8. GALACTIC AND EXTRA-GALACTIC RADIO FREQUENCY RADIATION DUE TO SOURCES OTHER THAN THE THERMAL AND 21-CM EMISSION OF THE INTERSTELLAR GAS

R. HANBURY BROWN

Jodrell Bank Experimental Station, University of Manchester, England

1. INTRODUCTION

At wave-lengths greater than about one metre the majority of the radio emission which is observed from the Galaxy cannot be explained in terms of thermal emission from ionized interstellar gas. This conclusion is widely accepted and is based on observations of the equivalent temperature of the sky and the spectrum of the radiation. The spectrum at metre wave-lengths is of the general form:

$$T_A \propto \lambda^n,$$

where T_A is the equivalent black-body temperature of a region of sky and λ is the wave-length. The exponent n varies with direction but lies between about 2·5 and 2·8, and is thus significantly greater than the value of 2·0 which is the maximum to be expected for thermal emission from an ionized gas. Furthermore the value of T_A is about $10^{5°}$ K at 15 m and thus greatly exceeds the electron temperature expected in H II regions.

At centimetre wave-lengths it is likely that the majority of the radiation observed originates in thermal emission from ionized gas; however, the present discussion is limited to a range of wave-lengths from about 1 m to 10 m where the ionized gas in the Galaxy is believed to be substantially transparent and where the origin of most of the radiation is believed to be non-thermal.

2. SOME FEATURES OF THE GALAXY AT METRE WAVE-LENGTHS

(a) *The general background radiation*

Early surveys of the sky showed that the general radiation is, broadly speaking, concentrated in latitude about the galactic plane and in longitude about the galactic centre. On the basis of these surveys, it was concluded that the sources of emission in the Galaxy, whatever they may be,

https://doi.org/10.1017/S0074180900026024 Published online by Cambridge University Press

have a space distribution like that of the common stars. Irregularities in the distribution, which are increasingly pronounced as the wave-length is decreased, were attributed to the effects of spiral structure in the Galaxy.

The early surveys were made with rather wide beams and it is now known that much important detail was lost. Thus a recent high resolution survey by Scheuer and Ryle, and also some unpublished work by Mills, suggest that the true distribution of intensity normal to the galactic plane is made up of perhaps three component distributions. Two of these components are narrow and have widths of about 2° and 10°. It is difficult, without more extensive surveys, to be sure of their independent existence and this is a problem which requires a considerable amount of further study. The third component appears to be much broader and to have a width of the order of 60°. The variation of these components with galactic longitude is not yet known satisfactorily and is clearly complicated by irregularities in galactic structure; nevertheless it is known that the narrow distributions show a marked concentration towards the galactic centre, while the broader component appears to be concentrated in that direction to a lesser extent.

The space distribution of the sources of the broad component presents a particularly interesting question, and it is difficult to escape the conclusion that the Galaxy has a radio corona which extends to great distances. In the earlier interpretations of the isophotes it was found that agreement with the general distribution of mass in the Galaxy could be obtained by assuming that a large fraction, about two-thirds, of the total background radiation was isotropic and probably of extra-galactic origin. It seems likely that a substantial fraction of this isotropic component must now be attributed to the Galaxy and associated with the broad distribution.

(*b*) *The discrete sources at metre wave-lengths*

The first surveys of the discrete sources or radio stars were made with interferometers and it was concluded from these results that the distribution of sources with direction from the sun is isotropic. While this is still believed to be true of the majority of sources, it is now recognized that the resolving power of the interferometers was so high that important sources of large angular diameter were missed. It is now apparent that there are at least two classes of source.

Class 1 sources, which form a minority of the total, are of relatively high intensity and show a pronounced concentration into the galactic plane. A surprising feature of these sources is that many of them are known to have apparent angular diameters greater than one degree.

Class II sources, which form the majority, appear to be uniformly distributed over the sky. The angular diameter of many of these sources is not yet known and it is important that they should be measured; however, the few results which are available suggest that, for the most part, their diameters are of the order of a few minutes of arc or less.

3. THE ORIGIN OF THE RADIO EMISSION FROM THE GALAXY AT METRE WAVE-LENGTHS

Any discussion of the origin of the radiation from the Galaxy must be highly speculative, since recent work has shown that our knowledge of the distribution of the background radiation is seriously incomplete. Furthermore, data on the spectra and angular diameters of the sources are confined to a few of the most intense.

The present evidence suggests that any theory may have to account for both the broad and narrow distributions, although it is by no means clear whether these distributions can be regarded as independent.

Two components of the narrow distributions are the thermal radiation from ionized gas in H II regions and class I sources. At metre wave-lengths the thermal radiation cannot account for the total intensity observed and it is tempting to ascribe the remainder to a population of sources which lie close to the galactic plane. However, this cannot be done, since so little is known about the class I sources; for example, it is not known whether they are a homogeneous population, nor how they are distributed in the Galaxy. Until more data are available we must be prepared to find that some other mechanism, as yet unknown, is responsible for the majority of the radiation. For example, it was suggested by Ginsburg some years ago that the non-thermal radiation might be due to cosmic ray electrons in interstellar magnetic fields.

The nature of the known class I sources is a fascinating problem. They appear to be rare bodies with a space-density in the neighbourhood of the sun which we may compare, solely for the purpose of illustration, with that of planetary nebulae. The spectra and apparent surface temperatures of a few of these sources is known and it is clear that some of them are radiating by a non-thermal mechanism. The large angular diameters of several of these sources, coupled with the few photographic identifications which have been made, suggest that they are associated with extended nebulosities. These nebulosities are of low photographic brightness and some of them have been found to contain filaments which are apparently moving at very high speeds. The nature of these nebulosities is controversial. At least two, if not three, of the sources have been identified with the remnants of super-novae, and it has been suggested that many of the other sources arise in the same way.

The physical mechanism by which these nebulosities radiate is also unknown. It seems likely that plasma oscillations cannot be invoked since the plasma frequency in the medium is too low, and the current idea is that the radiation arises from the deflexion of relativistic electrons in magnetic fields. The magnetic fields are presumed to be generated by turbulence in an ionized medium, and the fast electrons to be accelerated by the Fermi mechanism, by shock waves, or by some other process.

The origin of the broad distribution is also a challenging problem and it is an urgent task of observation to establish beyond doubt the shape and spectrum of this distribution. It has been suggested that, whereas the narrow distributions are apparently associated with populations concentrated into the galactic plane, the broad distribution arises in an extended halo which is roughly spherical and extends to radial distances of the order of 10,000 pc. It has also been proposed that the generation of the energy in this halo occurs in a very rarefied medium and is due to the deflexion of fast electrons in magnetic fields.

The origin of the majority of the discrete sources, the class II sources, may be extra-galactic. Recent work has shown that their distribution is remarkably isotropic and it is difficult to associate them with any of those components of the background radiation which are clearly of galactic origin.

4. EXTRA-GALACTIC SOURCES

A small number of radio sources have been identified with external galaxies, and on the basis of these results it appears that, as far as radio emission is concerned, we must recognize at least two major classes of galaxies, *normal* galaxies and *peculiar* galaxies.

(*a*) *Normal galaxies*

If the apparent radio magnitude of a galaxy is designated by m_R and its photographic magnitude by m_p, then it has been found for Sb galaxies that at a wave-length of about 1·9 m these two quantities are approximately equal if m_R is defined by the equation:

$$m_R = -53{\cdot}4 - 2{\cdot}5 \log I, \qquad (1)$$

where I is the intensity in watts m^{-2} (c/s)$^{-1}$.

Table 1 shows six type Sb galaxies which have been reasonably well identified.

The values of m_R shown in the table have been calculated by means of equation (1), while the values of m_p have been taken from de Vaucouleur's revision of the Shapley-Ames catalogue. The data for NGC 1068 and I 5267 have been taken from some unpublished work by Mills. The value for NGC 224 is probably too great, due to a failure to integrate satisfactorily over the whole source, and it is likely that the true value of $m_R - m_p$ for this galaxy is closer to $+1{\cdot}0$.

Table 1. *Sb galaxies*

Galaxy	Radio magnitude m_R (1·9 m)	Photographic magnitude m_p	$m_R - m_p$
NGC 224 (M 31)	6·0	4·0	+2·0
NGC 3031 (M 81)	8·9	7·8	+1·1
NGC 4258	9·8	9·1	+0·7
NGC 2841	10·4	10·2	+0·2
NGC 1068	8·9	9·6	−0·7
I 5267	11·1	10·8	+0·3

The data presented in the table, although admittedly scanty, indicate that type Sb galaxies radiate roughly the same ratio of radio to light, and that equation (1) may be used to calculate their approximate radio magnitude.

It is clearly of great interest to know how the value of $m_R - m_p$ varies with the type of galaxy, and this is one of the major observational problems. Some measurements of five Sc galaxies suggest that their radio emission, in comparison with their light, is between 1 and 2 magnitudes less than that observed from type Sb, while in the case of the Magellanic Clouds this deficiency has increased to between 3 and 4 magnitudes. At present the value of $m_R - m_p$ for a normal elliptical galaxy is unknown, but the failure to detect any of these galaxies suggests that they radiate weakly at radio wave-lengths in comparison with type Sb.

(*b*) *Peculiar galaxies*

In addition to normal galaxies a few radio sources have been identified with peculiar extra-galactic objects. A brief list of these objects is given in Table 2. The first is the well-known source in Cygnus which has been identified by Baade and Minkowski as the collision between two spirals. NGC 4486 is a galaxy in Virgo which has a peculiar jet protruding from the nucleus. NGC 1275 in Perseus has been identified with colliding galaxies; while NGC 5128 is a curious object of which the interpretation is controversial. The table shows that in at least three of these cases the radio emission is greatly enhanced by comparison with a normal Sb galaxy.

The origin of this enhanced radiation is not understood, but it is believed to be due to the collision of gas clouds at high speeds.

Table 2. *Peculiar galaxies*

Object	Radio magnitude m_R (1·9 m)	Photographic magnitude m_{pg}	$m_R - m_{pg}$
Cygnus	+2	+18	−16
NGC 4486	+5	+10	−5
NGC 1275	+7	+13	−6
NGC 5128	+4	+6	−2

5. A COMPARISON OF OUR OWN GALAXY WITH OTHER GALAXIES

Assuming that the distance of NGC 224 (M 31) is $1{\cdot}5 \times 10^6$ light years, then the value of m_R shown in Table 1 corresponds to an emission of $3{\cdot}5 \times 10^{20}$ watts ster^{-1} (c/s)$^{-1}$ at 1·9 m. The total radiation from our Galaxy cannot be found precisely since, among other difficulties, it is not known what fraction of the background radiation is of extra-galactic origin. It has been estimated by Hazard, from an integration of the isophotes of the sky at 3 m, that the total radiation is $3{\cdot}7 \times 10^{20}$ watts ster^{-1} (c/s)$^{-1}$ at 1·9 m, and other estimates range from this value up to about 10^{21} watts ster^{-1} (c/s)$^{-1}$. Since the absolute photographic magnitude of NGC 224 and our own Galaxy are believed to be about equal, it can be tentatively concluded that the ratio of radio to light emission from our own system agrees with that found in the Andromeda nebula; furthermore, within the limits of the present data, this ratio appears to be characteristic of other normal Sb galaxies.

It is also pertinent to inquire whether the distribution of intensity found in our own Galaxy is found in other similar systems. Any attempt to solve this question is beset by the considerable experimental difficulty of obtaining the necessary resolving power. A few attempts have been made to determine the distribution of intensity across NGC 224, but unfortunately the results are not free from difficulties of interpretation. The most significant datum appears to be that obtained by Baldwin with an interferometer using very large aerials. He found that the distribution of intensity at a wave-length of 3·7 m extended over a surprisingly large area, greatly exceeding the region of optical emission; what is even more surprising, he found that the distribution was also extended normal to the plane of the nebula. He interpreted these observations as showing that the nebula contains two separate populations, one distributed in a similar way to the general mass, and one which has approximate spherical symmetry and which reaches to radial distances of the order of 10,000 pc. The latter population contributes about two-thirds of the total radiation.

A comparison of these results with the data presented above suggests that the spherical system in NGC 224 corresponds to the broad distribution observed in our own Galaxy, and that the distribution which is similar to the mass corresponds to the narrow distributions in the Galaxy. Since the distributions across other normal Sb galaxies have not yet been measured we cannot pursue this subject further.

In conclusion, the present data indicate that our own Galaxy, as far as radio emission is concerned, is similar to NGC 224; furthermore, the ratio of radio flux to light appears to be characteristic of normal Sb galaxies.