OBSERVATIONS OF RADIO EMISSION FROM NORMAL GALAXIES

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Summary

The results of observations of 37 normal galaxies using the 210-ft steerable reflector of the A.N.R.A.O. at 1410 and 408 Mc/s are presented. All southern galaxies brighter than tenth magnitude were studied. Twenty galaxies were detected, fourteen of which were new identifications. Sc galaxies were found to have a mean radio index at 1410 Mc/s of $+3\cdot3$ with an r.m.s. deviation of $0\cdot6$. The ratio of optical to radio emission was significantly higher for irregular and early type galaxies than for Sb and Sc galaxies. Contrary to general belief, no constant relationship was found between the optical and radio sizes of spiral galaxies. Two discrete radio sources were detected in the Pegasus I cluster, one of which may be identified with the E1 galaxy, NGC 7626. The radio source found in Pegasus II coincided in position with the E3 galaxy, NGC 7501, in the cluster.

I. Introduction

The 210-ft steerable reflector of the Australian National Radio Astronomy Observatory has been used to observe the radio emission at 1410 and 408 Mc/s from a selection of the optically brightest normal galaxies in the southern sky. The 1410 Mc/s observations were the first high-resolution study of southern galaxies, and a high level of sensitivity enabled 20 galaxies to be detected out of a total of 37 investigated. All southern galaxies brighter than $m_{\mathrm{pg}} = 10$ were studied, together with a few others considered interesting. Fourteen of the twenty had not been detected in previous surveys.

The Magellanic Clouds have been the subject of a special investigation (Mathewson and Healey 1963), the details of which will not be included in this paper.

In addition to the observations of individual galaxies, a number of scans were made through the Pegasus I and Pegasus II clusters of galaxies, as it was thought to be of some interest to investigate the 20-cm continuum emission from this region, following the recent report by Penzias (1961) of the detection of H-line emission from Pegasus I.

The 408 Mc/s survey was carried out simultaneously to supplement the 1410 Mc/s observations, but its value was severely limited by confusion effects.

II. Observations

The source Hydra A was used to calibrate the aerial system. It was assumed to have a flux density of 45×10^{-26} W m^{-2}(c/s)$^{-1}$ at 1410 Mc/s and 130×10^{-26} W m^{-2}(c/s)$^{-1}$ at 408 Mc/s. These values were based on a combination of the results of Heeschen and Meredith (1961) at 3000 and 750 Mc/s, Harris and Roberts (1960) at 960 Mc/s, Edge *et al.* (1959) at 159 Mc/s, and Mills, Slee, and Hill (1958) at $85\cdot5$ Mc/s.

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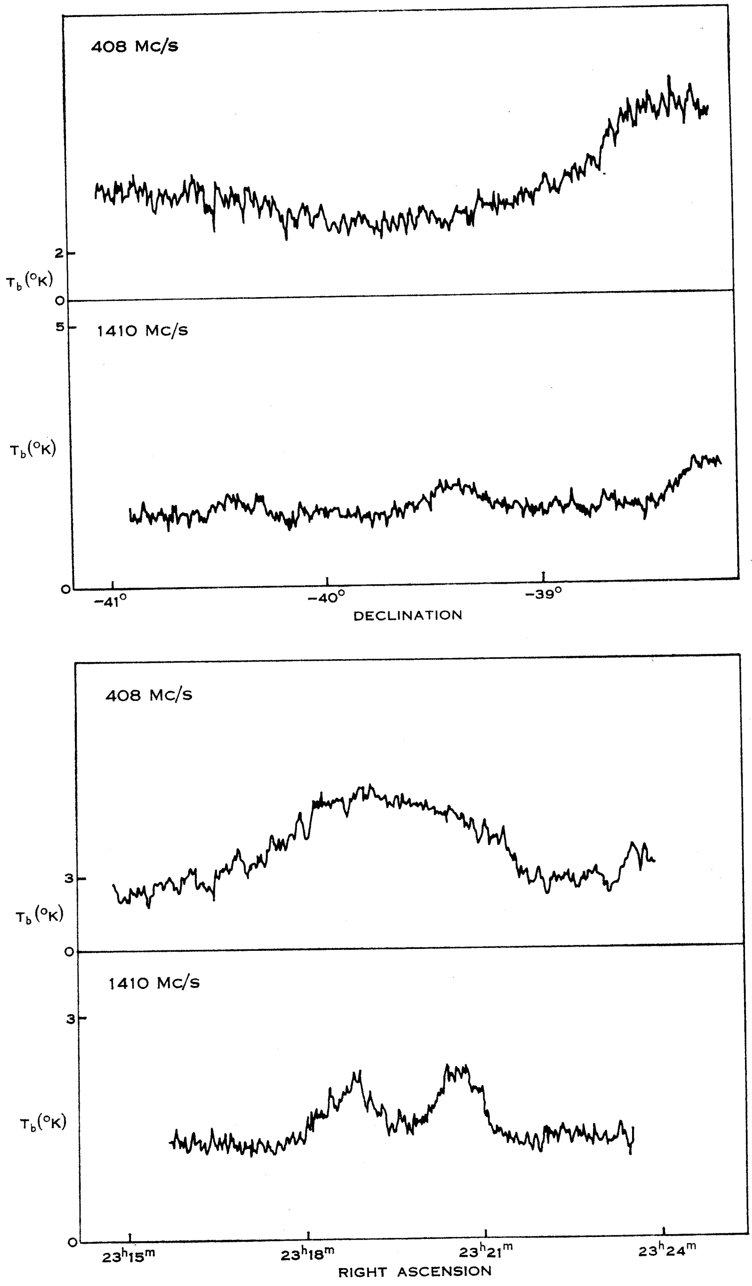

Fig. 1.—(Top) Scans in declination at 408 and 1410 Mc/s at right ascension $00^h\ 13^m\ 06^s$ through NGC 55. (Bottom) Scans in right ascension at 408 and 1410 Mc/s at declination +08°03′ through the Pegasus I cluster. (1962·5 coordinates).

TABLE 1

RADIO RESULTS AND OPTICAL DATA FOR OBSERVED GALAXIES

Galaxy	Type	Optical Position (1950·0) R.A. h m	Optical Position (1950·0) Dec. ° ′	Radio Position (1950·0) R.A. h m	Radio Position (1950·0) Dec. ° ′	Total Optical Magnitude Uncor-rected	Total Optical Magnitude Cor-rected	Optical Size (min of arc) Major Axis	Optical Size (min of arc) Minor Axis	Flux Density ($10^{-26}Wm^{-2}(c/s)^{-1}$) 1410 Mc/s	Flux Density ($10^{-26}Wm^{-2}(c/s)^{-1}$) 408 Mc/s	Radio Size at 1410 Mc/s (min of arc) R.A. Dec.	Radio Index at 1410 Mc/s
NGC 45	Sc	00 11·4	−23 27	—	—	10·7	10·6	8·8	7·2	<0·1	N	—	>+3·4
55[a]	SBm	00 12·5	−39 30	00 12·6	−39 30	7·8	6·8	30	4·0	0·72	C	8×5	5·1
247	Sc	00 44·6	−21 01	00 44·7	−21 02	9·4	8·6	18	5·5	0·20	<0·3	—	4·7
253[b]	Sc	00 45·1	−25 34	00 45·2	−25 33	7·5	6·5	21	5·3	5·6	12·3	<5	3·2
300[c]	Sc	00 52·6	−37 58	—	—	8·7	8·6	30	23	<0·1	N	—	>5·4
Sculptor	dE	00 57·5	−33 58	—	—	7·1	7·0	45	40	<0·1	<0·3	—	>7·0
IC 1613	I	01 02·3	+01 51	—	—	8·9	8·9	20	20	<0·1	<0·8	—	>5·1
NGC 628	Sc	01 34·0	+15 32	01 34·0	+15 31	9·8	9·8	8·0	8·0	0·22	C	<5	3·4
Fornax	dE	02 37·5	−34 44	—	—	7·5	7·3	50	35	<0·1	—	—	>6·7
NGC 1097	SBb	02 44·3	−30 29	02 44·3	−30 28	10·6	10·3	9	5·5	0·63	C	10×5	1·7
1232	Sc	03 07·5	−20 46	03 07·5	−20 48	9·95	9·95	7·0	7·0	0·14	<0·6	—	3·7
1291	SBO	03 15·5	−41 17	03 15·4	−41 20	9·4	9·4	8	7·5	0·20	C	—	3·9
1313[d]	SBc	03 17·6	−66 40	03 17·5	−66 41	9·5	9·5	9	8	0·38	1·3	<5	3·1
1365[e]	SBb	03 31·8	−36 18	03 31·8	−36 17	9·8	9·7	7·5	5·5	0·63	1·3	<5	2·3
1448[f]	Sc	03 42·1	−44 48	03 42·2	−44 50	11·0	10·0	8·2	1·8	0·40	C	—	+2·5
1553	SO	04 15·2	−55 54	—	—	9·6	9·4	4·0	3·0	<0·1	C	—	>4·6
1566	Sc	04 18·9	−55 04	04 18·9	−55 03	9·5	9·4	6	5	0·43	C	(<5)×11	3·1
1672	SBc	04 44·9	−54 20	—	—	10·8	10·5	4·3	2·0	<0·1	N	—	>3·5
1808[g]	SABO/a	05 05·9	−37 34	05 06·0	−37 35	10·8	10·7	12·6	9·8	0·63	C	8	1·3
2427[h]	Scd	07 35·1	−47 30	—	—	9·9	9·5	5·5	2·5	N	C	—	See notes
2903	Sc	09 29·3	+21 44	09 29·3	+21 43	9·5	9·3	12	7	0·55	C	—	2·9
2997	Sc	09 43·5	−30 58	09 43·5	−30 55	9·4	9·3	7	5·5	0·60	C	10×10	2·8
4594[i]	Sa	12 37·3	−11 21	—	—	8·9	7·7	6·5	2·0	<0·1	<0·3	—	>6·3
4945[j]	SBc	13 02·4	−49 13	13 02·5	−49 13	7·8	6·8	15	2·5	6·8	17·0	<5	2·7
4976	E5	13 05·9	−49 14	—	—	9·7	9·2	3	1·5	<0·1	N	—	>4·8

NGC 5236[k]	Sc	13	34·3	−29	37	13	34·2	−29	35	7·5	7·5	10	9	2·5	7·2	<5	3·0
5253	I	13	37·1	−31	24	—		—		9·8	9·4	3·5	1·5	<0·1	C	—	>4·6
5643	Sc	14	29·4	−43	59	14	29·4	−43	59	9·7	9·6	3	2·5	0·25	C	—	3·5
6215[l]	Sc	16	46·8	−56	55	—		—		9·7	9·6	2·0	1·5	<0·1	C	—	>+4·4
6221[m]	SBc	16	48·5	−59	08	—		—		9·6	9·5	3·0	2·0	C	C	—	—
6300	SBb	17	12·3	−62	46	—		—		9·9	9·8	2·5	2·0	<0·1	N	—	>4·2

[a] A Magellanic irregular which broadened the 14′ of arc aerial beam at 1410 Mc/s. From the peak brightness temperatures at 3000 Mc/s (Heeschen 1961) and 1410 Mc/s, observed with similarly sized beams, a spectral index of −1·5 was calculated, while the integrated flux densities at 1410 and 85·5 Mc/s (Mills 1955) gave a value of −0·6. As NGC 55 was near the limit of detection at 3000 Mc/s, small errors in the intensity would yield large errors in calculations of spectral index between 1410 and 3000 Mc/s, possibly explaining the steepness of the value found. This was supported by flux density measurements of the Large Magellanic Cloud at 1410 and 408 Mc/s (Mathewson and Healey 1963), 85·5 Mc/s (Mills 1959*b*), and 19·7 Mc/s (Shain 1959), which gave a spectral index of −0·5 over this range.

[b] A spectral index of −0·6±0·1 was calculated from flux density measurements between 3000 and 85·5 Mc/s.

[c] No source coincided with the centre of the galaxy at 1410 Mc/s, but a weak source lay about 7′ of arc west, within the field of the optical object. The 408 Mc/s record suffered from confusion effects, resulting in a broad source centred about 10′ of arc east and a few minutes south, in agreement with the results of Mills (1955), who also found a source in this position with a similarly sized beam at 85·5 Mc/s. No identification is claimed in this case.

[d] A spectral index of −1·0 resulted from the 1410 Mc/s and 408 Mc/s intensities, but the 408 Mc/s flux density may be too high as the result of confusion with nearby sources resolved at 1410 Mc/s.

[e] The 1410 and 408 Mc/s results gave a spectral index of −0·6. The 408 Mc/s flux density appeared reliable in this case, as no other sources were detected nearby with the 14′ beam at 1410 Mc/s.

[f] At 1410 Mc/s a source was detected on the position of the galaxy, but was only just resolved from another source of similar intensity about 15′ of arc north. No source was found in the position of 03–47, about 30′ north of the galaxy. At 408 Mc/s, the records showed a broad source about 15′ north of the galaxy, the broadening being apparently the result of confusion. The source may probably be identified with 03–47, which is a weak source (11×10^{-26}W m^{-2}(c/s)$^{-1}$) in the Mills, Slee, and Hill (1960) catalogue.

[g] This galaxy has a low value of radio index, although it is classified as an SO/a.

[h] An extended source (10′×10′) was found about 8′ of arc north of this late-type galaxy. It is possible that the extended source is a combination of the galaxy and a nearby source. If so, it is estimated that NGC 2427 could have a flux density at 1410 Mc/s of $0\cdot25\times10^{-26}$Wm^{-2}(c/s)$^{-1}$ and a radio index equal to +3·5.

[i] This eighth magnitude galaxy, with a radio index greater than +6·3 at 1410 Mc/s, is apparently a very weak emitter.

[j] The spectral index was found to be −0·7 over the frequency range 1410 to 408 Mc/s, and −0·4 from 408 to 85·5 Mc/s.

[k] Flux density measurements over a number of frequencies between 3000 and 85·5 Mc/s gave a spectral index of −0·9.

[l] A weak source ($0\cdot15\times10^{-26}$W m^{-2}(c/s)$^{-1}$) lay 11′ of arc south of the galaxy.

[m] This galaxy lies in a confused region; several weak sources were detected about 15′ of arc away.

TABLE 1 (*Continued*)

Galaxy	Type	Optical Position (1950·0) R.A. h m	Optical Position (1950·0) Dec. ° ′	Radio Position (1950·0) R.A. h m	Radio Position (1950·0) Dec. ° ′	Total Optical Magnitude Uncorrected	Total Optical Magnitude Corrected	Optical Size (min of arc) Major Axis	Optical Size (min of arc) Minor Axis	Flux Density ($10^{-26}Wm^{-2}(c/s)^{-1}$) 1410 Mc/s	Flux Density ($10^{-26}Wm^{-2}(c/s)^{-1}$) 408 Mc/s	Radio Size at 1410 Mc/s (min of arc) R.A. Dec.	Radio Index at 1410 Mc/s
NGC 6744	SBbc	19 05·0	−63 56	19 05·0	−63 57	9·1	8·9	15	10	0·29	<0·8	—	4·0
6822[n]	Im	19 42·1	−14 53	19 42·2	−14 57	8·9	8·6	20	10	0·24	C	—	4·5
IC 5267	Sa	22 54·4	−43 43	—	—	10·7	10·6	6·3	5·3	<0·1	N	—	>3·4
NGC 7496	SBb	23 07·0	−43 42	—	—	12·0	11·5	2·0	1·0	<0·1	N	—	>2·5
IC 5332	Sc	23 31·7	−36 22	—	—	11·0	11·0	4·0	4·0	<0·1	N	—	>3·0
NGC 7793	Sc	23 55·3	−32 51	23 55·6	−32 52	9·3	9·2	6·5	4·5	0·21	C	<5	4·1
Cluster													
Pegasus I[o]		23 18	+07 56	23 18·3	+07 58					1·0	C	<6	
				23 20·0	+07 56					1·2	C	<6	
Pegasus II[p]		23 08	+07 20	23 08·1	+07 20					1·6	6·4	<6	

[n] This galaxy is just resolved at 1410 Mc/s from a source of similar intensity about 14′ of arc away.

[o] A cluster of about 400 galaxies brighter than the 19th magnitude, about 2° in extent. Apart from the two sources listed in Table 1, there were several weaker sources in the cluster region resolved at 1410 Mc/s; confusion occurred on the 408 Mc/s record, making determination of the source flux densities difficult at this frequency.

[p] This cluster is about four times as distant (Humason, Mayall, and Sandage 1956) as Pegasus I. The radio source gave a spectral index of −1·1.

The aerial beam was circular, with a half-power width of 14′ of arc at 1410 Mc/s and 48′ of arc at 408 Mc/s; temperature differences of 0·2 degK at 1410 Mc/s and 0·5 degK at 408 Mc/s could be measured on the individual records. The observing procedure was to make at least six scans through each source in right ascension and declination; scans were also made along the major and minor axes of the galaxies NGC 55 and 253.

Except in certain very favourable cases, positive identification of a galaxy and reasonable measurement of its intensity could not be made at 408 Mc/s due to the presence of other nearby sources in the aerial beam, that were clearly resolved at 1410 Mc/s. Examples of the kind of confusion occurring are illustrated in Figure 1. Such examples must throw doubt on some earlier surveys of galaxies carried out with resolving power equivalent to or lower than that of the 408 Mc/s survey.

III. Results

The results of the radio observations are summarized in Table 1, together with relevant optical information. The optical data have been taken mainly from de Vaucouleurs (1956*a*), but were supplemented in some cases by more recent data (de Vaucouleurs 1952/53, 1956*b*, 1962; Mayall and de Vaucouleurs 1962). The optical data on the clusters have been taken from Zwicky (1959) and Humason, Mayall, and Sandage (1956). The "uncorrected" total magnitudes are the observed magnitudes corrected for light absorption in the Galaxy, while an additional adjustment for internal absorption of light in the object itself has been made using the results of Holmberg (1957) to obtain the "corrected" total magnitudes of Table 1.

An identification of a source with a galaxy was claimed if a source was found within 4′ of arc of the optical centre of the galaxy. The maximum error of the 1410 Mc/s position measurements was about 3′ of arc. The radio positions and sizes in Table 1 were all taken from the high-resolution 1410 Mc/s records. Angular sizes of the radio sources are listed where the signal-to-noise ratio was large enough to allow beam broadening to be measured. The sizes quoted were the extent in right ascension and declination of the sources; in some cases an upper limit of 5′ of arc is quoted if the aerial beam was clearly unbroadened by the source.

At 408 Mc/s, the presence of several sources in the aerial beam and sharply sloping backgrounds prevented accurate measurements of flux density except in a few cases. In those instances where the background was flat, limits were set on the flux density of undetected sources. In other cases, the letters "C" and "N" in column 11 of Table 1 indicate whether a region was obviously too confused for a source to be isolated, or whether the source was "not seen", being presumably too weak or in a confused extended region. Notes on interesting features of some of the galaxies and radio spectral indices where measurable are given in footnotes to Table 1.

IV. Radio Indices

The 1410 Mc/s flux densities have been used to calculate the 1410 Mc/s radio magnitudes using the relationship

$$m_{\mathrm{r}} = -53 \cdot 45 - 2 \cdot 5 \log S,$$

as defined by Hanbury Brown and Hazard (1961*a*), where S is the source flux density in watts $m^{-2}(c/s)^{-1}$ at 1410 Mc/s. The radio index R is defined by

$$R = m_r - m_{pg},$$

where m_{pg} is the corrected total photographic magnitude. The radio indices at 1410 Mc/s for the 20 galaxies detected are listed in Table 1; limits are set for undetected galaxies. In Figure 2 these indices have been plotted against galaxy type. Such a diagram illustrates the variation of the ratio light flux to radio flux both within and between different classes of galaxies.

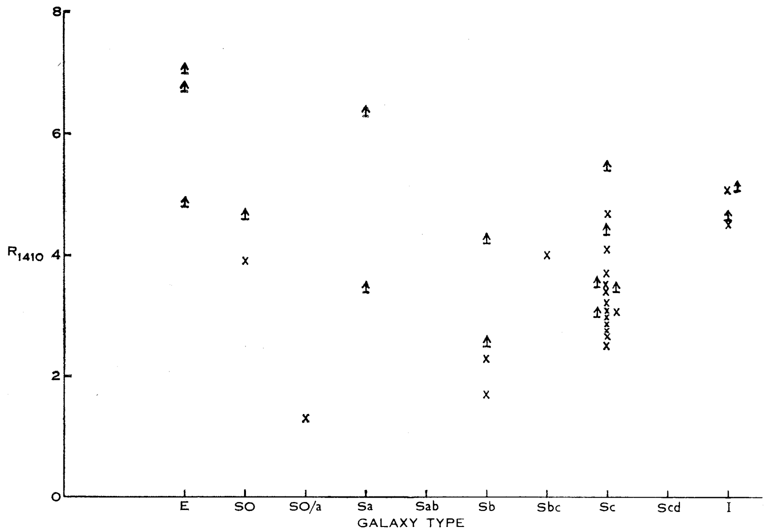

Fig. 2.—1410 Mc/s radio index values for different classes of galaxies. Arrows indicate lower limits.

Reasonable statistics are available only for Sc galaxies; these had a mean radio index of $+3 \cdot 3$ with an r.m.s. deviation of $0 \cdot 6$. NGC 300 is apparently a very weak radio emitter, or alternatively the radio emission may be distributed in a very extensive corona undetected in the survey (see Section V). The two Sb galaxies detected, NGC 1097 and 1365, had quite low radio indices, but in view of the lower limits set on R for the other two undetected Sb galaxies NGC 6300 and 7496, this is not significantly different from the range of values found for Sc galaxies. The four irregular galaxies NGC 55, 5253, and 6822, and IC 1613, support the idea that irregulars are relatively weak radio emitters similar to the Magellanic Clouds.

The radio indices calculated at 1410 Mc/s can be related to those of Hanbury Brown and Hazard at 158 Mc/s by using their values (Hanbury Brown and Hazard 1961*a*) of $+6 \cdot 86$ for the radio magnitude of their calibration source 14N5A at 158 Mc/s and $-0 \cdot 6$ for its spectral index. The relationship is

$$R_{158} = R_{1410} - 1 \cdot 43.$$

Thus for the 16 Sb and Sc galaxies detected, the present 1410 Mc/s survey leads to a mean value at 158 Mc/s of $R = +1 \cdot 7$, with an r.m.s. deviation of $0 \cdot 7$, while Hanbury Brown and Hazard found a mean value of $+1 \cdot 3$ from a total of 16 such galaxies. The values are not significantly different, and the discrepancy could be explained by a slightly steeper spectral index of 14N5A, or by an inconsistency in flux density measurements of the calibration sources. Also, Hanbury Brown and Hazard used the optical magnitudes and dimensions of Holmberg (1957) which extended to the $26 \cdot 5$ mag./sec^2 limit, while the results of de Vaucouleurs used in the present paper extended approximately to the 25 mag./sec^2 limit (de Vaucouleurs and de Vaucouleurs 1961); the effect of the different optical data is to increase the calculated 1410 Mc/s radio index relative to the 158 Mc/s value, making the two estimates of R more consistent.

V. Distribution of Radio Emission in Normal Galaxies

(a) *Sb and Sc Galaxies*

Hanbury Brown and Hazard (1959) have proposed a model for the distribution of radio emission within Sb and Sc galaxies on the basis of observations of M31 at 158 and 237 Mc/s with the 250-ft reflector at Jodrell Bank. On this model about 90% of the radio emission arises in an extensive corona which envelopes the visible nebula. The corona is assumed ellipsoidal in shape, with an axial ratio of $0 \cdot 5$, and the principal planes of the corona and the visible nebula coincide. The apparent angular size of the major axis of the corona between half-intensity points is taken as $1 \cdot 3$ times the maximum extent of the visible nebula as measured by Holmberg (1957). The remaining 10% is thought to arise in the disk component (Mills 1959*a*) roughly coextensive with the visible object. It has been found (Mathewson and Rome 1963) that the disk component of M31 has an apparent angular size of $1^\circ \cdot 4 \times 0^\circ \cdot 6$, while the dimensions of the visible object are $3^\circ \cdot 3 \times 1^\circ \cdot 5$.

However, in three of the Sc galaxies observed, NGC 253, 4945, and 5236, the radio emission appears to be concentrated entirely in a source near the nucleus, much smaller than the visible nebula. Experimental evidence for the weakness of any coronal radiation in these cases has been given previously (Mathewson and Rome 1963). In three others, NGC 1097, 1566, and 2997, the aerial beam was appreciably broadened by the source, there was no outstanding central component, and the radiation appeared to come from a corona compatible with the Hanbury Brown–Hazard model.

NGC 300, the largest spiral studied, could not be detected at all. However, if the radio emission were spread over a sufficiently large corona, this galaxy could escape detection even though its radio index was comparable to those of the other Sc galaxies; for example, for a corona of roughly twice the optical size and a radio index of $+3 \cdot 3$ at 1410 Mc/s, the calculated aerial temperature at 1410 Mc/s would be below the sensitivity of the system.

Previous workers have in fact assumed a constant relationship between the optical and radio sizes of spiral galaxies in determining the radio magnitudes of the weaker galaxies whose sizes could not be measured. As it has been shown that there is no such constant relationship, such results should be treated with some caution.

Size corrections are of the greatest significance where the galaxy is partly resolved, and become rather less important when the assumed corona and disk are considerably smaller than the aerial beam. Most galaxies in the present survey were much smaller than the aerial beam; consequently, any assumptions as to the distribution of the radio emission were unlikely to affect appreciably the estimates of their radio magnitudes.

(*b*) *Irregular Galaxies*

Scans along the major axis of the Magellanic irregular NGC 55 at 1410 Mc/s showed broadening of the 14′ of arc aerial beam and indicated that the emission originated in a source about 8′ of arc in extent. This is about one-third of the optical size. It has been suggested by Mills (1955) from studies of the Large Magellanic Cloud that this type of galaxy does not possess a corona and that most of the radio emission originates in a disk roughly coextensive with the visible object. It is interesting to compare NGC 55 with the Large Magellanic Cloud in which a large part of the radio emission is concentrated in a region about 7° in extent (Mathewson and Healey 1963). If the large Magellanic Cloud were removed to the distance of NGC 55, about 2·5 Mpc (de Vaucouleurs and de Vaucouleurs 1961), it would appear as a source about 8′ of arc in extent, similar to that found in NGC 55. The radio indices of the Large Magellanic Cloud and NGC 55 were found by Mills to be significantly higher than those of spiral galaxies, and this is confirmed by the present survey. Thus both of these irregulars are similar in their ratio of light to radio emission, and in both the radio emission appears to be concentrated in a disk component associated with the optical object.

VI. The Pegasus Clusters

The results of the observations of the two clusters are included in Table 1. Two sources were detected in the field of Pegasus I, the position of one lying within 5′ of arc of the centre of the cluster as given by Zwicky (1959) and within 3′ of arc of the E1 galaxy NGC 7626 in the cluster. The second source could not be identified with any NGC galaxy, and may or may not be associated with the cluster.

Penzias has recently reported detecting H I emission from this cluster using an aerial of beamwidth 0°·5 at a frequency of 1403·4 Mc/s. His drift scans through the centre of the cluster showed a maximum temperature of 0·3 degK over an angular extent of 1°. He interpreted this result as radiation from neutral hydrogen in the cluster. However, it now appears likely that he only detected the continuum emission from the two sources found in the present observations.

The radio source in Pegasus II lies within a minute of arc of the centre of the cluster, and within a minute of arc of the E3 galaxy NGC 7501.

These clusters are largely composed of E and SO galaxies which are in general weaker radio emitters than Sb and Sc galaxies of the same photographic magnitude (Hanbury Brown and Hazard 1961*b*). If all the galaxies in Pegasus I had radio indices similar to the SO, NGC 1291, detected in the present survey, the cluster should still be below the limit of detection of the radio telescope. It is possible that E and SO galaxies emit more when in regions of high space densities, and also that the intergalactic matter in the cluster may contribute appreciably to the emission. However, as the three radio sources detected in the cluster regions were unresolved by the aerial beam at 1410 Mc/s, it is possible that they represent emission from abnormal galaxies in the clusters, similar to those found in the Coma and Perseus clusters (Baldwin and Elsmore 1954; Large, Mathewson, and Haslam 1959).

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