PAPER 18

CURRENT PROGRESS IN DEVELOPMENT AND RESULTS OBTAINED WITH THE 'MILLS CROSS' AT THE RADIOPHYSICS LABORATORY

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The study of continuous spectrum cosmic radio waves in the Radiophysics Laboratory is based mainly on two large 'Mills Crosses': one on 85 Mc./s. which has been in use for a year, and another on 20 Mc./s. which is under construction. The principle of this instrument has been described by Mills and Little (1953) [1]. It utilizes two long thin arrays arranged in the form of a cross and gives an effective 'pencil-beam' response which records both the background and discrete sources simultaneously. Essential data relating to these Crosses are given in Table 1.

Table 1

	85 Mc./s. Cross	20 Mc./s. Cross
Length and orientation of arms	N.-S. 1500 ft. E.-W. 1500 ft.	N.-S. 3600 ft. E.-W. 3400 ft.
Width of dipole arrays forming arms	2 dipoles	1 dipole
Angular resolution (between half-power points, near zenith)	50′	85′*
Sensitivity limit (ideal conditions)	10^{-26} w.m.$^{-2}$ (c./s.)$^{-1}$	—
Present status	Working since 1954	Under construction

* Design figure.

The instrument is used as a transit instrument with the declination adjusted by phase adjustments in the north-south arm. For maximum sensitivity the beam remains at a fixed declination and the output is recorded as the sky passes overhead. For survey work and plotting isophotes the beam is switched successively (on the 85 Mc./s. Cross) between five declinations separated by about half a beam-width and the output on each declination recorded. This method utilizes one-fifth of the total time on each declination and the sensitivity is correspondingly reduced by a factor of about $\sqrt{5}$. During the past year the programme of observations on

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85 Mc./s. was based on the study of optical objects while at the same time work continued on the improvement of the equipment. This is now ready for a comprehensive survey of the sky visible to the instrument. The beam deteriorates at angles far removed from the zenith due to foreshortening effects, and the approximate limits of coverage are $\pm 45°$ from the zenith or, say, from declination $+10°$ to the south pole.

The observations described in this paper include a study of normal galaxies which is the subject of a paper by B. Y. Mills (1955) [2], and studies of the radio emission from various classes of objects: colliding galaxies, novae, and emission nebulae, which are reasonably advanced

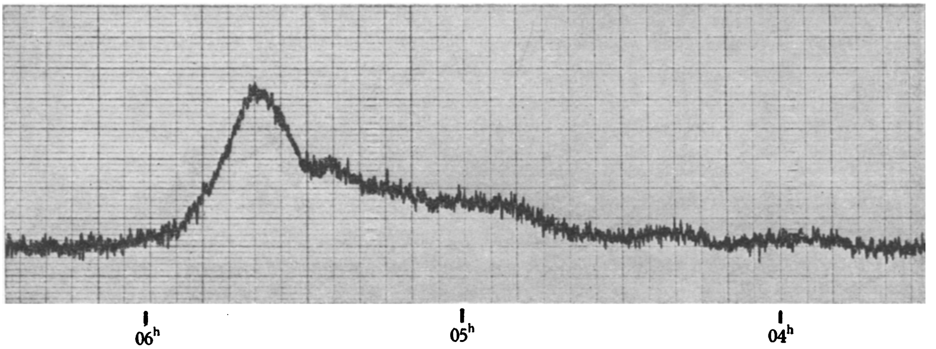

Fig. 1. A typical record of an extended source. The Large Cloud of Magellan traversed at declination $-69° 26'$.

items selected from those being studied by Mills and his colleagues, A. G. Little, K. V. Sheridan and O. B. Slee. The statistics of the thousand discrete sources so far listed are discussed in a separate note (paper 40, Pawsey) and some observations of discrete sources which appear to show variations (paper 31, Bolton).

Sample records are shown in Figs. 1 and 2. Fig. 1 illustrates the effect of an extended object, the Large Cloud of Magellan recorded on declination $-69° 26'$. Fig. 2 illustrates discrete sources of various intensities. In the upper record NGC 55 is near the limit for detection and several records were necessary before its existence was accepted. Its flux density is $1 \cdot 8 \times 10^{-26}$ w.m.$^{-2}$ (c./s.)$^{-1}$. The middle record shows an isolated source NGC 253 of flux density $1 \cdot 1 \times 10^{-25}$ w.m.$^{-2}$ (c./s.)$^{-1}$ and the lowest one shows no detectable source in the position of NGC 4594. Over the greater part of the sky the detection limit is set by sensitivity but large areas exist which are confusion-limited.

The different types of objects studied will now be discussed in turn.

The study of the radio emission by normal galaxies is based on observations of our own galaxy, of the Clouds of Magellan which are resolved by the Mills Cross, and of samples of various types of external galaxies which are so distant that only the integrated emission is observed.

Sample records of traverses across the Milky Way shown in Fig. 3 strongly suggest the dual distribution put forward by Shklovsky (1952, 1953) [3], a disk-like one presumably associated with population I objects and another having a very extensive, roughly spherical, distribution unlike

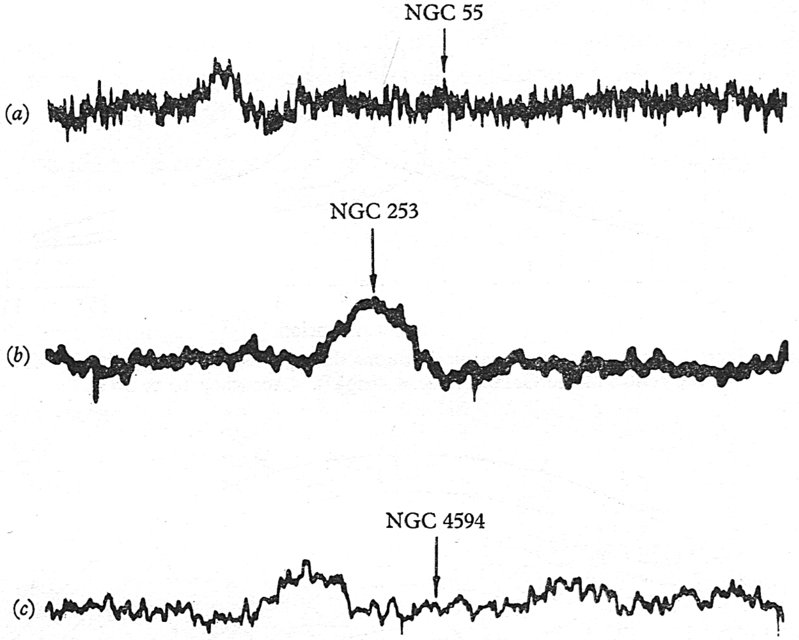

Fig. 2. Sample records showing discrete sources of small size. The sources noted are external galaxies. Flux densities NGC55 – 1.8×10^{-26}; NGC253 – 11×10^{-26}; NGC4594 (undetectable) $< 1.3 \times 10^{-26}$ w.m.$^{-2}$ (c./s.)$^{-1}$.

any known stellar population. Both distributions have spectra which show that the predominant emission at low frequencies is non-thermal.

Isophotes of the Clouds of Magellan are shown in Fig. 4. These conform better with the distributions of interstellar atomic hydrogen as given by 21-cm. observations and of bright stars than with other optical objects studied and suggest that the radio emission is associated in the Clouds with population I.

Nine globular clusters were examined and only one, NGC6121, can possibly be identified with a radio source. This source, however, appears extended so that its identification with the star cluster itself is unlikely. The clusters examined included the bright ones 47 Tucanae and NGC 362 and,

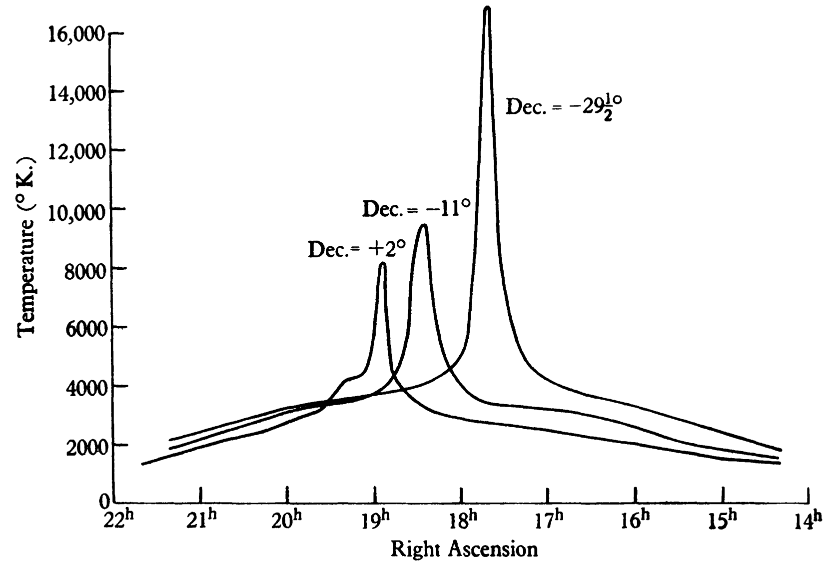

Fig. 3. Sample traverses at constant declinations through the Milky Way in the vicinity of the centre of the Galaxy (Dec. = $-29\frac{1}{2}°$). (Accuracy 10 or 20 %.)

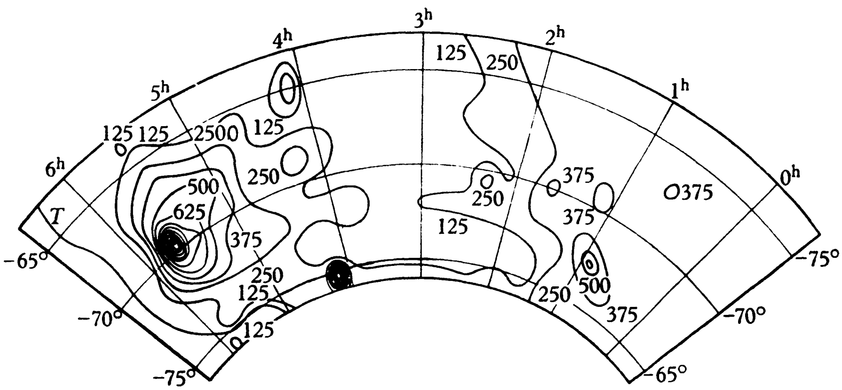

Fig. 4. 85 Mc./s. isophotes of the region of the Clouds of Magellan. Contour interval of brightness temperature 125° K.; all values specified as excess over a base level T estimated as 700° K.

in the former case if the ratio of radio to optical emission were the same as for late-type spirals, a signal 500 times the minimum detectable level would have been expected. Globular clusters with their type II population appear to be very poor radio emitters.

Attempts were made to observe thirteen bright southern galaxies of various types. These results, and those for the two bright globular clusters mentioned above, are listed in Table 2 together with photographic magnitudes. In order to have a convenient measure of the relative ratio of optical and radio emission the flux densities have been expressed on a magnitude scale defined by

$$m_{R(158)} = -53\cdot4 - 2\cdot5 \log_{10} S_{(85\ \mathrm{Mc./s.})} + 0\cdot47$$

which is similar to that used by Hanbury Brown and Hazard (1952) [4] with the addition of the final term 0·47 which is an estimated correction to convert from 85 Mc./s. to the latter's 158 Mc./s. The final column, $m_R - m_p$, is a measure of the required ratio in magnitudes. In Table 4 $m_{R(85)}$ is defined similarly except for the omission of the term 0·47 converting from 85 to 158 Mc./s.

Table 2. *A comparison of the radio and photographic magnitudes of some southern galaxies and globular clusters*

Nebula	Type	Flux density at 85 Mc./s. (w.m.$^{-2}$ (c./s.)$^{-1}\times 10^{-26}$)	$m_{R(158)}$	m_p	$m_R - m_p$
LMC	(M)	2000	3·8	0·5	3·3
SMC	(M)	300	5·9	2·0	3·9
NGC 55	(M)	1·8	11·4	7·8	3·6
NGC 253	Sc	11	9·4	7·6	1·8
NGC 300	Sc	4·8	10·4	8·5	1·9
NGC 5236 (M 83)	SBc	19	8·9	7·4	1·5
NGC 4945	SBc	12	9·2	7·8	1·4
NGC 6744	SBbc	3·0	10·7	9·1	1·6
NGC 1068 (M 77)	Sb	19	8·9	9·6	−0·7
I 5267*	Sb	2·5	11·1	10·8	0·3
NGC 4594 (M 104)	Sab	< 1·3	> 11·8	8·9	> 2·9
NGC 1291	SBo	< 1·5	> 11·6	9·5	> 2·1
NGC 3115	E 7	< 1·2	> 11·9	10·15	> 1·7
47 Tucanae	Globular cluster	< 2·6	> 11·0	3·0	> 8·0
NGC 362	Globular cluster	< 2·9	> 10·8	6·0	> 4·8

* Identification uncertain.

Having used Hanbury Brown and Hazard's scale it is possible to increase the sample by including six northern galaxies observed by them (1935) [5], namely, NGC 5194–5, 224, 3031, 4258, 2841 and 891. The ratio $m_R - m_p$ for both series was plotted against galactic type and a definite trend became evident. Spiral galaxies of types Sb and Sc tend to have a higher ratio of radio to optical emission ($m_R - m_p$ smaller) than do either elliptical or magellanic types.

In discussing this evidence Mills has suggested that the two types of distribution, diskoidal or population I and spherical, evident in our galaxy, are present in greater or less extent in normal galaxies. In the magellanic types the population I would appear to predominate. The spheroidal types lack this component and presumably the other is ill-developed. In the Sb and Sc types the spherical system appears to predominate and to be the main source of the relatively strong emission. Mills discusses the probable role of relativistic electrons in the emission.

2. COLLIDING GALAXIES

Colliding galaxies have been suggested as radio sources because three strong radio sources can be identified with galaxies which have peculiarities suggesting that a collision may be in progress. An attempt has now been made to detect radiation from four other galaxies which have been suggested as being in collision. The results shown in Table 3 are negative except for one example, NGC4038/39, where a slightly abnormal emission exists (about 2 magnitudes brighter than an average Sc galaxy). This abnormal emission is still very much less than that of the first three galaxies mentioned. If the four galaxies tested are really in collision it may be concluded that a collision does not always result in greatly enhanced radio emission.

Table 3. *Observations of galaxies suggested to be colliding*

(*a*) New observations

Galaxy and radio source	Flux density at 85 Mc./s. (w.m.$^{-2}$ (c./s.)$^{-1}\times 10^{-26}$)	$m_{R(158)}$	m_p	$m_R - m_p$
NGC4038/39*	4·7	10·3	10·6	− 0·3
NGC3256†	< 1·5	> 11·6	10·6	> 1·0
NGC1487†	< 2·5	> 11·0	11·9	> − 0·9
NGC520†	< 4·0	> 10·5	11·6	> − 1·1

(*b*) Previously known

Galaxy and radio source	Flux density at 85 Mc./s. (w.m.$^{-2}$ (c./s.)$^{-1}\times 10^{-26}$)	$m_{R(158)}$	m_p	$m_R - m_p$
Cygnus A	14,000	2·0	18·0	− 16·0
NGC1275, Perseus A	130	7·0	12·0	− 5·0
NGC5128, Centaurus A	5,000	2·8	6·0	− 3·2

* Suggested by R. Minkowski. † Suggested by G. de Vaucouleurs.

3. NOVAE

Supernovae and novae have been suggested as radio sources because of the identification of several strong sources as the remnants of supernovae. A selection of ten novae and two supernovae, one extra-galactic, has therefore been examined and the results are given in Table 4. Of these twelve objects the only certain identification is with Kepler's Star, the galactic supernova. Taken in conjunction with previously known identifications these results support the suggestion that supernovae give rise to intense radio sources, but give no support to the corresponding suggestion for novae. Quantitatively, the radio emission from the remnants of novae studied must be less than that from supernovae by at least a factor equal to the ratio of the light emitted at the maximum of each. Unfortunately the majority of novae occur near the galactic centre where the sensitivity of the equipment is much reduced.

Table 4.

Southern novae observations

Nova	Flux density at 85 Mc./s. (w.m.$^{-2}$ (c./s.)$^{-1}\times 10^{-26}$)	$m_{R(85)}$	m_p at max.	$m_R - m_p$	Remarks
1604 Ophiuchi	38	7·5	−2	9½	Kepler's star, a supernova
1860 Scorpii	< 10	> 9	7	> 2	
1895 Carinae	< 10	> 9	8	> 1	
1895 Centauri	< 5	> 10	7	> 3	A supernova in NGC 5253
1898 Sagittarii	< 5	> 10	4·7	> 5½	
1899 Sagittarii	< 10	> 9	8·5	> ½	
1899 Aquilae	< 10	> 9	7	> 2	
1910 Sagittarii	< 20	> 8·3	7·5	> ½	
1917 Ophiuchi	< 10	> 9	6·5	> 2½	
1918 Aquilae	< 10	> 9	−0·7	> 9½	Wrongly suggested as a strong radio source by Bolton, Stanley and Slee
1925 Pictoris	< 5	> 9·7	1·1	> 8½	
1942 Puppis	< 5	> 9·7	0·4	> 9½	
Northern novae					
1054 Tauri	1800	3·4	−6	9½	The Crab nebula, a supernova
1572 Cassiopeiae	170*	6·0*	−4	10*	Tycho Brahe's star, a supernova

* Estimated from Manchester 158 Mc./s. observations.

4. EMISSION NEBULAE

It is known from theoretical considerations that emission nebulae should emit thermally in the radio spectrum by the free-free transition mechanism, and the intensity of emission at each frequency can be estimated from optical data. Such objects should be observed in emission if the background brightness temperature were lower than the electron temperature in the nebula, in absorption if higher. A number have been observed in emission at high frequencies (order of 1000 Mc./s.) where the thermal emission is relatively high, but none has been reported on lower frequencies where it is relatively low.

Table 5. *Observations of emission nebulae*

Nebula	Flux density at 85 Mc./s. Observed (w.m.$^{-2}$ (c./s.)$^{-1}$ $\times 10^{-26}$)	Flux density at 85 Mc./s. Estimated from optical data (w.m.$^{-2}$ (c./s.)$^{-1}$ $\times 10^{-26}$)
η Carinae nebula	150	—
NGC 2237	130	160
30 Doradus	30	35*
Orion nebula (M 42)†	37	15*
I 2177	15‡	—
NGC 2264	8‡	—

* Estimated assuming the nebula is optically thick and electron temperature = 10,000° K.

† Also observed at N.R.L. at frequencies of 1400 and 3200 Mc./s. with flux density 450.

‡ The background in these neighbourhoods is complex so that the identifications are not yet certain. The question should be settled when detailed contours over the region become available.

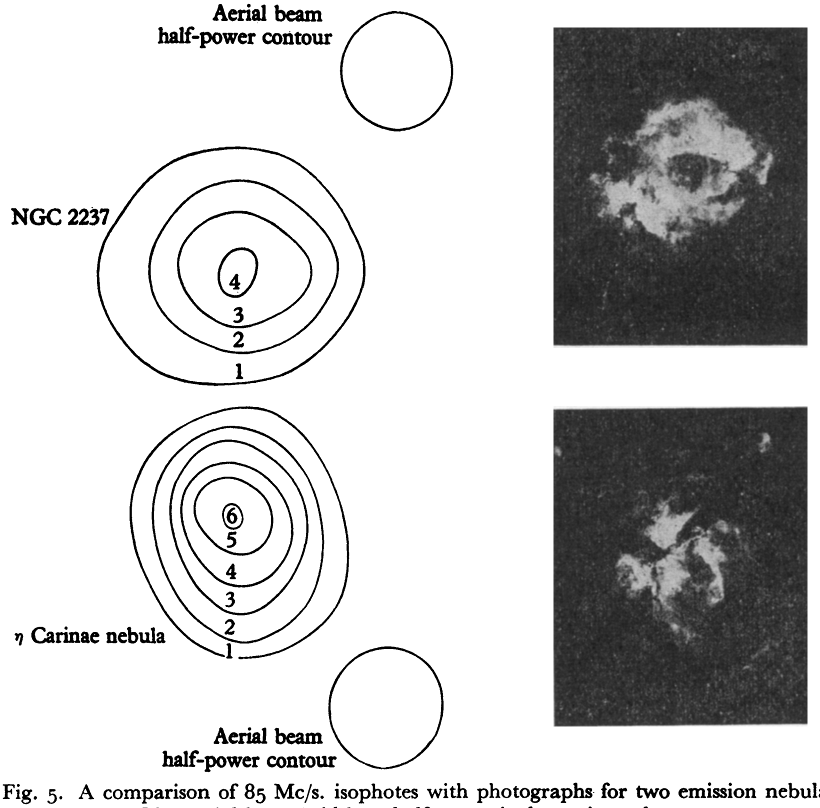

Fig. 5. A comparison of 85 Mc/s. isophotes with photographs for two emission nebulae. The aerial beam-width to half-power is shown in each case.

Our new equipment, however, has sufficient sensitivity and resolution to permit observation of a considerable number. Six bright nebulae situated in regions of relatively faint background have probably been observed in emission, five of these having not previously been reported observed at radio frequencies (see Table 5). In the cases where adequate optical data exist the observed radio emission has been computed and this value is also shown. The larger nebulae can be resolved and the radio isophotes are compared with photographs in Fig. 5. The evidence indicates that many emission nebulae emit thermally in the expected manner and do not contain intense non-thermal sources.

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Note added in proof.

Subsequent calibrations indicate that the flux densities in this paper are too low by a factor of approximately 2. This does not seriously affect physical conclusions.