RADIO ASTRONOMY

Chapter 1 - Birth of Radio Astronomy.

Radioastronomy is a new branch of astronomy which is concerned exclusively with the study of the radio waves that are constantly reaching the Earth from the Universe around us. For centuries past optical astronomers have studied the light waves which originate in various natural processes throughout the cosmos, and from this have built up a remarkably detailed picture of the countless millions of star systems with which the skies are studded. Since the beginning of time electrons in motion throughout the universe have also radiated radio waves, but it is only within the past two decades that electronic techniques have reached the stage where study of these radio signals from space has become feasible. Radioastronomy is thus making it possible to paint a picture of the heavens in a completely new "light", that of the radio waves. Those engaged in this work have been christened radioastronomers and, naturally enough, the instruments they use have come to be known as radiotelescopes. In the excitement of the early discoveries what the radioastronomers "saw" with their strange new instruments were called "radio stars" because they did not coincide with any of the bright visible stars. However, this picturesque name has turned out to be a misnomer because with the exception of our Sun, perhaps a few nearby stars and possibly also the curious objects known as pulsars (see Chapter), the majority of them are almost invariably not stars at all, but electrons at work in other spectacular ways.

The particular advantages of using radio methods in astronomy which first caught the attention of serious astronomers were firstly, that they often provide new as well as confirmatory information about some of the celestial objects that they have been studying for centuries; and secondly, that they have drawn attention to things not optically visible at all, either because they are beyond the range of optical telescopes or because, by their nature, they emit radio waves rather than light waves. This comes about because although light and radio are both electromagnetic waves, they can arise from somewhat different processes within the atoms. Radio-astronomy thus both supplements and complements the traditional optical methods, and in providing a new look at the Universe around us has focused attention on some remarkable and quite unexpected features which might otherwise have gone unnoticed for further centuries. It is scarcely surprising that in the process, it has raised more questions than it has so far been able to answer. Man, however, has always been intrigued and mystified by the "wondrous splendours of the everlasting stars", and the marvel is that we should have been able to uncover so much about objects which exist in such countless numbers and at such fantastic distances from us that we gaze at them, as it were, down the long corridors of time. Even though light travels at the rate of 186,000 miles each second, many of them we see as they existed before the Earth was born, not as they are now. But perhaps we should begin at the beginning and take things step by step.

Astronomy is the oldest of the sciences. From the dawn of time the Sun by day and the majesty of the heavens by night were, for primitive man, an awe-inspiring reminder of his insignificance in relation to the capricious forces which governed all aspects of his constant struggle to survive. As tribal life developed he gradually came to recognize that, against a background pattern of stars which were apparently fixed in the firmament, the Sun by day and the Moon by night followed their own recurrent patterns in their daily travel across the sky. He observed too that these were connected in some way with the regular progression of the seasons, and the periodic death and subsequent rebirth of the life-giving forces of Nature. The foundations of observational astronomy thus were laid well before the end of recorded history. In a community ruled by awe and riddled with superstition the keen observers naturally acquired power and prestige as they discovered how to foretell such dramatic national events as eclipses. The first astronomers were thus the witch doctors and high priests; in their hands astronomy remained closely linked with superstition and religion until well into mediaeval times. Considering the exceedingly primitive methods of observation available to them they showed remarkable skills. The concept of a year divided into twelve months each of 30 days, and of days divided into hours, minutes and seconds was already well established by 2000 B.C. By about 500 B.C. the early astronomers had collected enough detailed information to be able to recognize virtually all the intricate periodicities which regulate the occurrence of eclipses of the Sun and Moon - and hence to predict them, with conspicuous success, well in advance.

As long as observations of the heavens were limited by the powers of the unaided eye it is understandable that the stars were regarded as fixed and immutable, and of little account in the scheme of things. They were taken to be distant but by no means numberless, since the number that could be counted on a clear night only ran into several thousand. Interest was centred mainly on the Sun, and its family of planets, and on the Moon, with the Earth as the fixed centre around which all else whirled in complicated motion. This misconception, taught and reinforced by the famour Greek natural philosophers Aristotle and Ptolemy, became firmly embedded in the doctrines of the Church of Rome and remained in vogue until well into the seventeenth century A.D. Copernicus, the founder of modern astronomy was the first to expound the view (1543) that the Sun and the stars were at rest and the earth revolved around the Sun; but this concept did not gain acceptance until more than a century later. The introduction of the telescope - a Dutch invention - by Galileo in 1610 began to produce evidence which could not be reconciled with the Aristotelian outlook - of "imperfections" on the Moon for example and changes on the surface of the Sun - and Galileo suffered harsh treatment at the hands of the Inquisition for holding and expounding such heretical views. He applied his primitive device mainly to observations of the solar system, but with it he noted a great increase in the number of visible stars and expressed the view that the Milky Way probably consisted of a very large number of individual stars. The telescope opened the way to explortation further afield and the first major step out into space came late in the 18th century at the hands of the Herschels, father and son. With their telescope of aperture 48" they gazed out at the Universe and saw it as a gigantic mass of indivual stars, moving as a whole around their common centre of mass.

The modern view of the cosmos is of an enormous number of "island universes" enormously remote from each other, each consisting of countless millions of indivual stars separated from each other by such fantastic distances that the average density of space is not far from that in a vacuum. Our whole Milky Way system of stars is just one of these island universes.

This remarkable picture stems from the detailed work of Hubble and his associates in the years since 1920, with the aid of the series of large optical telescopes that have been perfected in the U.S.A. - notably the 100" at Mt. Wilson and the 200" at Palomar. As the astronomers sharpened their techniques for measuring distances in the almost unimaginable vastness of space has come the realization that the Universe is not only limitless, but apparently expanding, because all the galaxies*

*A galaxy is the name given to an aggregate of stars, numbering hundreds of millions which originated from the same dust cloud, and so belong to the same system. The Milky Way of which our Sun is a member is such a system and is usually referred to as the Galaxy. A radio source located within it is a galactic source; radio waves which come from outside are extragalactic seem to be rushing away from each other the faster the further away they are. This apparent expansion of the Universe as a whole is deduced from the fact that radiation from a source which is receding shows a Doppler shift towards the red, i.e. is shifted to longer wavelengths by an amount which depends on its speed of recession. Light waves from remote galaxies show such Doppler shifts.

It was in this context of an exploding Universe that radio astronomy was born - not as a deliberate effort to forge a new tool for the further exploration of space, but as an elegant exercise in modern electronics, in the hands of a band of enthusiastic radio engineers and physicists who were keen to explore some of the anomalies that had been revealed during the major World War conflagration of 1939-45. It was soon clear that the world of radio stars which they revealed was the familiar world of the optical astronomers viewed through a completely new window through the atmosphere, one that gave wider perspective, new information and more distant views. Figure 1.

Cosmic Radio Waves

Several years after the historic discovery of radio waves by Hertz in 1887 the first recorded suggestion that such waves might originate in the Sun and perhaps be detectable here was made by Thomas Edison (1890). If he did try to detect these waves he was obviously unsuccessful, as was also Sir Oliver Lodge, who made an attempt to do this some time between 1897 and 1900. This was scarcely surprising since amplifiers had not then been invented and the best available receivers relied on crude "coherers" made of metal filings as detectors. There are no further recorded attempts to receive radio emission from the Sun for almost 50 years, when advances in radio receiver techniques, aided by the revolution in electronics which had been stimulated by the forced-draught developments of of World War II, had reached the stage where detection of the solar radio waves was beginning to be feasible.

Radio Waves from the Milky Way

The first radio waves of extra terrestrial origin to be detected came however not from the Sun but from the direction of the Milky Way - thanks to a nice piece of detective work by Karl Jansky, a young radio engineer of the Bell Telephone Laboratories, New Jersey. Jansky had been assigned the task of investigating the incidence of a form of interference known as "static" on the short-wave radio circuits in the 15 metre* band which were coming into use in the early 1930's. Jansky found that, unlike at the longer wavelengths (which had been the only ones available before) static was generally at a low level except when there were active thunderstorms nearby. However, he noted that a very steady form of interference which sounded like a hiss was continuously present and that its direction of arrival changed steadily throughout the 24 hours. In January 1932 he recorded "during the month of December this followed the Sun almost exactly, making it appear that perhaps the Sun causes this interference, or at least has something to do with it". However by February 1932 he realised that the direction of arrival was no longer following the Sun but was preceding it in time as much as an hour. As the months went by the deviation from the Sun's direction continued to increase steadily, ruling out any seasonal effect, and Jansky finally came to the conclusion that the disturbances were of extraterrestrial origin, coming from "a direction that

* Radio waves may be specified either by their wavelength or by their frequency (f): they travel with the velocity of light (c) so $f \times \lambda = c$. If f is expressed in megahertz (megacycles per second) and λ in metres then $f \times \lambda = 300$, i.e. radio waves of frequency 20 MHz have a wavelength (in air) of 15 metres.

always lies in a plane that is fixed in space". This direction coincided with that of the centre of our Galaxy, the Milky Way in the constellation Sagittarius. He concluded that the source of these radio waves must lie "either in the stars themselves, or in the interstellar matter distributed throughout the Milky Way". Jansky was thus the first to observe radio waves of extra terrestrial origin whose source was not the Sun but the Galaxy. The historic paper announcing his discoveries was published in 1933 and several others describing aspects of his findings followed soon after. Somewhat later he was transferred to other duties and took no further part in the aerial exploration of cosmic "noise" - so called because the sound of the extra terrestrial signals resembled that of the valve and circuit noises with which radio engineers were familiar. Except for another lone American worker, Grote Reber, interest in radio astronomy appears to have lapsed. Reber, a keen radio amateur who had "worked all continents" and was looking for other fields to conquer, was inspired by news of Jansky's discoveries and decided to explore the way in which the intensity of cosmic static varied with position in the sky, and at different wavelengths. He decided that the only feasible type of antenna system would be a parabolic reflector or mirror and thus pioneered the idea of the paraboloidal antenna for use in radio astronomy. In his spare time, and using his own funds, he produced a wooden dish 31 ft. 5 ins. in diameter and surfaced with galvanized iron in the remarkably short time of four months, from June to September 1937: the original dish is now preserved at the American National Radio Astronomy Observatory, Greenbank, West Virginia (Plate 1).

Reber's first attempts were made at a wavelength of 9 cms., which was near the shortest wavelength then attainable. He found no signals which were unquestionably of celestial origin, nor was he any more successful when he built himself new equipment for use at 33 cms. By then he was convinced that he needed higher sensitivity and to work at longer wavelengths, so he revised and rebuilt his receivers for use at 187 cms. First tests provided quite a shock "since all kinds of man-made electrical disturbances could now be heard which were not known to exist" - chief among them that due to automobile ignition. However, during the nights in the early spring of 1939, unmistakeable evidence was obtained of cosmic static from the direction of the Milky Way. After further improvements to his equipment Reber carried out a complete survey of the skies and by 1944 produced the first radio map of the heavens. The varying contours showed that there were a number of subsidiary maxima within the Milky Way, notably in the constellations of Sagittarius, Cassiopeia and Cygnus. Portion of this is shown in Figure 2, together with a section of a more modern survey.

Radio Waves from the Sun

The point at which radio waves from the Sun were first detected and recognized is obscured by the fact that this occurred during World War II, when the normal free interchange of scientific information was interrupted by the requirements of secrecy. G.C. Southworth and his colleagues at the Bell Telephone Laboratories, Holondal, New Jersey, U.S.A., were almost certainly the first to receive solar radio waves. This occurred on 29th June, 1942, when they pointed their antenna at the Sun and noted an increase in the noise output from the receiver, at a wavelength of 3.2 cms. About a week later they obtained similar results at 9.8 cms. , and made further observations at intervals during the following months, as their wartime activities permitted. Reber, about a year later, discovered quite independently that he could receive radio waves from the Sun and was actually the first to publish evidence of this. In retrospect, however, It is clear that solar radio waves had made their presence felt as early as 1936-37, when a number of keen short-wave listeners had reported hearing strong hissing sounds from their receivers: these occurred only during daylight hours, and sometimes just before the onset of a radio fadeout. These were years of maximum sunspot activity, but the "noise" was not then recognized as being of solar origin. Again, in February 1942, Army radar sets in England, scanning the skies for signs of approaching enemy raiders, reported strong signals which were noise-like in character and moved in position during the day, but were always within a few degrees of the Sun. They were recorded as almost continuously present from dawn to sunset on 27th and 28th February 1942. Subsequent analysis by J.S. Hey of the bearings and elevations measured at widely separated sites throughout Great Britain provided strong evidence that the disturbances were of solar origin. Southworth's results, however, were not formally published until 1945, and Hey's until 1946.

A significant step in the history of radio astronomy was the decision by (the late) J.L. Pawsey of the Radiophysics Laboratory of the Australian Commonwealth Scientific and Industrial Research Organization (the "C.S.I.R.O."), located in Sydney, to investigate reports he had received from Hey of the intense radio "noise" from the Sun which had jammed British radar sets in 1942. Using an improvised receiver connected to the aerial of a Royal Australian Air Force radar station near Sydney, Pawsey, McCready and Payne Scott first detected the Sun on 3rd October 1945 at a wavelength of 1.5 metres. Daily observations were continued and soon revealed a picture very different from that found by Southworth at centimetre wavelengths: the general background level was enormously higher, corresponding to that from a black body at a temperature of about a million degrees, and superimposed on this were increases which showed a day-by-day correlation with the visible sunspots. D.F. Martyn, also of the C.S.I.R.O. explained the high observed temperature as due to the fact that radio waves of metre wavelengths have their origin in the solar corona, not in the photosphere in which the Sun's light chiefly originates and which we know to be at a temperature of about 6000°C. Shorter radio wavelengths come from lower levels in the solar atmosphere where the temperature above that of the photosphere, but lower than that in the corona.

The correlation with sunspots was investigated by Pawsey and his colleagues in a now famour series of observations which began at Dover Heights, near Sydney on 7th February 1946, using a radar aerial system located on the edge of a cliff 280 feet above the sea. See Plate II. These observations mark an important historic milestone in the development of radio astronomy because they represent the first use of an interferometer to perform accurate direction finding on an extraterrestrial object. (Interferometers are devices in which two or more aerials are combined in such a way as to simulate the direction-finding ability of a much larger aerial system, and are dealt with more fully in Chapter 3.) In the following days Pawsey and his colleagues established that locally-emitting regions were present on the Sun and that these were associated with the regions in which sunspots were visible. It is perhaps a fortunate coincidence that one of the largest single sunspots ever to be observed should appear just when radio interferometer techniques were ready to be tried out for the first time. New ventures in science are rarely rewarded so generously, or so promptly as followed on this occasion. These early discoveries were reported in letters to the English scientific weekly "Nature", and were the first of a series of some thousands of scientific papers on radio astronomy which form an important part of the documentation of this new branch of science.

The Dover Heights observations mark the beginning of a continuing series of studies of the radio Sun in which

Australian radio astronomers have continued to take the initiative. Another key observation was made in Sydney on 8 March 1947 when one of the greatest outbursts of all time was recorded (Fig. 3). "Outbursts" are the sudden increases or "outbursts" of solar emission which Appleton and Hey in England had found to be associated with solar flares. Striking features of the record obtained on that morning are the very great intensity, corresponding to a black body temperature greater than 10^{13} degrees Kelvin, and the progressive delay in time of arrival high frequencies first, low frequencies last. The latter feature prompted Wild and McCready to develop a receiver which could be tuned rapidly over a wide range of frequencies: this was the first of a series of "radio-frequency spectrographs" which have proved invaluable in the xxx study of the Sun, and led to the discovery of a series of short-period disturbances in the solar atmosphere. The first and most spectacular of these was recognition of a disturbance moving outwards in the solar atmosphere, exciting plasma oscillations at successive levels on the way, as the source of particles streams ejected from the Sun. These particles are responsible for magnetic storms and major disturbances in the ionosphere when they enter the earth's atmosphere some 36 hours later. Radio studies of the solar atmosphere have continued in Australia more actively perhaps, than anywhere else in the world: the most recent contribution to observational techniques in this difficult field has been the Culgoora Radioheliograph developed by J.P. Wild at the CSIRO Radiophysics Laboratory. This remarkable device provides radio pictures of the Sun at a wavelength of 3.75 metres at the rate of two per second, one in xx each of two planes of polarization, and this effectively continuous watch has already led to clarification of some of the complex phenomena which take place in the solar atmosphere. A fuller account of work on the radio Sun is given in Chapter .

Radio Stars

Another of the historic "firsts" made from the cliff tops at Dover Heights, near Sydney, was the discovery and identification of the first radio stars. While Reber had found subsidiary maxima embedded in the Milky Way, and Hey and his colleagues in England had located sharply-defined peaks in the strength of the radio waves in the direction of the Galactic Centre, and in the constellation Cygnus, it was J.G. Bolton and G.J. Stanley who first showed (in 1947) that the Cygnus source was less than 8 minutes of arc in diameter, that is, effectively a "point" source. This was also demonstrated shortly afterwards by Ryle and Elsmore in England.

Bolton and Stanley observed with the cliff interferometer which had previously been used for solar observations. They pointed their aerial toward the eastern horizon and detected radio sources as they rose above the sea. In addition to the source in Cygnus, which they named Cygnus A*, they found several other sources, and located their positions with sufficient accuracy to be able to identify one of them (the Crab Nebula in the constellation Taurus) with a visible object. This, the first radio source (apart from the Sun) which could also be seen optically,

---

FOOTNOTE (to Cygnus A)

The first system of naming discrete sources, introduced by Bolton, used the name of the constellation followed by a letter indicating the order of discovery. Ryle, Smith and Elsmore (Cambridge) introduced a system based on the hour of right ascension followed by a serial number beginning from .01. Mills introduced a grid reference system using the hour of right ascension and the sign (+ or -) and tens digit of the declination. Bolton's source Cygnus A is thus 19.01 according to the Cambridge system, and 19+4 in the Mills' catalogue. As increasing numbers of sources were located it became necessary to adopt a more refined classification and that now universally used is a grid reference system similar to that introduced by Mills, but making use of the hour and minutes of right ascension, together with the sign of the declination and its value in degrees. The modern nomenclature for Cygnus A becomes 1957+40.

is associated with an unusual object the remains of an exploding star, or supernova, observed by Chinese astronomers in A.D. 1054. Bolton and his colleagues found also that two nebulae, NGC 4486 and NGC 5128 coincided within their limits of error with two other radio sources. No celestial object appeared to correspond to the Cygnus source, however, and it was not until some years later that this was identified. The need for a radio telescope providing a fine pencil beam for accurate position finding was the challenge which led B.Y. Mills of the Australian C.S.I.R.O. to develop the cross xxxxxx antenna which bears his name (see Chapter), and Mills was the first to draw attention to a nebulous object near the position of the Cygnus source. However it was a more precise position found by Smith, and Elsmore at Cambridge which led Palomar astronomers, Baade and Minkowski, to undertake a special study of that area with the 200" telescope. This proved to be a highlight of the early achievements in radioastronomy because the radio waves turned out to be coming from what the astronomers interpreted as two galaxies in collision, a cosmic catastrophe taking place in such a remote corner of the Universe as to be near the limit of visibility with the world's largest telescope - and yet the object "shines" as the second brightest radio star in the skies. Advances in astronomy have invariably followed the introduction of new methods of observation, and the advent of radio techniques has been no exception. The implication that horizones could be extended well beyond their present limits by the use of radio methods did much at that time to confirm radio astronomy as the most promising new development to have appeared for many decades.

At the outset despite the fact that the original work on cosmic radio waves had been done by Jansky and Reber in the U.S.A., virtually all the pioneering developments in this new field xx were carried out in Australia and England. As new discoveries were announced, and the scope and power of the new methods of observation became apparent larger and more sophisticated radiotelescopes have appeared until every major country of the world has now built up advanced facilities for work in this field. In the process the parent technologies of radio and electronic engineering have been set new goals and given new impetus by the demands of the astronomers. The need for receivers of very low noise level, for example, has led to the development of new devices and new amplifying techniques which make possible the attainment of sensitivities that were undreamt of scarcely a decade ago, - and have been of immense benefit in connection with the programme of space exploration by satellites. However the motive for and end product of these investigations is primarily a better knowledge of the physical processes at work throughout the cosmos - and satisfaction of man's eternal curiosity to know more about the origin of the Universe and of life itself. Scientists agree that conditions for life as we know it almost certainly exist elsewhere in the Universe: so far there is no sign of intelligently modulated signals amongst the spectrum of cosmic radio waves, but the recent discovery of emissions from such molecules as water, ammonia and formaldehyde provide clear evidence that not only the conditions but also that the necessary ingredients for life are apparently present in abundance at many points within our Galaxy.