, asteroids, satellites and space-probes; the radio wavelengths best suited to these investigations are centimetre waves at which wavelength the parabolic reflectors develop their highest gain. Other investigations will concentrate on meteor trails, the Sun's corona, streams of ionized gas leaving the Sun, planetary ionospheres and the gaseous tails and markers of rockets. Centimetre waves are not reflected from these tenuous gases as well as are metre waves and for these investigations waves in the range about 3 m. to 15 m. will be most effective. Yet longer waves cannot be used because they are reflected by the ionosphere.

8.1 *Meteor astronomy*

Apart from the planets and asteroids, the solar system contains vast numbers of smaller bodies moving in diverse ways. Most of these are small, no more than grains of sand; a few weigh tons. When one of the smaller particles enters the Earth's atmosphere as a meteor it flares for a moment and then disappears. The light comes from a cap of luminous gas thrust ahead of the particle which moves at a typical speed of 90,000 miles per hour. The meteor finally disappears because it becomes so hot that it evaporates; this is not surprising because its kinetic energy is about one million joules per gram compared with a few thousand joules per gram of TNT.

Many broad features of meteor astronomy had been established before the advent of radar. Meteors have been observed visually and photographically by single observers and by pairs of observers. Observed from two stations the trail of a meteor in three dimensions may be found and the orbit of the particles around the Sun determined. On a clear moonless night about ten meteors per hour may be seen by the unaided eye. Occasionally, however, meteors arrive in showers when the Earth passes through great streams of particles, sometimes referred to as 'flying gravel banks'. Under these conditions the meteors all appear to arrive from a single point in the sky called the 'radiant' of the particular shower. This is an effect of perspective, the shower meteors arriving at the Earth from a single *direction.*

The radar method of meteor study developed from the radar techniques of World War II and has been pursued most energetically by A. C. B. Lovell and his associates at Jodrell Bank. The basic elements of the necessary equipment is shown in Fig. 20. The transmitter sends pulses of duration a few millionths of a second at a recurrent rate of several hundred per second. The time delay of the echo is measured on a cathode-ray tube indicator and this immediately tells us the distance of the reflecting meteor trail. The strength of the echo provides an indication of the thickness of the reflecting column of electrons and of the electron density. Finally the rate at which the echo decays indicates the rate of diffusion of the electrons from the original compact column.

From these results it was found that typical meteors, having zenithal magnitudes $+6$ and 0, produced approximately 10^{12} and 10^{14} electrons per cm. path respectively. It was also evident that with simple radar sets and aerials, working in the range 4 to 10 m., all meteors within the visual range of magnitudes could be readily detected and that reasonably long-duration echoes would be obtained. With equipments of higher power, using larger aerials, meteors considerably below the visual range (magnitude $+9$) could be detected.

This facility, together with the fact that radar observations may be made as well during the daylight hours as at night, has led to the discovery of a number of daytime meteor streams. These streams were first observed in 1947 and have been studied in considerable detail. They last from a few days to a few weeks, corresponding to the time taken for the Earth to cross the path of the myriad particles in their orbit around the Sun. A time of passage of one week corresponds to a thickness of the 'flying gravel bank' of about 10 million miles.

With further refinement of the radar equipment various features of meteor trails could be measured quickly and accurately. The heights of large numbers of trails were measured and at the same time the velocities of the meteors. These results are useful in determining the upper atmosphere gas density distribution. Other observations were made of the drift of meteor trails due to upper atmospheric winds; these attain speeds of nearly 100 miles per hour and vary in speed and direction with the time of day.

One important point to be settled by radar astronomy was the possibility of an interstellar origin of some of the meteors. Most meteors are members of the solar system, moving around the Sun in periods of a few years. By measuring the velocities of large numbers of meteors it was shown that they are *all* members of the solar system, having velocities too small to allow them to escape the gravitational field of the Sun.

8.2 *Radar echoes from the Moon*

Radar astronomy of the Moon was initiated by J. H. De Witt and E. K. Stodola using U.S. Army equipment in New Jersey. The transmitter power was low and so, to provide the necessary sensitivity, the pulse length was made long and the receiver bandwidth correspondingly narrow. These results, and others made in Australia, were of considerable interest but the echoes received were not clear and did not provide as accurate distance estimates as desired.

Within the next few years centimetre-wave transmitters with peak powers up to 2 million watts became available and were used at the Royal Radar Establishment in England and the U.S. Naval Observatory in the U.S.A. The high power and the large aerials, 45–50 feet in diameter working at a wavelength of 10 cm., allowed the use of pulses of duration only 2–5 microseconds and receivers with wide-frequency bands. The result was a ranging accuracy of about one-fifth of a mile in a total return path of about 480,000 miles. The result was satisfactory but there were other difficulties inherent in the early equipment and to a lesser extent in the more powerful equipment.

The light we see reflected from the Moon comes from the whole of the illuminated part of its surface. Such is not necessarily the case for radio echoes because of the longer wavelength and it was not known for a number of years whether the power returned to the Earth was reflected from the whole of the visible disk or from a smaller central region. This was a very important point to settle, not only because it would provide information about the nature of the lunar surface, but also because it would determine whether or not the Moon could be used to reflect radio-telephone signals from one side of the Earth to the other. Such a system would provide a very useful communications channel because, although a large amount of power would be needed to cover the 480,000 miles to the Moon and back, the system could be operated at a high enough frequency to be independent of ionospheric effects which plague the present links.

If the Moon echoes came from all over the visible surface, some of them would have travelled about 2000 miles farther than others; this is because the Moon is a sphere of radius about 1000 miles. These signals would be delayed about one-hundredth of a second after the first arrivals and this would cause hopeless distortion of transmitted speech. The answer to this important question lay in the complex fading patterns within the reflected pulses.

The answer was sought with even larger radar telescopes, using the 250-foot reflector at Jodrell Bank and an 85-foot fixed reflector (cut into the ground) in Maryland, U.S.A. The first interesting effect found was slow fading of the returned signal which was caused by Faraday rotation (see Chapter 3) of the linearly polarized waves passing through the ionosphere. Suppose the polarization of the receiving aerial were set, like that of the transmitting aerial, in a north–south direction. In the absence of an ionosphere the full returned signal would be accepted by the aerial. However, in the ionosphere the plane of polarization would be rotated by a varying amount (depending on the number of electrons present) so that sometimes the returned signal would be polarized east–west and would not be accepted by the aerial. This discovery was of interest in its own right because it allowed the electron content of the upper ionosphere to be estimated. This was found to be about twice the value of previous estimates.

The Faraday fading effect was easily removed by using a circularly polarized aerial which has no preferred plane of polarization. When this was done a complex pattern of fast fading remained which was interpreted as due to interference between echoes from different areas of the lunar disk. The echoes showed a power spectrum which was consistent with the reception of signals from only the central part of the lunar disk. Thus the Moon behaves quite differently as a reflector of radio and light waves. The latter are reflected equally well from all over the disk because the irregularities in the lunar surface of rock and dust are large compared with the wavelength. In the same way a sheet of matt, white paper appears uniformly bright when viewed from any direction. On the other hand the radio waves are longer than the small-scale irregularities and the behaviour of the Moon as a reflector more nearly resembles that of a silvered sphere held in a beam of light.

This result was very heartening for the communications engineers, but the full story was not yet told. It now appears that in addition to the above specular reflection there is weak diffuse scattering from the entire visible surface. What had seemed a fairly simple reflection phenomenon has proved most complex and it is proposed to devote half the working hours of the 600-foot paraboloid being built in Virginia (section 1.5) to studies of the Moon as a passive communications relay station.

8.3 *Radar studies of the planets*

If all other factors remain unchanged, the transmitter power required to detect the planet Venus is 10 million times that required to detect the Moon. In view of the original difficulty in detecting the Moon, the more difficult feat of obtaining signals from the nearest planet seemed impossible in those days.

Fortunately there are other ways than increased transmitter power to increase the performance of radar telescopes. There have been improvements in aerial gain, receiver background noise and so-called 'correlation detection' techniques. It was this last factor which played a major part in the successful reception of echoes from Venus by the M I T Millstone Hill radar in Massachusetts. If a single echo from a source is observed on an oscillograph scan it may be so weak as to be invisible among the random noise generated by the receiver. Suppose, however, that we record a hundred or more scans and add them together in such a way that if an echo *were* present it would always occur at the same place on the scan. The hundred weak echoes then reinforce one another while the myriad weak oscillations due to the noise tend to cancel one another. It may be shown mathematically that if a hundred scans are added then the relative strength of the echo to the noise increases by a factor of ten. If 10,000 scans are used then an increase of a hundred is obtainable. By this laborious process it is now possible to increase the performance of a radar telescope by a hundred or more.

An interesting new unit was defined at a meeting of the Space Science Board of the U.S. National Academy of Science. It is the 'millstone', being the sensitivity of the Millstone Hill equipment which succeeded in detecting Venus. It must be 10 million times as sensitive as a radar set capable of similarly detecting the Moon.

When it is closest to the Earth in 1971 Mars will require some some ten millstones for detection and Mercury, Jupiter and Saturn will require about 100, 300 and 10,000 millstones, respectively, during their closest approaches. The asteroid Eros should be observed with 10,000 millstones and the other major asteroids and also Uranus with a million millstones; Neptune will require a further increase to 10 million.

Apart from sensitivity, the radar sets which will detect some of the planets will need a great deal of patience. The signal from Venus was returned in about five minutes but that from Neptune will take nearly ten hours. This will limit the times of day during which observations may be made because the planet must be well above the horizon at the times of both transmission and reception.

During the past decade, radar transmitter powers have increased from about 10 to 1000 kilowatts and receiver sensitivities by a factor of 20 or so (section 2.3). The correlation detection technique gives a gain of about a hundred so that, apart altogether from aerial systems, the overall gain of the systems has been about 200,000 and further increases in these ways are certain. However, the greatest gain in efficiency is available by increasing aerial sizes. An increase in aerial dimensions (the diameter of the reflector) by a factor of 10 gives an increase in overall sensitivity of 10,000. The reason for this large gain is that the same aerial is used both for transmitting and receiving and in each case its power gain increases with its area by a factor of 100. In the case of a normal *radio* astronomy telescope the overall gain is only 100.

Several aerial systems are now being built or planned with performances of 10,000 millstones or more and so will be capable of detecting nearly all the planets and large asteroids. The largest aerials are the 1000-foot hole-in-the-ground in Puerto Rico and the 600-foot steerable paraboloid in Virginia (section 1.5). The former is being built primarily for planetary radar studies and the latter partly for lunar echo studies.

As seen above an increase in aerial size for a given radar wavelength provides a much greater increase in efficiency. Even without changing the aerial dimensions the gain may be increased by using shorter waves. A decrease in wavelength by a factor of 10 say, increases the efficiency or 'gain' of the aerial as a transmitter by a factor of 100. As a receiving aerial the area and hence the power-gathering ability remain unchanged and so the overall radar efficiency increases by a factor of 100. The planets, being solid bodies, reflect as efficiently at short as at long wavelengths and so the former should be used, as short as 10 cm. if the reflecting paraboloid can be made accurately enough to operate efficiently at that wavelength.

A great deal of information will be obtained from radar studies of the planets; the first objective is to accurately determine their distances from the Earth. At present we know the distances to the Sun and planets to one part in a million or 10 million, as long as we express the results in terms of the 'astronomical unit'. However, this unit itself is not known to better than one part in 500. We are very good at measuring angles and so finding relative distances, but we do not have as yet any accurately known baseline. If the time of flight of a radar signal to a planet can be measured to say ten microseconds then the distance is known to about a mile or one part in 26 million in the case of Venus. Distances to all other members of the solar system would then be known to better than one part in a million, more than a thousandfold improvement.

Perhaps the most interesting scientific contribution of planetary radar will be studies of their surface condition. We have already seen in the case of the Moon that the nature of the returned signal depends on the reflecting surface; it also depends on the rotation of the reflecting body as this controls the Doppler frequency shifts from different parts of the surface. We do not even know the rotation periods of two of our nearest neighbours, Venus and Mercury, but these should be revealed by radar studies. When these are known the nature of the reflecting surface may be studied.

8.4 *Other astronomical radar studies*

If a radio wave is able to penetrate far enough into the Sun's ionized atmosphere it eventually reaches a level where the refractive index of the medium is zero and the wave is reflected (section 3.1). However, in its passage through the ionized gas the wave suffers absorption due to the collisions between the electrons and protons. Centimetre waves penetrate deeply into the solar atmosphere to regions where the gas is dense and the collisions correspondingly more frequent. So strong is the absorption of these waves that they are wiped out before they can reach the level of reflection. Longer waves on the other hand are reflected from levels high in the corona where absorption is slight so that the wavelengths used for radar studies of the Sun are in the range 5 m. to 20 m.; at wavelengths above this range the waves are reflected by our own ionosphere.

Theoretical studies show two major difficulties in obtaining solar radar echoes. The first is fairly obvious: the corona has a temperature of about a million degrees Kelvin and so provides a great deal of thermal emission which must greatly increase the noise level in the receiver. Thus modern low-noise receivers are useless for solar radar work. The second difficulty was overlooked in early studies of the problem but is very important. It results from the known fact that the corona is very irregular in form and that reflection would occur, not from a small central portion as for the Moon, but from regions scattered over the whole hemisphere facing the Earth. This would not matter greatly except that the corona rotates with the Sun; gas on the eastern side is moving towards us at a speed of about 3 km. per second, gas on the west side moves away. The waves received from the east side have shorter wavelengths than the original wave, because of the Doppler shift; those on the west side have longer wavelengths. The spread of energy over a wider spectrum reduces the efficiency of the system.

In spite of those difficulties, radar echoes of the Sun were obtained in 1959 at Stanford University using a 12-metre transmitter feeding an array of eight rhombic aerials. The transmission consisted of alternate 15-second on-and-off-periods lasting for 15 minutes, approximately the time of flight to the Sun and back. As the first signals were due to return the transmitter was shut down and the aerial transferred to the receiver. The signal was processed by a digital computer which showed that it came more or less uniformly from a wide range of depths in the corona. This indicates a very irregular shape of the corona and it is hoped that further experiments will permit this shape to be mapped.

The solid surfaces of rockets and space probes will also provide echoes; in this case the advantages of centimetre wave radar sets are available. A set with a sensitivity of one millstone should be capable of detecting a flat metal sheet one metre square, at a distance of 10,000 miles. In order to do so, however, the location of the sheet must be known and also its motion if that is appreciable. In order to *locate* a sheet (or satellite or space probe with equal reflecting efficiency) of unknown position and velocity a much more powerful set is required. With the development of sets with sensitivity 10,000 millstones or more we may look forward to detecting and accurately locating satellites and space probes at distances much greater than 10,000 miles.

One practical application of satellite radars will undoubtedly be their use as passive radiotelephone relay stations (for active or responder relay see section 7.4). The first successful experiment in this direction was made in August 1959, in which speech-modulated radio waves were bounced off a satellite, providing a telephone link across the American continent. The satellite, Echo I, was a balloon, 100 feet in diameter and covered with a thin metal skin. It seems only a matter of time before a few such satellites in suitable orbits will make it possible to relay a television programme to all parts of the world. Whether the results of such a technical achievement are desirable or not may be debatable.

Glossary

Some astronomical and radio terms which are not defined in the text:

ANGSTROM A unit of length equal to one hundred millionth of a centimetre (10^{-8} cm.).

ASTEROID A small planet revolving around the Sun.

ASTRONOMICAL UNIT A unit of length used by astronomers, being the distance between the Earth and the Sun – about $1{\cdot}5 \times 10^{13}$ cm.

BLACK BODY A body which absorbs all incident electromagnetic radiation; such a body is also a perfect radiator, the energy radiated at any wavelength depending only on its temperature, according to Planck's Law.

COSMIC RAYS and COSMIC-RAY ELECTRONS Elementary particles moving at very nearly the speed of light; cosmic-ray electrons are correspondingly high-speed electrons.

C/S cycles per second.

DEGREES KELVIN or ABSOLUTE (°K) A temperature scale with intervals equal to the Centigrade scale and zero at $-273°$ C.

DOPPLER SHIFT The frequency shift due to relative motion of a radiating object and an observer. If the distance between the two is decreasing then the frequency is seen to increase; if the distance is increasing, as for external galaxies, then the frequency decreases and the light becomes more red (the 'red-shift').

ELECTRON VOLT The energy gained by an electron (or other particle having unit electrical charge) when it moves freely across a potential difference of one volt.

FEEDER The electrical connexion between two parts of a radio receiving or transmitting system: for example, between the aerial and receiver.

FLUX DENSITY The strength of a radio (or any other electromagnetic) wave is defined as the amount of power incident per unit area.

GALAXY The Galaxy is the aggregate of stars (including the Sun), gas and dust, which is visible as the Milky Way; countless other galaxies lie beyond our own system.

GALACTIC LATITUDE AND LONGITUDE A system of directional co-ordinates in which the galactic plane (the centre of the Milky Way) is zero latitude.

GAMMA RAYS Electromagnetic waves of length less than about 10^{-10} cm.

HI, HII HI is neutral hydrogen and HII is ionized hydrogen (electrons and protons); HI clouds and HII clouds are interstellar clouds of these gases.

I.C. The Index Catalogue of nebulae and star clusters compiled by Dreyer in 1895 (see also N.G.C. and Messier).

IONS Elementary electrically charged particles; most numerous are protons with a positive charge and electrons with an equal negative charge.

IONOSPHERE The part of the Earth's atmosphere above about fifty miles; so-called because some atoms are broken into ions by the solar ultraviolet and X-radiation.

ISOPHOTE In plotting the strength of radiation from different parts of the sky an isophote is a line along which the strength of the radiation is everywhere equal.

KC/S kilocycles per second.

KELVIN *See* DEGREES KELVIN.

LIGHT-YEAR A distance unit defined as the distance traversed by a ray of light in one year – $9{\cdot}5 \times 10^{17}$ cm.

MC/S Megacycles per second.

MESSIER An early catalogue of nebulae and star clusters, compiled by the Frenchman Messier in 1787 (*see* also I.C. and N.G.C.).

NEBULA An astronomical object other than a single star or a cluster of stars; it may be an external galaxy, or a cloud of gas or dust.

N.G.C. The New General Catalogue of nebulae and star clusters compiled by Dreyer in 1888, containing many fainter objects than those listed by Messier. Nebulae are frequently referred to by their N.G.C. number (or Messier number).

PLASMA Gas whose atoms (some or all) are ionized.

QUANTUM Electromagnetic waves, including radio and light waves, travel as small, more or less discrete packets of energy called quanta.

RADIO NOISE Any body which is not absolutely cold generates radio waves or oscillations of a random nature and spreads over a wide band of frequencies. If these waves are amplified and made audible they provide a hissing sound and so are called radio noise.

RED-SHIFT *See* DOPPLER SHIFT.

SOLAR MASS It is convenient to measure the masses of stars and nebulae in terms of the mass of the Sun – about 2×10^{33} gm.

SPECTROSCOPE, SPECTROGRAPH Devices for observing and recording spectra, the relative strengths of radiation (light or radio) at different wavelengths.

STERADIAN The unit solid angle being $\frac{1}{4\pi}$ the solid angle subtended by the whole surface of a sphere at its centre.

SUPERHETERODYNE A type of radio receiver in which the frequency of the received signal is changed before amplification.

SUPERNOVA The result of a catastrophic explosion of a star, comprising a smaller star and an expanding gas cloud.

ZENITHAL MAGNITUDE The magnitude of a star or meteor is a measure of its brightness in a logarithmic scale. The ZENITHAL MAGNITUDE of a meteor is the magnitude if the meteor were at the same height but in the observer's zenith. A larger magnitude denotes decreased brightness.

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