THE OBSERVATION AND INTERPRETATION OF RADIO EMISSION FROM SOME BRIGHT GALAXIES

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Summary

Preliminary attempts to observe 13 bright southern galaxies are described. Of these 10 were detected, including the Magellanic Clouds. The latter were studied in detail. Supplementary measurements on the Milky Way near the galactic centre were made and also some unsuccessful attempts to observe two globular clusters. Taking these results in conjunction with some observations of Brown and Hazard it is possible to derive a consistent picture of the radio emitting properties of " normal " galaxies. It is found that radio emission probably occurs with two markedly different distributions, one displaying characteristics of a type I population, the other having a very extensive, roughly spherical, spatial distribution quite unlike any known stellar population. Both distributions have a non-thermal spectrum, and the relative contributions of each appear to vary between different galaxy types. In general terms, although not altogether in detail, these results support the conclusions reached by Shklovskii concerning the distribution of radio emission in the Galaxy ; also his interpretation of the spherical distribution as the result of relativistic electrons radiating in weak magnetic fields is examined, and found, with some modifications, to afford a plausible explanation of the observed differences between the radiating efficiencies of different types of galaxies.

I. Introduction

A large radio telescope intended primarily for the study of cosmic radio-frequency radiation has recently been put into operation near Sydney. The telescope, which consists of a cruciform arrangement of two arrays of dipoles, operates at a wavelength of 3·5 m, has a beam width between half-power points of 50 min of arc and a sensitivity which, under ideal conditions, approaches 10^{-26} W m^{-2} (c/s)$^{-1}$; the principle of operation has been described by Mills and Little (1953). It is arranged as a transit instrument and altered in declination by phasing the elements of the arrays. As a consequence, at zenith angles greater than about 45°, the sensitivity and resolution begin to deteriorate rapidly. The sky coverage for useful observations from Sydney (latitude 34 °S.) therefore lies between declinations of about +10° and −80° in most circumstances. A detailed account of the equipment is being prepared for publication by Mills, Little, and Sheridan.

This radio telescope, being a pencil beam instrument, may be used to study both the discrete sources and the general background radiation, and eventually

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a detailed survey of the distribution of cosmic noise in the southern sky will be undertaken. Before commencing such a survey, however, it has been found desirable to spend some time testing and calibrating the equipment, while at the same time observing special objects of astronomical interest. This paper describes the results of observing some bright galaxies, including the Magellanic Clouds, and some regions of the Milky Way.

For the purpose of studying their radio emission, " normal " galaxies may be divided into three classes : (i) comparatively distant and faint galaxies in the magnitude range from 7 to 11 for which the only observation possible with this instrument is their total radio emission (or lack of it) ; (ii) close galaxies such as the Magellanic Clouds and M31 (the latter unfortunately being outside the coverage of the aerial) in which the distribution of radio emission over the galaxy may be mapped and compared with that of various stellar populations ; (iii) the Milky Way which is unique in the wealth of detail which may be obtained, but in which the edge-on view leads to difficulties of interpretation requiring the use of supplementary information derived from studies of the first two types.

Attempts have been made to observe 11 galaxies of the first type of which 8 were probably detected ; also both Magellanic Clouds have been observed and their radio and optical properties compared. In addition a few galactic sections have been obtained in the region of the galactic centre. Taken together these observations appear to provide a consistent picture of the distribution of radio emission throughout a galaxy and of its dependence on the constituent stellar populations. In general the observations tend to support the ideas of Shklovskii (1952, 1953) in which the galactic emission is considered to be distributed in two subsystems, one showing a discoidal distribution highly concentrated towards the galactic plane, and the other a very dispersed and approximately spherical distribution concentric with the galactic centre. However, contrary to Shklovskii's interpretation, it is found that the contribution of thermal emission from ionized hydrogen to the discoidal distribution is likely to be small.

II. Radiation from the Magellanic Clouds

Study of the radio emission of the Clouds is difficult because both have a relatively low surface brightness compared with irregular variations in background brightness in their neighbourhood. The Small Cloud presents the greatest difficulty, particularly in its outer regions, but even in the Large Cloud the distribution of emission can be determined with confidence only near its centre. A further difficulty arises because a radio telescope of this type is relatively insensitive when observing extended distributions ; consequently, very high stability is required from the equipment, and random drifts must be kept below the level of thermal noise fluctuations for the period of the observations, that is, about 7 hr. The electronic portion of the equipment meets the stability requirement, but it is not yet known how the aerial itself is affected by changes in temperature or humidity. Fortunately, the main conclusions do not depend on an exact knowledge of the detailed structure in the outer parts of the Clouds.

In Figure 1 is shown a facsimile of a record taken on the Large Magellanic Cloud at a declination of $-69° 26'$. Recordings of this type were made at declination intervals of one beam width between declinations of $-62\frac{1}{2}°$ and $-75\frac{1}{2}°$, together with "scanning" records over the central regions of both Clouds. In the scanning observations the aerial beam is electrically scanned back and forth over five declinations slightly less than half a beam width apart, and the section at each declination is separately recorded. It has been shown by Bracewell and Roberts (1954) that no information is lost by making measurements at intervals of less than a certain critical interval which is approximately half the beam width. Outside the central regions where scanning was not employed the critical interval was exceeded so that fine detail in the distribution may have been overlooked.

To construct a contour map from the series of sections so obtained it is desirable to obtain absolute levels of brightness. However, the calibration of the equipment was not sufficiently accurate to enable an undistorted map to be constructed, since small variations between different declinations and on different days were of the same order as the excess brightness due to the outer regions of the Clouds. Therefore a method of matching the temperatures at a particular Right Ascension has been adopted. A region from 23 hr 00 min to 23 hr 40 min has been chosen because observations with other equipment suggest that over the declination range of interest the galactic radio isophotes lie roughly parallel to an hour circle. As a first step all temperatures were equalized over the chosen period after excluding any weak discrete sources which were present. The resulting isophotes suggested strongly that north of $-68°$ the temperatures were all too high and consequently all temperatures north of this declination were reduced by 100 °K and the isophotes redrawn. The result is shown in Figure 2 (*a*). The contour interval is 125 °K and the temperatures are all measured above a base temperature T. The value of T is estimated as approximately 700 °K.*

The optical centres for the Clouds are, for the Large Cloud, 05 hr 24 min and $-69 \cdot 8°$, and for the Small Cloud, 00 hr 51 min and $-73 \cdot 1°$, so that in Figure 2 (*a*) the excess radiation near the centres of the Clouds may be readily seen. However, the isophotes also include irregularities in the background radiation and discrete radio sources so that it is difficult to determine the outer boundaries of the Clouds or their integrated emission. In Figure 2 (*b*) are shown the outer boundaries derived from a careful examination of the original records. The dark areas include radiation connected to the main systems by strongly closed contour lines and therefore almost certainly belonging to the Clouds.

* It has been shown that with a radio telescope of this type the absolute temperature is obtained very closely by the addition of two temperatures, one corresponding to that of the pencil beam and showing the fine detail and the other corresponding to the absolute temperature of the arrays (Mills and Little 1953). This method was used for estimating the temperature T, but variations of the array temperatures at other Right Ascensions were ignored since they have only a very small gradient. Because of this, errors of up to 100 °K may be produced at any one point, but the shape of the contours would not be significantly affected.

The lighter areas are regions of excess radiation, often quite strong, but in which the connexion with the Clouds is not so obvious; they represent the extreme limits to which Cloud radiation may be detectable with the present equipment. The dotted lines are the limits from which the 21 cm line radiation from neutral hydrogen has been detected by Kerr, Hindman, and Robinson (1954). It will be noted that the bright region south of $-75°$ stretching from one Cloud to the other shown in Figure 2 (*a*) has been omitted in Figure 2 (*b*). There is no evidence to show that it is associated with the Clouds, and from the distribution of brightness along it the alternative explanation that it represents an irregularity in the galactic radiation is more probable.

The agreement of the outer boundaries of both the 21 cm line radiation and the $3\cdot5$ m radiation over extensive regions is striking and suggests, inter alia, that the excess $3\cdot5$ m emission north following the main body of the Small Cloud is actually associated with it, something which is quite impossible to decide from the records themselves. The " link " between the Clouds at a

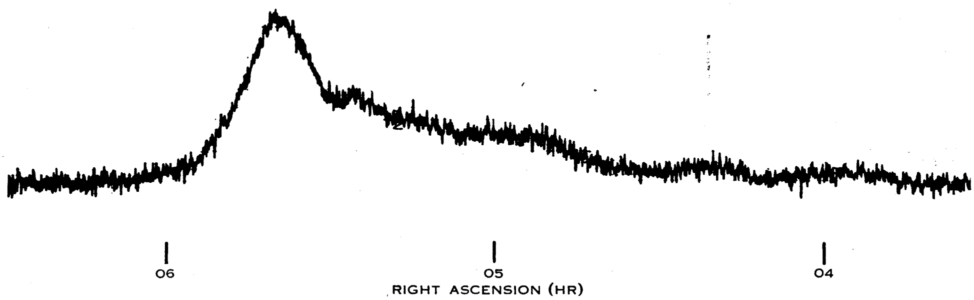


Fig. 1.—A typical record of the Large Magellanic Cloud at a declination of 69° 26′ S.

declination of $-72°$ may not be real, as such an effect could result from a small error in the original matching of the profiles or from long-period drifts in the equipment. However, there is no internal evidence in the observations to throw doubt on its existence, so it has been retained in the diagram as a possible feature of the systems. The link is some 2° to the north of a possible link suggested by the optical evidence.

A photograph of the Clouds is shown in Plate 1, Figure 1. There appears to be little resemblance between the photographic appearance and the distribution of radio emission, because of differences in the shapes of the brighter features and the apparently greater extent of the radio distributions. However, de Vaucouleurs (1954), by means of long exposure photographs and star counts, has traced the outer regions of the Large Cloud over very wide areas, in places exceeding the radio boundaries. He finds no optical extension of the Small Cloud in a north-easterly direction, corresponding to the possible extension of radio emission.

It is interesting to compare the brighter features of the three distributions in $3\cdot5$ m continuous spectrum radiation, in 21 cm line radiation, and in visible radiation. A striking circumstance is the complete absence of the bright visible axial bar of the Large Cloud at a wavelength of $3\cdot5$ m, although it is slightly visible in the 21 cm line radiation. A similar discrepancy in the Small Cloud, although present, is not so obvious. The greater tilt of this system makes it more difficult to observe such structural features. In both Clouds the region of maximum radio emission is displaced towards the greatest concentration of

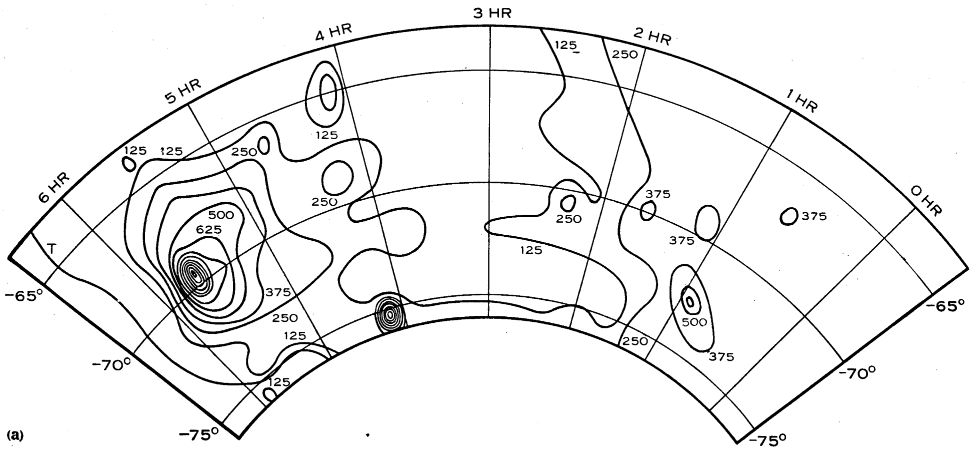


Fig. 2 (*a*).—Contour maps of the 3·5 m isophotes in the vicinity of the Magellanic Clouds ; the contour interval is 125 °K.

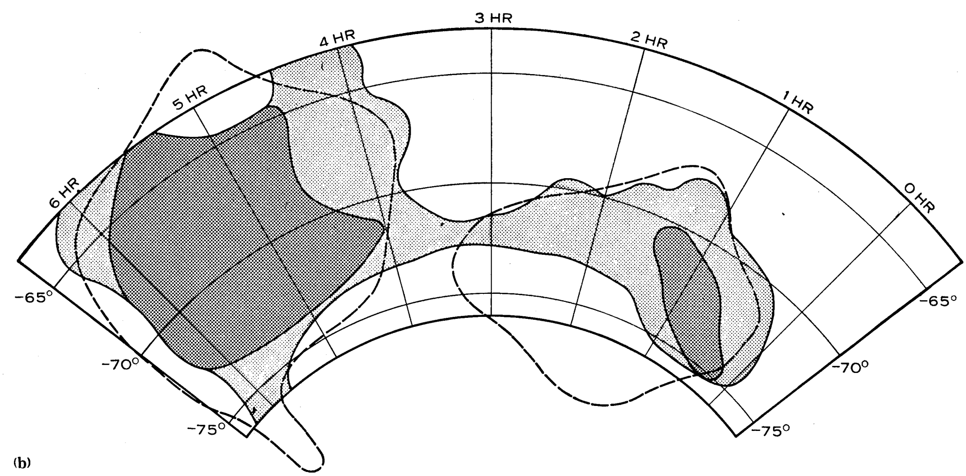


Fig. 2 (*b*).—The boundaries of the Clouds at 3·5 m wavelength compared with the hydrogen line emission boundaries. The dark areas represent definite regions of 3·5 m radiation and the lighter areas possible regions of the radiation. The dotted lines outline the neutral hydrogen boundaries.

bright stars ($m<14$) which, according to de Vaucouleurs (1955*a*, 1955*b*), also show no concentration in the axial bars. However, the " wing " of the Small Cloud, although very rich in such stars, shows no trace of 3·5 m radiation. The positions of maximum brightness of the two types of radio emission agree

RADIO EMISSION FROM SOME BRIGHT GALAXIES

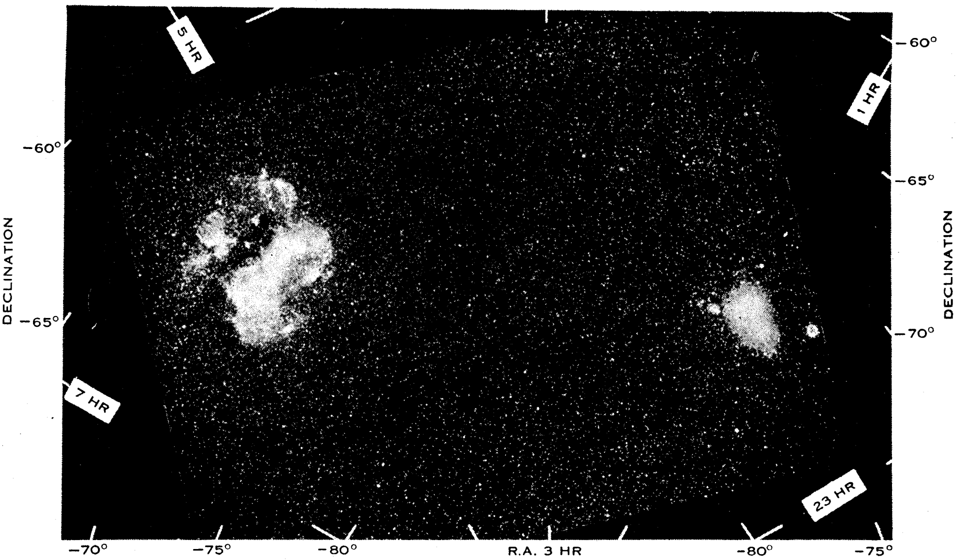


Fig. 1.—A photograph of both Magellanic Clouds.

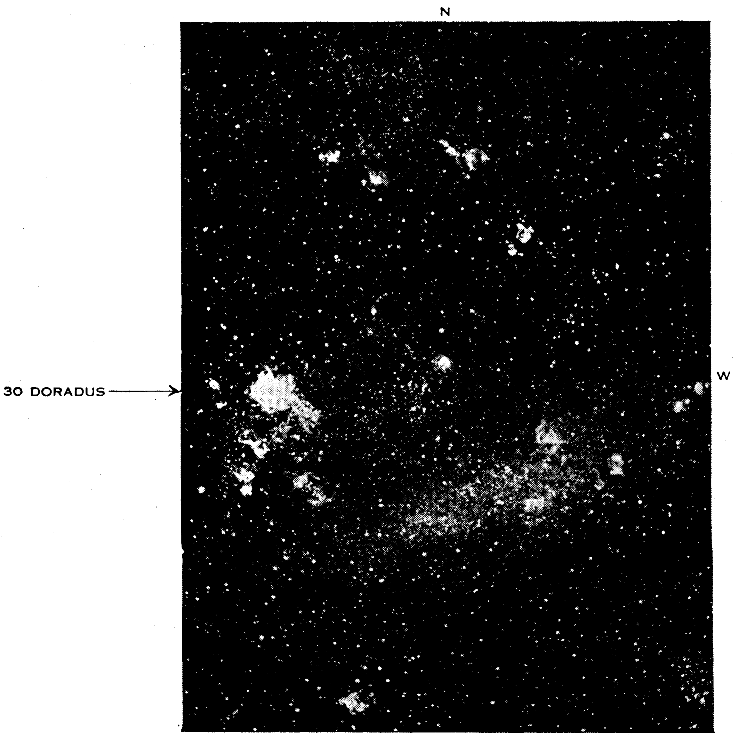


Fig. 2.—A photograph of the Large Magellanic Cloud in Hα light.

closely, being for the Large Cloud, 05 hr 40 min, —69·6° at 3·5 m* and 05 hr 38 min, —70° for the hydrogen line emission and, for the Small Cloud, 00 hr 56 min, —72·9° at 3·5 m and 01 hr 00 min, —73·1° for the hydrogen line emission ; the agreement is within the experimental error. The general distributions of the radio emissions are also similar except for the discrepancies in the axial bar of the Large Cloud and the lack of 3·5 m radiation south following the main body of the Small Cloud where there is an extensive region of neutral hydrogen.

TABLE 1

CENTRES OF THE LARGE MAGELLANIC CLOUD DISTRIBUTIONS

Centre	R.A. (hr	min)	Dec. (deg)
Centroid of neutral hydrogen	05	35	—68·5
Centroid of bright stars	05	33	—67·7
Optical centre (brightest part)	05	24	—69·8
Centre of rotation (radio data)	05	20	—68·8
Centroid of 3·5 m radiation	05	17	—69·3

Comparisons may be extended further by considering the centroids of the various distributions (Table 1) and their average radial decrements. The centroid of the 3·5 m distribution in the Large Cloud has been calculated by making reasonable estimates of the percentage of radiation originating in the outer regions and is probably accurate to about half a degree. Ignorance of the distribution of weak radiation far from the centre is the chief cause of uncertainty. Other data have been taken from de Vaucouleurs (1955*a*) and Kerr and de Vaucouleurs (1955).

TABLE 2

CENTRES OF THE SMALL MAGELLANIC CLOUD DISTRIBUTIONS

Centre	R.A. (hr	min)	Dec. (deg)
Centroid of neutral hydrogen	01	20	—72·5
Centroid of bright stars	01	00	—72·5
Optical centre (brightest part)	00	51	—73·1
Centre of rotation (radio data)	01	10	—73·25
Centroid of 3·5 m radiation (bright regions only)	00	54	—72·7

All the centres differ in position, but in view of the uncertainties involved no definite conclusions can be drawn.

A similar comparison may be made for the Small Cloud (Table 2) but the uncertainty in the centroid of the 3·5 m radiation is even greater. The value

* The prominent maximum in the distribution of 3·5 m radiation near this position is thought to be due to the nebula 30 Doradus, as explained later. The maximum in the general emission remains, however, after the effect of the nebula is subtracted.

given is that of the dark area of Figure 2 (*b*). If the suspected outer component is included the centroid would be moved in a north-following direction.

Again the centres differ and the uncertainties are such that it is difficult to come to any conclusions. It does seem, however, that the main mass of the system is east of the brightest regions so that again the indications are that the 3·5 m radiation could extend in the manner suggested.

Following de Vaucouleurs (1955*a*), the distributions in the Large Cloud may be further compared by plotting average values at given angular separations from some assumed centre, in this case taken as the optical centre. It does not seem worth while carrying out this procedure for the Small Cloud, however, because of its marked elongation and asymmetry. The data for the Large Cloud are presented in Figure 3 where the number density of bright stars, the

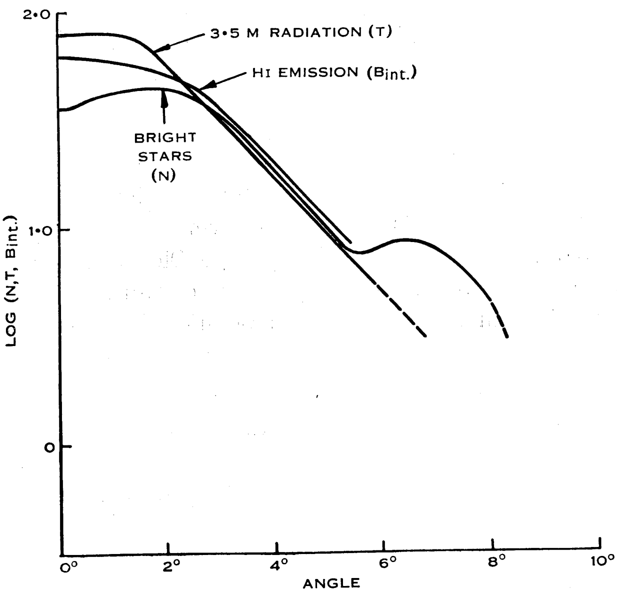


Fig. 3.—A comparison of the average radial distributions of 3·5 m radiation, 21 cm hydrogen line radiation, and bright stars in the Large Magellanic Cloud.

H line integrated brightness, and the 3·5 m temperatures are plotted as logarithmic functions of the radius, with arbitrary zeros. The general similarity is obvious, particularly for radii between 2° and 6° where the logarithmic decrements are identical. Differences towards the centre reflect the detailed differences already discussed.

Although neither these bright stars nor the neutral hydrogen show a one-to-one correspondence with the distribution of 3·5 m radiation, all the distributions have a considerable similarity, which strongly suggests that the radiation is associated with the presence of interstellar matter and of bright stars, that is, that it has a Population I type of distribution. The possibility that a large proportion of the radiation might be due to thermal emission of ionized hydrogen therefore demands investigation. This is most readily checked in the Large Cloud. An inspection of Figure 2 (*a*) reveals a marked concentration of radiation at a position centred on R.A. 05 hr 40 min and Dec. $-69\cdot3°$. The source is not resolved in an east-west direction but is slightly extended at right angles.* The excess radiation most likely originates in the giant emission nebula 30 Doradus at a position of 05 hr $39\cdot9$ min, $-69\cdot1°$ and the neighbouring emission regions to the south. With this interpretation the flux density of 30 Doradus is about 3×10^{-25} W m^{-2} (c/s)$^{-1}$ and the average of the other emission regions is about $2\cdot5\times10^{-25}$ W m^{-2} (c/s)$^{-1}$. These values seem quite consistent with thermal emission, since, if 30 Doradus is assumed to be optically thick at a wavelength of $3\cdot5$ m, of angular size 15 min, and of temperature 10,000 °K, the flux density would be $3\cdot4\times10^{-25}$ W m^{-2} (c/s)$^{-1}$.

This result may be used to show that the greater part of the radiation from the large Cloud probably has a non-thermal origin. Thus it is shown later that the integrated emission from the whole Cloud is approximately 2×10^{-23} W m^{-2} (c/s)$^{-1}$ so that, if this also were due to thermal emission, the mass of ionized hydrogen in 30 Doradus would be very small compared with the total mass of ionized hydrogen in the Cloud. This seems very improbable; see, for instance, a photograph of the Large Cloud taken in Hα light by C. Gum of Mt. Stromlo Observatory (Plate 1, Fig. 2) where the nebula 30 Doradus dominates the whole picture. Recently this conclusion has received confirmation from some unpublished results of J. H. Piddington and G. Trent of the Radiophysics Laboratory who, observing with an aerial of 3° beam width at a wavelength of 50 cm, find that the only detectable excess radiation in the region is a source of small angular size close to 30 Doradus and of flux density very roughly $1\cdot5\times10^{-24}$ W m^{-2} (c/s)$^{-1}$. Since the flux density at a wavelength of 50 cm would be equal to or greater than that at $3\cdot5$ m if the emission had thermal origin, the conclusion that at $3\cdot5$ m thermal gas emission is only an insignificant proportion of the total appears inescapable. The radiation from the Small Cloud is too weak to apply similar tests, but there seems to be no reason for assuming that the results would be any different. The probable extensions of the radio emission of the Cloud in regions where no emission nebulae are observed (see, for instance, Henize and Miller 1951) support this conclusion.

A further check on the relation of radio emission to population types is afforded by the presence near the Small Cloud of two bright globular clusters, NGC 362 ($m_p=6\cdot0$) and 47 Tucanae ($m_p=3\cdot0$). Neither gives any detectable radio emission although, if the ratio of radio to optical emission in 47 Tucanae were the same as in late-type spirals, a signal nearly 500 times the minimum detectable level would be expected. It therefore appears safe to conclude that the bright type II stars found in globular clusters do not contribute significantly to the total energy of cosmic radio waves.

* At the large zenith angles at which these observations were made the aerial beam becomes elongated in a north-south direction, but the apparent extent of the source is greater than that of the aerial beam.

Summing up the results of these comparisons it appears that at a wavelength of 3·5 m the emission from the Magellanic Clouds originates principally in a non-thermal process and has a distribution which is closely related to the inter-stellar gas and bright stars. The bright type II stars of globular clusters are not associated with radio emission, but whether the fainter type II stars found in elliptical galaxies and the disks of spirals are so associated needs further investigation, including comparisons of the Clouds, which appear to lack such stars, with other galaxies.

III. The Integrated Emission of the Clouds

The total emission from each of the Clouds can be obtained by direct integration of the contours, the flux density being given by the relation

$$S=\frac{2k}{\lambda^2}\int T\mathrm{d}\Omega.$$

The value obtained is naturally very dependent on the distribution in the outer regions where, although the temperature is low, the solid angle is very great. Values obtained assuming an extent given by (*a*) the minimum shown by the dark area in Figure 2 (*b*) and (*b*) the possible extent indicated by the light area in the same figure are as follows :

LMC $S_{(a)}=1\cdot7\times10^{-23}\ \mathrm{W\ m^{-2}\ (c/s)^{-1}}$
$S_{(b)}=2\cdot2\times10^{-23}\ \mathrm{W\ m^{-2}\ (c/s)^{-1}}$

SMC $S_{(a)}=1\cdot15\times10^{-24}\ \mathrm{W\ m^{-2}\ (c/s)^{-1}}$
$S_{(b)}=3\cdot7\ \times10^{-24}\ \mathrm{W\ m^{-2}\ (c/s)^{-1}}$

The flux density of the Large Cloud may be estimated in another way from the radial decrement curve of Figure 3. This method has been used by de Vaucouleurs (1955*a*, 1955*b*) and by Kerr and de Vaucouleurs (1955) in estimating the total stellar populations and the mass of hydrogen. The curve of log T plotted against radial angle is extrapolated to infinity as a straight line of uniform slope, and the integral performed. This integral will always converge, and in the present case leads to a value of the total emission of $1\cdot95\times10^{-23}\ \mathrm{W\ m^{-2}\ (c/s)^{-1}}$ in very good agreement with the results above. The value is, however, rather lower than $S_{(b)}$, indicating that not all the excess radiation in the vicinity is associated with the Cloud.

For comparisons with other galaxies it is convenient to assign definite values to the flux densities which are estimated to be as follows :

LMC $S=2\times10^{-23}\ \mathrm{W\ m^{-2}\ (c/s)^{-1}}\pm15\%$
SMC $S=3\times10^{-24}\ \mathrm{W\ m^{-2}\ (c/s)^{-1}}\pm30\%.$

The flux density of the Large Cloud is hardly affected by the uncertainties in the outer boundaries, and the main allowance in the estimated probable error is for calibration errors in the equipment. The relative importance of the errors is reversed in the Small Cloud, and here the flux density is taken nearer the higher value as it is considered probable that most of the excess radiation within the confines of the Cloud, as defined by the hydrogen boundaries, is associated with it. It will be shown later that this assumption is consistent with what is known of the distribution of radiation in other galaxies.*

To compare the flux densities of the Clouds with those of other galaxies it is convenient to express them in the magnitude scale of Brown and Hazard (1952), applying a correction for the difference in wavelength so that the northern and southern observations may be directly compared.

The uncorrected values are as follows:

$$\begin{array}{ll} \text{LMC} & m_{R(3\cdot5\,\mathrm{m})}=-53\cdot4-2\cdot5\log_{10}S_{(3\cdot5\,\mathrm{m})} \\ & \qquad\qquad =3\cdot35\pm0\cdot15 \\ \text{SMC} & m_{R(3\cdot5\,\mathrm{m})}=5\cdot4\pm0\cdot35. \end{array}$$

To convert to the wavelength of $1\cdot9$ m (158 Mc/s) used by Brown and Hazard it is assumed that the spectrum is of the form $S\propto\lambda^{0\cdot7\pm0\cdot1}$, which gives a difference in magnitude of $0\cdot47\pm0\cdot06$. We therefore have for the radio magnitudes at $1\cdot9$ m:

$$\begin{array}{ll} \text{LMC} & m_R=3\cdot8\pm0\cdot2 \\ \text{SMC} & m_R=5\cdot9\pm0\cdot4. \end{array}$$

IV. Observations of Other Bright Galaxies

Attempts have been made to observe eleven other bright galaxies in the southern sky. Of these, eight were probably detected and three could not be observed. Several of the galaxies were barely above the sensitivity limit of the equipment so that an accurate position measurement and certain identification could not be expected. Others are in regions of radio source concentrations, again leading to difficulties of identification and of flux density measurements.

The aerial may be directed to a series of standard declinations at approximately 20′ intervals. Observations were therefore made by directing the beam to the declination nearest to that of the galaxy and observing its meridian transit. If no signal could be detected after two such transits the galaxy was noted as undetectable and an estimate made of the upper limit of its flux density. If a source was observed at the correct Right Ascension (within $0\cdot2$ min for the stronger sources and $0\cdot5$ min for the weaker ones) checking observations were made at declinations on either side. The result was a declination accuracy of only about half a degree, but it was considered that this was adequate to ensure generally that no spurious identifications were made. Intensity measurements

* The values above may be compared with some early measurements obtained with the experimental version of the aerial, of 8° beam width (Mills and Little 1953), and quoted in an U.R.S.I. report (1954). They were as follows:

$$\left.\begin{array}{ll} \text{LMC} & S=3\cdot1\times10^{-23} \\ \text{SMC} & S=9\cdot0\times10^{-24} \end{array}\right\}\lambda=3\cdot1\text{ m}$$

It seems fairly clear that because of the low aerial resolution all the excess radiation in the vicinity was then included in both Clouds.

are accurate to about 10 or 20 per cent. and are expressed in the same magnitude scale as used for the Clouds. The results of observations of these galaxies, the Clouds, and the previously mentioned globular clusters are summarized in Table 3. The individual observations are discussed in more detail below.

The Large Magellanic Cloud

The radio observations have been discussed already. The photographic magnitude is an estimate of de Vaucouleurs (Buscombe, Gascoigne, and de Vaucouleurs 1954) and is based on several discordant published measurements. It does not have a very high weight. Exactly the same difficulties arise in obtaining the photographic and radio magnitudes, that is, an uncertainty as to the contribution from the faint outer regions.

TABLE 3

A COMPARISON OF THE RADIO AND PHOTOGRAPHIC MAGNITUDES OF SOME SOUTHERN NEBULAE

Nebula	Type	m_R	m_p	m_R-m_p
LMC	(M)	3·8	0·5	3·3
SMC	(M)	5·9	2·0	3·9
NGC 55	(M):	11·4	7·8	3·6
NGC 253	Sc	9·4	7·6	1·8
NGC 300	Sc	10·4	8·5	1·9
NGC 5236 (M83) ..	SBc	8·9	7·4	1·5
NGC 4945	SBc :	9·2	7·8	1·4
NGC 6744	SBbc	10·7	9·1	1·6
NGC 1068 (M77) ..	Sb	8·9	9·6	—0·7
I 5267	Sb	11·1	10·8	0·3
NGC 4594 (M104) ..	Sab	>11·8	8·9	>2·9
NGC 1291	SBo	>11·6	9·5	>2·1
NGC 3115	E7	>11·9	10·15	>1·7
47 Tucanae ..	Globular Cluster	>11·0	3·0	>8·0
NGC 362	Globular Cluster	>10·8	6·0	>4·8

The Small Magellanic Cloud

Again the photographic magnitude is an estimate of de Vaucouleurs (Buscombe, Gascoigne, and de Vaucouleurs 1954) and the same difficulties apply. However, in this case the uncertainty in the radio magnitude probably exceeds that in the photographic.

NGC 55

The astronomical data for this and the following have been taken from "A Revision of the Harvard Survey of Bright Galaxies" (de Vaucouleurs 1952–53), supplemented at times by additional information supplied by its author. In this Catalogue the photographic magnitudes are total magnitudes and are based on the best available standards. There is some difficulty in classifying NGC 55, as it is seen nearly edge-on, but the photographic evidence for classification as a Magellanic type appears quite strong and it has therefore been adopted. As will be seen later this is consistent with the radio evidence. The source was near the limit of detectability and several observations were required to be sure of its existence. A sample record is shown in Figure 4 (*a*). The flux density is $1 \cdot 8 \times 10^{-26}$ W m^{-2} (c/s)$^{-1}$ and the radio magnitude has been calculated as before.

NGC 253

This is a relatively strong source and quite free of confusion so that reliable measurements are possible. The photographic magnitude is also reliable. A sample record is shown in Figure 4 (*b*).

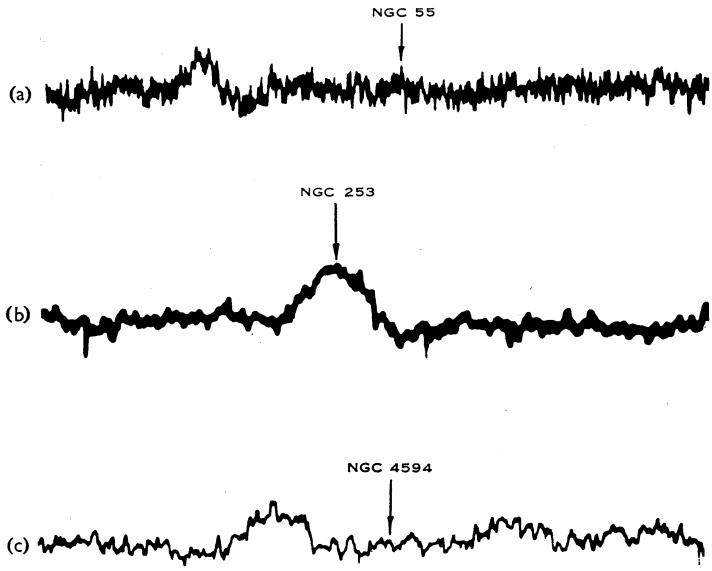


Fig. 4.—Records obtained on some bright galaxies. (*a*) A very weak radio source, NGC 55; (*b*) A relatively strong radio source, NGC 253; (*c*) The region around NGC 4594 (M104), a galaxy which could not be detected.

NGC 300

This galaxy is in a region of many weak radio sources and it is therefore difficult to estimate its radio emission or even to be sure of the identification. The radio source appears superimposed on a weaker source of large angular size and its apparent position is about 10 min of arc east of the galaxy, but the displacement could well be due to insufficient resolution. The photographic magnitude is also uncertain as the galaxy has a very low surface brightness and the published measures differ widely. The value quoted is an unpublished "best estimate" of de Vaucouleurs. Not very much weight can be given to the final value of $m_R - m_p$.

NGC 5236 (M83)

This galaxy gives a clear record without confusion but the photographic magnitude is of low weight.

NGC 4945

A good radio observation but the photographic magnitude does not carry much weight particularly as the galactic latitude is low and absorption effects uncertain. The galaxy is a late type seen nearly edge-on but the exact classification is in some doubt.

NGC 6744

The radio observations of the galaxy are good but the photographic magnitude has not much weight, particularly as the galactic latitude is relatively low.

NGC 1068 (*M77*)

Both the radio and optical observations of this galaxy are reliable. Although classified as an Sb it is of a fairly unusual type which shows strong and broad emission lines in the nucleus (Seyfert 1943). The relatively high value of radio emission is therefore not unexpected.

I 5267

An attempt was made to observe this comparatively faint galaxy primarily because a similarity in its appearance to that of NGC 5128 and NGC 1316 had been suggested by Evans (1949) and both the latter are now thought to be strong radio sources. The identification is not a good one as it is based on one observation only at an adjacent declination and there is some confusion from nearby sources. However, it is considered that there is a good chance that the identification is correct and the observation is in any case interesting as it demonstrates that the radiation is not markedly abnormal, if at all. Moreover, on plates taken by de Vaucouleurs there is no obvious similarity to NGC 5128.

NGC 4594 (*M104*)

This is a measurement of theoretical importance as M104 is a giant galaxy very rich in type II stars and also relatively bright. A sample record is shown in Figure 4 (*c*). Although there are several sources preceding and following the galaxy the region of its immediate vicinity shows no trace of excess emission. It is possible that a depression of the background radiation coincides with the position of the galaxy, but a more natural and likely interpretation is that the radio emission is too weak to be detected. Two particularly good records permit a very low upper limit to be set on its radio emission.

NGC 1291

This is one of the brighter early types accessible to the instrument, but the photographic magnitude is not known accurately and the value quoted is a " best estimate ". There is no trace of radio emission.

NGC 3115

This is an almost completely dust free and probably gas free system and the photographic magnitude has a very high weight. Again there was no trace of radio emission on two consecutive high quality records.

Several northern galaxies have been detected by Brown and Hazard (1953). Their measurements are given in Table 4. One of their suggested identifications (NGC 5457) has been omitted as the position agreement was considered too poor, the discrepancy amounting to nearly 3°. The photographic magnitudes

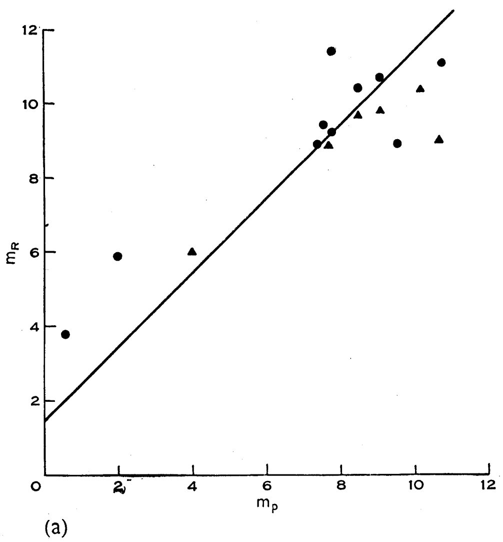
TABLE 4

A COMPARISON OF THE RADIO AND PHOTOGRAPHIC MAGNITUDES OF SOME NORTHERN NEBULAE

Nebula	Type	m_R	m_p	$m_R - m_p$
NGC 5194–5 (M51) ..	Sc	9·7	8·5	1·2
NGC 224 (M31)	Sb	6·0	4·0	2·0
NGC 3031 (M81)	Sb	8·9	7·75	1·1
NGC 4258	Sb	9·8	9·1	0·7
NGC 2841	Sb	10·4	10·2	0·2
NGC 891	Sb	9·0	10·7	—1·7

are again derived from de Vaucouleurs' revision of the Shapley-Ames catalogue, and therefore differ from those quoted by Brown and Hazard who used the original catalogue.

The two sets of observations are combined in Figures 5 (*a*) and (*b*) in which, firstly, the radio magnitudes are plotted against the photographic, and secondly,



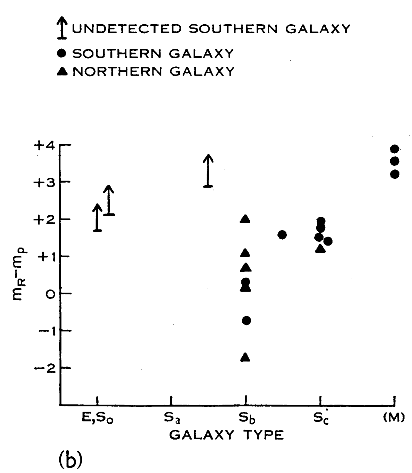


Fig. 5 (*a*).—A comparison of the radio and optical emission of all galaxies which have been detected.

Fig. 5 (*b*).—Illustrating the different radio emitting efficiencies of different galaxy types.

the differences between the two magnitudes are plotted against the type of galaxy. If all the galaxies had a constant ratio of radio to optical emission the points in Figure 5 (*a*) would lie on a straight line of slope 1·0. The line of this slope which fits the data best is shown ; it corresponds to a mean value of

$m_R - m_p$ of $+1 \cdot 4$, individual galaxies having a dispersion of $1 \cdot 5$ magnitudes. The northern galaxies fall mainly below this line and the southern galaxies mainly above it so that some calibration discrepancy might be suspected. However, there is no reason for supposing that galaxies of all types should have similar radio emitting efficiencies and it is desirable to compare the galaxy types separately.

In Figure 5 (*b*) where this is done it can be seen at once that there is no suggestion of any discrepancy. Unfortunately, the northern and southern galaxy types so far observed have little overlap, and significant cross checking of calibrations is not possible. However, it appears fairly safe to conclude that galaxies of intermediate type are more efficient emitters than both earlier and later types. The means of the various types, excluding the Sbc galaxy, together with their standard errors, are as follows :

$$\begin{aligned}
&\text{Sb,} \quad && m_R - m_p = +0 \cdot 3 \pm 0 \cdot 4, \\
&\text{Sc,} \quad && m_R - m_p = +1 \cdot 6 \pm 0 \cdot 2, \\
&\text{(M),} \quad && m_R - m_p = +3 \cdot 6 \pm 0 \cdot 2.
\end{aligned}$$

The difference between Sb and Sc galaxies is hardly significant but the Magellanic types are very significantly weaker in radio emission than both. In view of earlier evidence concerning the type I distribution of emission in the Clouds, it is surprising that the Magellanic type galaxies which contain proportionally the greatest mass of type I population should be relatively weak radio emitters. This apparent anomaly will be discussed later after reviewing the evidence from the distribution of radio emission in our own galaxy. It is found to have a natural interpretation.

V. Radiation from the Milky Way

Although many attempts have been made to study the distribution of radio emission in the Galaxy, none has been completely successful. The difficulty is that at long wavelengths the aerial resolution has been insufficient to obtain unambiguous results while at short wavelengths the low receiver sensitivity and the low brightness of the non-thermal background component combine to restrict the useful information available. The resolution limitation imposed by a long wavelength, wide beam aerial has often been overlooked, but it is of vital importance because detail below a certain size is irretrievably lost (Bracewell and Roberts 1954). In one well-known survey (Bolton and Westfold 1950) this lower limit of size is nearly 8°. Some interferometer measurements of Scheuer and Ryle (1953) partly overcame this difficulty and gave effectively a high resolution at right angles to the galactic plane, but the poor resolution along the plane and the assumption of symmetry which had to be made produced results of doubtful quantitative value. Nevertheless, it is now found that these observations appear to give a good qualitative picture of the distribution at the longer wavelengths.

A complete survey of the southern sky is to be undertaken soon which, it is hoped, will give an accurate overall picture of the distribution, but, owing to the vast amount of detail which is discernible, it will be some time before the results become available. Meanwhile it is possible, by obtaining a few galactic sections near the centre at fixed declinations, to check the various distributions already proposed. Three such sections are shown in Figure 6, and it can be seen at once that these do not fit the concept deriving from some of the earlier surveys, namely, that the spatial distribution is similar to that of the mass of the Galaxy (Westerhout and Oort 1951). Under such a hypothesis the width between half-brightness points should be about 17°. It appears instead that two galactic distributions are involved, one very sharply concentrated towards the galactic plane with a width between half-brightness points of about 3°, and less sharply but quite markedly towards the galactic centre; the other very broad

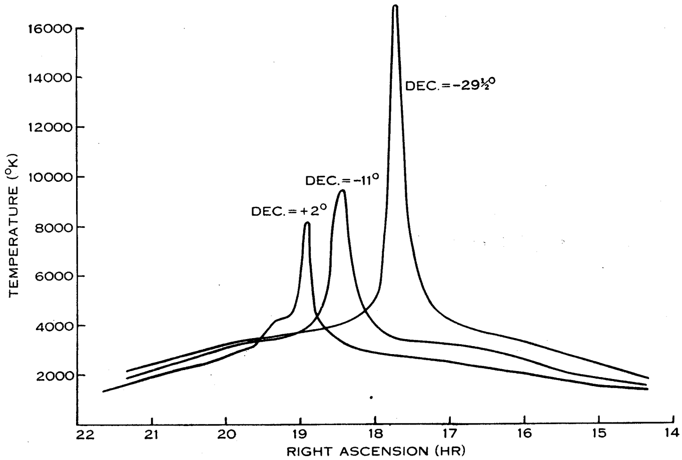


Fig. 6.—Some galactic sections near the centre. (Accuracy is about 10–20 per cent.)

and flat, with an estimated angle between half-brightness points (after allowing roughly for an isotropic extragalactic contribution) of 60 or 70°. The exact amount of extragalactic radiation cannot be estimated from these observations. It is no longer permissible to equate it to the temperature at the galactic poles which could be largely due to the very broad galactic distribution.

Such an overall picture has already been deduced by Shklovskii (1952, 1953) from an analysis of previous surveys. He maintains that the flattened distribution is due to thermal emission from ionized gas, and the broad distribution, which he concludes forms a spherical spatial distribution concentric with the galactic centre, to synchrotron type emission from relativistic electrons radiating in weak magnetic fields. Also from consideration of the contours of the Andromeda nebula obtained by Brown and Hazard (1951) he deduced a similar spherical distribution in that galaxy. The latter deduction has received support from some later measurements of Baldwin (1954).

The symmetry of the broad distribution of Figure 6 with respect to the galactic centre cannot be checked with a few observations because of the many and large brightness irregularities. However, two obvious properties of a spherical spatial distribution that might be roughly tested are that at a given declination the sky brightness should, after excluding the contribution from the flattened subsystem, have its maximum value at the Right Ascension of the galactic centre and be a function only of the angular separation from the centre. Reference to Figure 6 shows that the sections are approximately consistent with these properties, and a few other observations of absolute temperatures which have been made also seem consistent.

It therefore appears safe to conclude that a division of the galactic radiation into the two subsystems proposed by Shklovskii can be assumed as a working hypothesis. It does not follow, however, that his interpretation of the mechanisms involved need be accepted ; in fact it is quite easy to show that, contrary to his suggestion, the major contribution to the radiation from the flattened subsystem in the vicinity of the galactic centre must have a non-thermal origin. This follows immediately from a comparison with two higher frequency surveys, namely, those of Piddington and Minnett (1951) with a beam width of 2·8° at a wavelength of 25 cm, and by McGee and Bolton (1954) with a 2° beam at 75 cm wavelength. At a declination of $-29\frac{1}{2}°$ these surveys yielded temperatures of 17 °K at a wavelength of 25 cm,* and 150 °K at a wavelength of 75 cm ; at 3·5 m the temperature of the flattened subsystem at the same declination is 13,000 °K. The apparent temperature spectrum of a mass of thermally emitting gas is given by $T \propto \lambda^n$, where n lies between 0 and 2, depending on the opacity. The temperature at 3·5 m is far too high to be fitted by this law which would predict a temperature less than 3400 °K at that wavelength. However, comparisons between the two other measurements suggest that the radiation at shorter wavelengths is predominantly due to thermal emission from the ionized gas. By means of similar comparisons it is easy to demonstrate that the spherical subsystem also has a non-thermal spectrum.

The thickness of the flattened subsystem near the galactic centre is about 400 parsecs, corresponding to the observed angular width of 3°. This is comparable with the thickness of the neutral hydrogen layer, which suggests a relation to the Population I component of the Galaxy. A similar estimate for the spherical subsystem is necessarily very crude. The value obtained, which depends greatly on the form of the radial distribution, is of the order of 10 kiloparsecs. The radio emission undoubtedly extends much further in an attenuated form. It is not possible to decide at present whether the distribution is oblate, or truly spherical. The observations tend to favour the first possibility.

VI. Discussion

The radio emitting properties of a selection of galaxies have now been examined. Data have been presented showing the total emission of considerable

* The discrete source near the galactic centre has been ignored in estimating the observed temperature of Piddington and Minnett because it is quite clear from several other observers' results that its declination is approximately $-28\frac{1}{2}°$, i.e. well removed from the comparison declination of $-29\frac{1}{2}°$. The declination scale of Piddington and Minnett appears to be in error by about $1\frac{1}{2}°$.

numbers of relatively bright galaxies, the total emission and the distribution of radiation in the Magellanic Clouds and some features of the distribution of radio emission in the Milky Way. It is interesting to speculate on the interconnexion between the sets of observations and to attempt to explain the data by a general theory of the radio emission of a " normal " galaxy.

It has been shown that the galactic radiation can be assumed to originate in two distinct subsystems, one highly flattened and apparently related to the type I population of the Galaxy and the other, roughly spherical, concentric with the centre of the Galaxy and very diffuse, forming a corona surrounding the system. One or the other of these subsystems is recognizable in other galaxies also. In the Clouds the Population I type appears to predominate, as the distribution of radio emission is similar to that of the gas and early type stars. However, the almost plan view of the systems precludes a direct measurement of the thickness of the distribution. In M31 and possibly on a very much smaller scale in the Small Cloud the spherical subsystem can be recognized. In both the Galaxy and M31 this spherical system must be the major source of radiation since in the former it is easily seen that its integrated emission far exceeds that of the sharply concentrated type I component even though the data are insufficient to compute the ratio with any accuracy ;* similarly the contours of M31 obtained by Brown and Hazard show no evidence of a flattened subsystem so that, if present, it must be weak. A natural assumption is that the same two subsystems are present in a greater or lesser degree in all normal galaxies. The relatively high emission of intermediate type galaxies may then be interpreted as due to the possession of a more developed " corona " than either earlier or later types.

It is interesting to observe that the " abnormal " radio galaxy NGC 5128 also displays two subsystems of radio emission, one associated with the band of dust crossing the nucleus and the other forming an extensive corona surrounding the system (Mills 1953).

The flattened subsystem has two basic components. One is due to free-free emission from ionized hydrogen : as the brightness due to this emission process is independent of the wavelength when the opacity is small, it becomes important at the shorter wavelengths. This emission process in the Galaxy has been discussed by many authors, e.g. Reber (1940), Piddington (1951), Westerhout and Oort (1951), Shklovskii (1952, 1953), Haddock, Mayer, and Sloanaker (1954), and many others. The other component is of non-thermal origin and increases in brightness at the longer wavelengths to dominate the picture entirely. Identifications which have been made between some strong radio sources and peculiar galactic nebulae (see for instance a summary by Pawsey (1955)) suggest the possibility that the integrated emission from similar nebulae may be the main source of the non-thermal component in the Galaxy. If so, it is possible that it cannot be classed as purely a Population I type of distribution because

* A rough estimate of the ratio is about 5 or 10.

included among these identifications are the nebulous remains of supernovae, and it is thought that these may be associated with Population II.*

The spherical subsystem, while superficially resembling a pure Population II system, lacks the high central concentration which they display, and in fact, as pointed out by Shklovskii, is quite unlike any known optical feature of the Galaxy. In addition radio emission is absent from the type II stars of globular clusters and a relatively low upper limit can be set to the emission from early type galaxies which have a high proportion of Population II. It therefore appears that this subsystem is unrelated to any distribution of Population II stars, and in general the total radiation of a galaxy at the longer wavelengths cannot be ascribed to a subclass of objects belonging to Baade's Populations I or II.

Turning now to speculation concerning the mechanism of non-thermal radio emission, it has been suggested by Hoyle (1954) and Twiss (1954) that some of the galactic radio nebulae which are associated with highly turbulent ionized gas may represent localized regions containing high energy electrons accelerated by the turbulent gas in a Fermi type process to relativistic energies (Fermi 1949). The relativistic electrons would then radiate at radio frequencies in the concomitant magnetic fields. The observed properties of such nebulae are readily explicable in this way and the necessary physical conditions are reasonable. It is natural to attempt to extend this concept to the spherical subsystem also.

It has been shown by Pikelner (1953) that magnetic fields are likely to exist in the highly rarefied medium between gas clouds with approximately the same average strength as they exhibit inside the clouds. From equipartition considerations this implies that the random macroscopic velocities of the rarefied medium are higher than those of the gas clouds by a factor of the order of 10. It is easily shown that, because of its high velocity, this rarefied medium and its associated magnetic fields must tend towards a spherical spatial distribution. Shklovskii (1953) has suggested that the source of the spherical subsystem of radio emission is the radiation from relativistic electrons moving in this spherical field system. However, he ignores the dynamic effect of the turbulent medium in accelerating charged particles and consequently considers the relativistic electrons to be introduced at their full energy from an external source, in fact, from novae and supernovae. While it is possible that these could be a source of high energy electrons, it appears probable that the electron energy would be increased or at least maintained against radiation losses by the energy of the

* Shklovskii (1953) maintains that all non-thermally emitting nebulosities are the remains of supernovae, but Baade and Minkowski (1954), basing their argument on the frequencies of supernovae observed in external galaxies, conclude that such objects must be comparatively rare and, if their figures are accepted, could account for only an insignificant proportion of the total observed brightness. It is hoped that a current series of radio observations of some southern emission nebulae will help clarify the matter.

turbulent gas which would most likely be the dominant factor in determining the total radio emission.*

This theory has attractive features and leads to a simple explanation of the observed differences in the radio emission of different classes of galaxies. Early type galaxies, comparatively lacking in interstellar gas, are deficient in the corona of gas and magnetic fields ; consequently the emission is low. Late type galaxies of the Magellanic type, on the other hand, possess abundant supplies of gas but do not have sufficient gravitational energy to retain a high velocity corona. Intermediate types possess a good supply of gas from their type I population and a high gravitational energy because of their type II population and therefore radiate strongly.†

The operation of this radiation process in the Galaxy may be investigated quantitatively to determine the physical conditions required. First we may estimate the mean energy of relativistic electrons by equating the rate of gain of energy due to " magnetic collisions " (Fermi 1949) to the rate of loss by radiation (Schwinger 1949), thus,

$$\left(\frac{V_c}{c}\right)^2 . E . \nu_c \sim 1\cdot 6 \times 10^{-15} H^2 \frac{E^2}{(m_0c^2)^2}, \quad \ldots\ldots\ldots\ldots \quad (1)$$

where V_c is the turbulent velocity of the corona, ν_c is the " magnetic collision frequency " in the corona, E is the electron energy, and H the magnetic field. The latter may be obtained from the following relation :

$$\frac{1}{8\pi}\overline{H}^2 = \tfrac{1}{2}\rho_c \overline{V}_c^2, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where ρ_c is the density of the coronal gas.

Combining (1) and (2) and inserting some physical constants we have

$$E \sim 3 \times 10^{-7} \frac{\nu_c}{\rho_c} \text{ eV}. \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

* In his theory of particle acceleration Fermi (1949) found that the rate of gain of energy of electrons is insufficient to counterbalance the loss by ionizing collisions with hydrogen atoms. However, he was considering regions very close to the galactic plane where dense neutral hydrogen clouds abound and random velocities are low. If a corona of tenuous high velocity gas does exist, the rate of gain of energy, which is proportional to the square of the velocity, must be increased by several orders of magnitude. It also seems possible that such a gaseous envelope would, at least in the Galaxy, be largely ionized because the shielding effect of the dense hydrogen clouds would be small in directions normal to the plane. The radius of a Stromgren sphere in a medium of density 10^{-2} atoms cm^{-3} surrounding an early type star is of the order of several thousand parsecs (Stromgren 1939) ; so that ionization is possible at large distances from the plane. Collisional ionization is also a possibility. Such an ionized corona would be unobservable optically since its emission measure would be only of the order of 10 to 100.

† An attempt has been made to extend this idea a little further by comparing the radio emission of a galaxy with the kinetic energy of its corona. In a few cases the kinetic energy has been estimated by assuming a mass proportional to the Population I component and a velocity determined by the total gravitational energy. By adopting reasonable values for these parameters a strict proportionality between kinetic energy and radio emission is obtainable. However, uncertainties in the astronomical data are so large at present that no positive conclusions can be drawn.

Plausible values of ν_c and ρ_c are 10^{-10} sec^{-1} and 3×10^{-26} g cm^{-3} respectively, yielding an average electron energy of 10^8 eV.

By using some formulae given by Ginsberg (1951) the frequency of maximum radio emission ($\nu_{\mathrm{max.}}$), may be calculated, and also the electron density n required to produce the observed radio emission at that frequency, thus

$$\nu_{\mathrm{max.}} = 5\times10^{-5}HE^2, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$n = 10^{23}\frac{kT}{HD}\left(\frac{\nu_{\mathrm{max.}}}{c}\right)^2, \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

where D is the distance through the corona in the direction the measurement is made and T is the brightness temperature of the radio emission.

The magnetic field H may be estimated from equation (2) using the value adopted earlier for ρ_c and a velocity of 200 km/sec. The velocity has been obtained using the virial theorem which seems permissible since the corona is approximately spherical. The resulting field is of the order of 10^{-5} gauss which, when substituted in equation (4), yields a frequency of maximum emission of the order of 5 Mc/s.

No observations are available at this frequency, the nearest being those of Higgins and Shain (1954) at a frequency of 9·5 Mc/s. If their results are extrapolated to the lower frequency a brightness temperature of about 5×10^6 °K is obtained near the galactic centre. Taking D equal to 6×10^{22} cm we then find from equation (5) that the electron density is of the order of 10^{-11} to 10^{-12} electrons cm^{-3}.

All the calculated values seem very plausible and do not appear to contradict any observational results. We may therefore conclude that the mechanism is a possible one.

VII. Conclusions

It appears that the major portion of the radiation of " normal " galaxies at metre wavelengths can be explained qualitatively and perhaps even quantitatively by emission from relativistic electrons radiating in weak interstellar magnetic fields. It should be emphasized, however, that this conclusion does not follow as a *necessary* consequence of the data. For this reason the theory has been developed only in a very sketchy form.

On somewhat firmer ground is the conclusion that radio emission can occur with two separate and distinct distributions, one displaying characteristics of Baade's Population I, and the other having a diffuse roughly spherical spatial distribution forming a " corona " around a galaxy not, however, related to the corona of globular clusters often observed. Both distributions have a non-thermal spectrum and the relative contributions of each vary between different galaxy types. Very late type galaxies such as the Magellanic Clouds possess a high proportion of the Population I type while early type galaxies are deficient in both. Intermediate type galaxies, by virtue of an extensive " corona ", are the most efficient radio emitters.

VIII. Acknowledgments

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