Chapter 4 - The Nature and Distribution of Radio Sources

The basic observations in radio astronomy are the sky surveys, which provide details of the variations in radio brightness across the sky, and lists of the positions of the prominent radio sources derived from them. This is tedious and difficult work, calling for extremely stable equipment, a detailed knowledge of the radiation pattern of the aerial system and of its inherent errors, and good physical insight in the interpretation of the results. The first such contour map of the radio sky was drawn by Reber from his observations at 160 and 480 MHz: it showed concentrations chiefly in the constellations of Cygnus, Cassiopeia and Sagittarius. Many other observers have carried out surveys at other wavelengths, mostly with aerials of low resolving power, but two which were outstanding at the time of their publications were one made in 1958 by Hill, Slee and Mills in Australia (using the Cross which bears his name) on 3.5 metres, and the other, also in 1958, by Westerhout in Holland on 22 cm. Portion of the Mills survey is illustrated in Figure 1. It shows local concentrations, the discrete sources, embedded in a general background of emission.

The first list of discrete radio sources was published by Bolton from his observations at Sydney: it contained 22 entries. Shortly afterwards Ryle, Smith and Elsmore at Cambridge (England) compiled a catalogue of 50 radio stars. The first of the major catalogues, however, was based on the second Cambridge, the 2C, survey, carried out in 1953. It used a four-aerial interferometer at a wavelength of 3.7 metres and listed nearly 2000 sources. Rather poor agreement with the results obtained by Mills in the case of sources located in the portion of sky common to both surveys highlighted the difficulties and weaknesses of position measurements by means of interferometers. Interferometers tend to have a many-fingered lobe pattern, so that sources can be recorded via side lobes even when the aerial is not pointing directly at them. A second cause of misleading results is that sources close together may blend together, unless the aerial beam is very narrow, to produce a composite deflection of the pen recorder, which may provide a completely false picture of the position and brightness of the individual sources. This effect is known as confusion. Mills's survey had the benefit of a nominal pencil beam instrument, and, although not without errors, was much more reliable. Most of the inherent errors were overcome in the later Cambridge 3C survey, which was done at a wavelength of 1.9 metres and lists 471 sources.

The most reliable of all source catalogues so far available is that made with the Parkes 210-ft radio telescope, whose surface accuracy and mechanical stability had previously been carefully studied. The Parkes list includes over 2000 sources in the declination range from 27° N. to the south celestial pole. The initial finding survey on which this is based was carried out at a wavelength of 75 cm, where the telescope's beamwidth is about 3/4°. Observations were made by scanning the skies in a square search pattern at a telescope drive rate of 2¼° per minute: some typical scans are shown in Figure 2. Sources are usually visible on two or three adjacent scans and their positions can be gauged to about 5 minutes of arc. Each source was then observed again at a wavelength of 21 cm to be determined a more precise position, which was confirmed by observations at 11 cm and sometimes also at 6 cm. An example of the detail available at the latter wavelength is given in Figure 3. The Parkes catalogue thus provides a basic list of positions which are accurate to 1 minute of arc, together with the intensity at three wavelengths - i.e. information about the spectra of the sources. For some 700 of these objects a special series of observations made near meridian transit have yielded position coordinates accurate to within 15 seconds of arc.

Identifications with Optical Objects

The ratio of radio to optical brightness varies widely among radio sources, most of the plane in our own solar system being at the low end of this range and only detectable because of their relative nearness, while the spectacular emitters known as "radio galaxies" are at the upper end of the range. These objects are of great cosmological significance because they appear to offer means of probing depths of the universe that are beyond the useful range of optical telescopes.

The earliest identifications with objects outside our solar system were put forward by Bolton and Stanley based on their observations with the cliff interferometer near Sydney and during an expedition to New Zealand. They were able to put an upper limit of about 7 minutes of arc to the size of sources in the constellations of Taurus, Virgo and Centaurus, and better than this on a source in Cygnus that had previously been reported by Hey in England , and were the first to establish that the sources were discrete entities. When star charts for these regions were searched for unusual objects the first three mentioned above were found to coincide to within the error limits, with visible nebulous objects. The first of them, the Crab nebula, was known to be the remnants of a supernova, and the associated expansion turbulence and high electron temperature known to exist from optical observations suggested that conditions favouring the production of radio frequency emission might well be present also. The other two objects also had unusual features; one of them M87 in Virgo is unique in having a pronounced jet emerging from its nucleus, and the other, NGC 5128 in Centaurus, a pronounced bar of absorption across it. There was no apparent optical counterpart for the Cygnus source, and despite a number of attempts it was not until some three years later that this, the second most powerful radio star in the skies, was identified. The Australians, Mills and Thomas, after along and careful series of observations with the

Mills Cross, found that many faint stars and one extragalactic nebula lay within the error limits of their position, and when Smith of Cambridge obtained a similar position with smaller probable errors Baade and Minkowski made a close examination of it with the 200" Palomar telescope. They found that what had appeared to be one galaxy was an irregular-shaped object whose spectrum showed emission lines of unusually high excitation, and a red shift indicating a distance of 550 million light years (see Plate XII). This was originally interpreted as two galaxies in the process of colliding with each other, the energy for the radio emission coming from that released in the collisbn . This explanation is no longer accepted, however, and Cygnus A is now regarded as one of a special class of objects which have been christened radio galaxies. The source of their energy release is still a mystery.

The difficulties experienced in tracking down the powerful but extragalactic source in Cygnus suggested that some at least of the several thousand other known sources may well be of similar type but even further away from us, and hence even fainter optically. The rate at which new identifications have been made in subsequent years has tended to confirm this. The process of searching for identifications has been to examine a star chart of the region surrounding the source position, e.g., the Palomar 48-inch Sky Survey. The large amount of detail shown on these plates in most parts of the sky emphasises the difficulty in securing identifications unless the radio position can be accurately specified. The number of new identifications has increased in recent years with the availability of more accurate position data, but a limit is necessarily set by the faintest objects recorded on the survey plates. This is rapidly being approached. Of the 2500 sources list in the Parkes catalogue, for example, some 450 have been identified, of which 38% correspond to galaxies, 26% to quasi-stellar objects (see Chapter). The remainder have not yet been identified - presumably most of them are galaxies beyond the limit of the Sky Survey plates. The task of searching for identifications has been somewhat simplified with the aid of modern computers, a typical procedure being to store coordinates of a selection of the brighter visible stars and when a source position has been found have the computer produce a plot on a transparency of the ten nearest visible stars, together with the rectangle for the radio source. This overlay can then be placed direct over a Sky Survey plate with the aid of the reference stars.

Types of Sources

Sources can conveniently be grouped according to their distance from us, i.e., within the solar system: galactic, i.e. belonging to our Milky Way system; and more remote extragalactic objects.

Solar System

The Sun is the outstanding emitter of the solar system, both of thermal radiation as a result of the high temperatures existing in its gaseous corona, and of non-thermal emission associated with radio spots (analogous to the well known sun spots) and accompanying storms and explosions within the sun itself. These are discussed in detail in Chapter 5 below.

Thermal radiation from the Moon shows that on the whole it behaves like a black body at 250°K. Considerably higher sensitivity is required to detect thermal radiation from the planets. Mars was the first to be detected (1956) at a wavelength of 3.15 cm, followed by Venus, Saturn, Mercury and Jupiter. Jupiter, however, had figured in a surprise discovery in 1955, when Burke and Franklin announced that they had observed intense and variable bursts of emission from it in wavelengths of 13.6 and 8.6 metres. Following this announcement Shain found that there were many instances of Jupiter's burst on records he had obtained at Sydney, with a longer wave version of the Mills Cross. They had been mistaken for bursts of static, which they resembled. This radiation is strongly polarized, indicating the presence of a magnetic field on Jupiter, and has been identified as originating from synchrotron processes in Van Allen belts surrounding Jupiter. Non-thermal radiation has not been detected from any of the other planets.

Radio emission from the planets is dealt with more fully in Chapter 5.

Galactic Sources-

The modern view of our galaxy as one of a countness number of star systems, or island universes, enormously remote from each other and floating separately in the fathomless depths of space, stems largely from the work of Hubble and his successors with the aid of the 100-inch telescope at Mount Wilson and the 200-inch at Palomar. Our Sun and the whole solar system amount to an insignificant speck on this assemblage of some 10,000 million stars which are distributed as a lens- or disc-shaped aggregate of diameter about 30,000 parsecs,* whirling majestically about a common centre once every years (see Fig. 4). The Sun is some 10,000 parsecs from the centre of the Galaxy, which is situated in the constellation Sagittarius, but is not visible because our view in that direction is severely curtailed by clouds of absorbing material. Optical observations show that most of the stars are situated in the galactic disk but that there are also a large number of globular clusters distributed almost uniformly within a sphere of diameter 40,000 parsecs. In some areas there are

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*Astronomers specify distances in either parsecs or light years. A parsec is the distance at which the Earth's orbit would subtend an angle of 1 second of arc: a light year the distance travelled by light in one year at the rate of 186,000 miles per second - i.e. miles. One parsec equals 3.26 light years.

clouds of hot ionized hydrogen, or HII regions. In addition, and severely restricting the optical view in many directions, there are clouds of absorbing material, referred to as "dust" clouds and consisting of atomic debris large enough to intercept light waves - possibly predominantly of carbon. The dust clouds, however, are effectively transparent to radio waves so that radio astronomy makes it possible to "see" regions which have previously been hidden from us, and thus to supplement in important ways the picture of the skies as derived from optical observations.

The various sources of radio frequency emission within the Galaxy are as follows:

Background Continuum

Sky surveys show that radiation covering the whole range of wavelengths observable in radio astronomy is received from the Milky Way. On metre wavelengths this is extremely strong but weak at centimetre wavelengths. It is made up of two components, a narrow band a few degrees wide which follows the galactic equator, and a weaker component extending over the whole sky. The former is referred to as the disk component and the latter as the halo. Numerous more compact sources are superimposed on this radiation, as mentioned below.

The brightness temperature of the background at long wavelengths (in excess of 250,000°K at 15 metres) is so great that it clearly cannot be of thermal origin; for many years its origin was a mystery but there is now no doubt that it comes from high-energy electrons spiralling in a magnetic field. The existence of high energy electrons in interstellar space is clearly indicated by the presence of the cosmic rays as observedon Earth, and of magnetic fields in the Galaxy by the polarization of light from stars, and also by the Faraday effects observed by Gardner et al. on radio sources. The disk component is generated in the magnetic field which exists within the spiral arms; the halo is almost certainly produced also by the synchrotron process acting in the more general but weaker field in which the Galaxy is immersed.

At decimetre and shorter wavelengths thermal radiation is much weaker and difficult to detect. A large part of the radiation received at these wavelengths comes from a very concentrated zone along the plane of the Galaxy and consists of thermal emission from the ionized hydrogen which is present between the stars: at a wavelength of 22 cm the thermal and non-thermal components of the disk radiation are about equal.

Gaseous Nebulae - Hot Hydrogen

The ultra-violet radiation from a star will heat any hydrogen clouds which happen to be in the vicinity - up to 150 parsecs away for the hottest stars - to a temperature of the order of 10,000°. In this mass of ionized gas,free electrons are accelerated as they pass near protons (free-free collisions) and emit radio waves over a continuous spectrum - i.e. the energy radiated per unit frequency interval is independent of frequency. Some light is also emitted from the ionized gas clouds, not only that characteristic of hydrogen but also that of other ionized atoms present, such as helium, oxygen, etc.

The dimensions of most of the gas clouds are rather small, but the larger ones, particularly the closer ones from some of the attractive nebulae to be seen with a small telescope or on photographic. Examples are the Orion nebula, the Rosette nebula, the Omega nebula (see Plate IV, page). Most of the visible nebulae of this kind are radio sources, and in addition a number which are not visible optically, presumably because of absorbing material in their line of sight.

Neutral Hydrogen - HI Regions

In the vicinity of stars the interstellar gas chiefly of hydrogen is hot and ionized but in the vast spaces between the stars it is cold, 100°K or colder, and optically invisible. In the ground state of the unionized hydrogen atom, however, there happens to be two possible levels, the quantum of energy given out when the electron flips from one position to the other being appropriate to a radio wave of just over 21 cm wavelength (exact frequency 1420.403). The probability of this happening for an individual atom is very low - only once in some millions of years - and the density of interstellar gas is also very low - 1 to 100 hydrogen atoms per cubic centimetre - yet the dimensions of the Galaxy are so great that there are enough transitions taking place to produce H-line radiation that can be detected. Radio emission originating in this way turns out to be extremely important because it provides the only available means of locating the neutral hydrogen in the Galaxy, which amounts to 1-2% of its total mass. In Chapter 8 we will see how detailed studies of the distribution of the unionized hydrogen reveal that it is located in distinct arms and hence that our own Galaxy has the spiral catherine-wheel structure that we can see in so many of the other galaxies   island universe with which the skies are studdes.

Supernova Remnants

The [illegible] first discrete source to be separated from the galactic background was a supernova, the Crab nebula, discovered by Bolton and Stanley at Sydney in 1947. This well-known nebula, M1, the first entry in a catalogue of nebulae compiled by the French astronomer Messier in 1784, is all that remains of a star that exploded to a brightness greater than that of the planet Venus for a few brief days in 1054 A.D. The remnants are still expanding. Conditions favouring the production of radio waves are present in such bodies, and a number of other supernova remnants have also been found to be radio sources. After the Crab that in Cassiopeia is perhaps the next best known, and this is the brightest of all the radio sources. These are discussed in more detail in Chapter 7.

Flare Stars

The radio emission from our sun during its most active periods (see Chapter 5) reaches levels which suggested that emission of this kind from stars of similar type could perhaps be detected. Certain stars, known as "flare stars" are observed to exhibit occasional short-period increases in visual brightness and a number of these have therefore been kept under observation to see whether they also emit radio waves at times of these flares. A number of significant coincidences in increases in optical and radio brightness have been observed and there is little doubt flare stars are to be included in the count of galactic sources. So far stars can be listed in this category. Figure shows coincident increases observed at Parkes for V371 Orionis.

Pulsars

A completely new and different kind of source which must be counted as galactic are the pulsed radio sources or "pulsars" which were discovered in 1968. These objects emit short pulses of radio frequency energy with periods which are remarkably constant and range for the pulsars so far discovered from about 1/10 second to 2 seconds. They probably represent oscillations in the outer levels of neutron stars - i.e. stars in which the atoms have been completely stripped of electrons and which therefore are fantastically dense. The wide bandwidths and long integration times used in radio astronomy to reduce background fluctuations and so improve sensitivity have, of course, militated against the detection of sources which pulsate so rapidly, and their discovery was more or less accidental. They are dealt with more fully in Chapter 12.

Extragalactic Sources

It was Mills who pointed out as a result of the survey carried out with the Mills Cross in Sydney in that that radio sources appeared to fall into two groups: one whose members lie in or close to the plane of the Galaxy and are probably galactic, and a second group which are grouped more or less uniformly around us and are probably objects outside the Galaxy. This has been amply confirmed.

The first of the external galaxies whose radio emission was detected was the famous Andromeda nebula (Plate XIII), a spiral galaxy whose properties are very similar to those of our galaxy. Its radio spectrum is similar to that of the non-thermal component of galactic radio emission and confirms that it originates in the synchrotron process. This is true also of radiation from all the extragalactic sources: the role of thermal emission from ionized hydrogen in galaxies is thus only a minor one. Numerous other external galaxies have also been identified as radio sources, many of them being considerably larger in extent than their optical counterparts - i.e. they apparently possess a halo analogous to that of our galaxy. Enough information is now available to provide a comparison between the visual and radio brightness of galaxies. Astronomers have their own magnitude scale for brightness, and for convenience radio flux densities are also specified on a radio magnitude (m_r) scale, defined by $m_r = -54.4 - 2.5 \log S_r$, where S_r is the flux density in watts per square metre per cycle per second at a wavelength of 1.9 metres. The constant was chosen so that the radio and optical magnitudes would be about the same for normal galaxies.

Figure 5 shows a comparison of the radio (m_r) and optical (m_{pg}) magnitudes of the galaxies which are also radio emitters. The galaxies have been separated into their usual astronomical classifications of normal spirals, elliptical, abnormal or double, and it can be seen at once that the lower part of the diagram is occupied entirely by normal spiral galaxies. This means that for all these galaxies the ratio of radio to optical emission is essentially the same. The most powerful radio sources appear to the left of the diagram, and the greater the ordinate the greater the radio emission for a given optical brightness. The extragalactic galaxies thus fall into two broad classes so far as their radio emission is concerned: normal galaxies (like Andromeda) and the very much more powerful objects which are generally referred to as radio galaxies. The latter category includes a wide variety of objects, including spirals of the most common type (S_b and S_c), elliptical or spherical galaxies, and galaxies with two nuclei, one common feature being large dimensions and high intrin sic luminosity, while most of the radio sources are double - i.e. have two main components. The first of the radio galaxies to be discovered was the historic Cygnus A (Plate XI, page). Many of the magnificent spectacles of the heavens are included in this category - e.g. Virgo A, with its peculiar jet (Plate XIV), Centaurus A (NGC 5128, Plate III, page).

Astronomers have observed what appear to be luminous clouds acting as bridges between remote galaxies, suggesting that galaxies may occur in clusters. It has been suggested by Shklovsky and Burbidge that the extragalactic radio sources may represent matter which has been ejected from galaxies. Radio emission has been observed from clusters of galaxies at longer wavelengths, but at the present time there is far from sufficient information to decide on the origin and nature of these enormously powerful emitters.

Quasars

The discovery of the quasi-stellar objects or quasars has been one of the most important and stimulating later discoveries of radio astronomy. The picturesque title of radio stars which was given to the radio sources when they were first being discovered was discarded as they were found to be associated with diffuse objects, nebulae perhaps, but certainly not stars. However, by the early 1950's several radio sources were known which appeared to coincide with rather faint stars in our own galaxy; then in 1962 came the discovery of the first quasar - a radio source associated with a visible object which looked like a star on photographic plates. Many of them have lines in their optical spectrum from which Doppler or red shift can be obtained, and these imply that the quasars are situated at very great distances. If this is so then they are certainly the most luminous objects known, their emission being as much as one hundred times that of the brightest galaxies.

The problem of such enormous output from so small a volume, and whether the measured red shifts are indeed cosmological in origin, has posed some of the most intriguing puzzles of modern astronomy. Quasars are discussed more fully in Chapter 11.