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RADIO OBSERVATIONS OF GALAXIES

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ABSTRACT

Observations of normal galaxies have been made at four wavelengths. Positive results at one or more wavelengths were obtained for 18 galaxies, while 19 galaxies yielded negative results. It is shown that the radio spectra of these galaxies are similar to the spectra of non-thermal discrete sources in general. A mean spectral index of -0.93 is found from the 14 galaxies for which reasonably consistent data are available at several wavelengths. The range in spectral index is small — only two spectra have indices which differ from the mean by more than $\pm$ 0.3. There is evidence that some spectra may flatten somewhat and that others may become very steep at short wavelengths, but the data are inconclusive in these respects. A comparison of radio and optical emission is made. It is suggested that the observed dispersion in $m_r - m_{pg}$ is due largely to a dispersion in the absolute radio magnitudes of the observed galaxies. The material gives no evidence regarding possible variations in $m_r - m_{pg}$ with galaxy type.

I. INTRODUCTION

In discussing radio emission from extragalactic sources it has been the practice to distinguish between "normal" galaxies, which have weak radio emission and no obvious visual peculiarity, and "peculiar" galaxies such as M 87 and NGC 5128 which have been identified with more intense radio sources. While it seems likely that these are two distinct, perhaps unrelated, classes of radio source, this cannot yet be shown definitely to be the case, and there is at present no unambiguous criterion for defining normal and peculiar radio galaxies.

There is one artificial difference between normal and peculiar radio galaxies which should be noted. Normal radio galaxies have usually been detected as the result of a specific search for radio emission from bright galaxies. In general, they do not appear in the major surveys of radio sources. Peculiar radio galaxies, on the other hand, have generally been first detected in source surveys and only later identified with specific extragalactic objects. Thus the selection effects are very different for the two types of radio galaxies.

This paper is concerned with "normal" radio galaxies in the qualitative sense described above — that is, with bright galaxies which have relatively weak radio emission and show no striking visual peculiarity.

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The first radio observations of nearby bright galaxies were made in 1950 by Brown and Hazard (Brown and Hazard 1952). Since then, radio emission has been detected from most galaxies brighter than ninth magnitude, principally by Brown and Hazard (1959) and by Mills (1958). Except in the case of M 31 no observations of galaxies have been reported in the literature at wavelengths shorter than 1.9 meters, and no spectral information is available. M 31 has been observed fairly intensively at various frequencies between 38 mc and 408 mc, and the general properties of its radio emission are well established (Brown and Hazard 1959). There remains, however, considerable uncertainty regarding the spectrum of M 31 (Baldwin and Costain 1960; Lynds 1961a). No information has been published about the radio frequency spectra of the Magellanic Clouds. Thus relatively little is known about the radio spectra of even the nearest and brightest galaxies.

During the period June, 1959, to April, 1961, observations were obtained at the NRAO of a number of bright galaxies, as part of a general program of investigation of the spectra of extragalactic radio sources. A few bright galaxies, such as NGC 5128, have been excluded because they are relatively intense radio emitters and have obvious optical peculiarities. A few border-line cases, such as NGC 1068, have also been excluded. These objects will be discussed in another paper dealing with the spectra of peculiar radio galaxies. M 31, although a normal radio galaxy, was not observed because its large angular diameter makes both the observations and their interpretation difficult, in terms of the objectives of this investigation.

The principal purpose of this program was to obtain data for investigating the spectra of the total flux of radio emission from normal radio galaxies. The observational results are presented in this paper. A later paper will deal with their interpretation in terms of the physical processes responsible for radio emission from normal galaxies.

The observations are complete for Sc galaxies in the Shapley-Ames catalogue brighter than photographic magnitude 9.4. Essentially all galaxies of other types brighter than 9th magnitude have also been looked at, generally with negative results. The available material is a very small sample which is neither homogeneous nor complete, except over a very narrow range in photographic and radio magnitude. In addition, the material contains serious uncertainties, which are described in detail in later sections. This must therefore be considered a very preliminary survey of the spectral characteristics of normal radio galaxies.

The observations, their uncertainties, and the corrections which were applied are discussed in sections II, III, and IV. The derived spectra are described in section V, and section VI gives comparisons of some of the optical and radio properties of the galaxies observed.

II. OBSERVATIONS

Observations were made at four wavelengths — 68.2 cm, 40 cm, 21.4 cm and 10 cm — using the 85-foot Tatel telescope. The telescope and receiver characteristics have been described previously (Heeschen 1961; Heeschen and Meredith 1961), and the pertinent parameters are summarized in Table 1. Observing and reduction procedures were also the same as described in the above references, with one exception. Because of the weakness of these sources and the poor resolution of the telescope at 68.2 and 40 cm, four comparison regions were used at these wavelengths — symmetrically placed north, east, south and west of a source — in an attempt to reduce the confusion.

TABLE 1

ANTENNA AND RECEIVER CHARACTERISTICS

λ (cm)	Antenna Beamwidth (min. of arc)	Receiver L. O. Freq. (mc/s)	Receiver Bandwidth (mc/s)
68.2	110	440	2 x 2.5
40	69	750	2 x 2.7
21.4	37	1400	2 x 5
10	16	—	200

All observations were obtained in the form of source/Cas A ratios. To convert these ratios to flux densities, the flux density of Cas A at 1400 mc has been taken as 25.0×10^{-24} w $m^{-2}(c/s)^{-1}$. A spectral index of -0.80 (Whitfield 1957) has been used to obtain flux densities of Cas A at other wavelengths.

For some purposes it is useful to express flux density by a magnitude system. Two different magnitude scales have been used in discussing radio observations of normal galaxies. The first, introduced by Brown and Hazard (1952), was defined by the relation

$$m_R = -53.45 - 2.5 \log S \text{ (158 mc)}.$$

Various authors have applied this relation to observations at other wavelengths by reducing their observed fluxes to fluxes at 158 mc with the aid of an assumed spectral index, usually -0.7. This procedure is reasonably satisfactory for frequencies close to 158 mc, but can be very unsatisfactory when dealing with data covering a wide range of frequencies, particularly if the average spectral index is not -0.7, or if there is a wide range of indices.

More recently Brown and Hazard (1959) have introduced another magnitude system which overcomes the above difficulties. In this system, they have adopted a constant magnitude at all frequencies for a standard calibration source, 3C 295, with the zero point set so that the magnitude is the same as it would be in the earlier system at 158 mc. If the standard source, 3C 295, has a constant spectral index x_0 the relation between magnitude, flux density and frequency in this system is

$$m(\nu) = -53.45 - 5.5\, x_0 - 2.5 \log S - 2.5\, x_0 \log \nu.$$

Unfortunately, however, the spectral index of 3C 295 is not constant. It varies from about -0.4 to -1.1 over the frequency range 38 mc to 3000 mc (Heeschen, in preparation). Nonlinear terms are therefore required in any quantitative expression of this magnitude system.

Neither of the above systems is particularly well suited to our needs. Probably a generally useful system cannot be established until much more data are available. Never-the less, for the purposes of this paper we define a magnitude system by the relation

$$m(\nu) = -48.50 - 2.5 \log S(\nu) - 2.25 \log \nu.$$

The zero point of the system has been chosen so that at 158 mc the magnitudes are the same as in the two systems of Brown and Hazard. The scale has been chosen in such a way that, for the data discussed in this paper, the average radio "color index", defined as $m(\nu_1) - m(\nu_2)$ $(\nu_1 > \nu_2)$, is close to zero. It is shown in a later section that the average spectral index obtained from the available spectra is about -0.9. Thus, in this magnitude system, a source with spectral index of -0.9 has a magnitude independent of frequency.

To summarize the calibration and magnitude system used for these observations:

1. All observations were obtained using Cassiopeia A as the primary calibration standard.

2. The adopted flux density of Cas A as a function of frequency is

$$S_{\text{Cas A}} = 25.0 \times 10^{-24} \left(\frac{\nu}{1400}\right)^{-0.80}.$$

   This relation has been used to obtain flux densities from the measured source/Cas A ratios.

3. The adopted magnitude system is defined by

$$m(\nu) = -48.50 - 2.5 \log S(\nu) - 2.25 \log \nu.$$

   The source/Cas A ratios, flux densities and magnitudes on the above system are given in Table 2 for four commonly used standard sources. As can be seen from the magnitudes, none of the sources except Cas A has a constant spectral index.

TABLE 2

CALIBRATION DATA FOR STANDARD SOURCES

	Cas A		Vir A = M 87			04N3A = 3C 123			14N5A = 3C 295		
λ cm	Flux Density 10^{-26}w $m^{-2}(c/s)^{-1}$	m_R	S/Cas A	Flux Density 10^{-26}w $m^{-2}(c/s)^{-1}$	m_R	S/Cas A	Flux Density 10^{-26}w $m^{-2}(c/s)^{-1}$	m_R	S/Cas A	Flux Density 10^{-26}w $m^{-2}(c/s)^{-1}$	m_R
10	1360	0.88	.077	105	3.62	.0174	23.6	5.24	.0080	10.9	6.08
21.4	2500	0.91	.084	210	3.61	.0194	48.5	5.19	.0098	24.5	5.94
40	4119	0.98	.086	356	3.64	.0195	80.2	5.26	.0094	38.5	6.06
68.2	6310	1.06	.091	574	3.66	.0189	119	5.37	.0086	54.3	6.22

The results of the observations are shown in Tables 3 through 6. In each table column 1 gives the NGC or IC number, columns 2 and 3 the observed source/Cas A ratios and internal probable errors, and columns 4 and 5 the flux densities and magnitudes in the system defined above. These results were obtained from measurements of peak intensities. Therefore, they are measures of total flux only if the radio size of a galaxy is

TABLE 3

68.2 CM MEASUREMENTS

NGC *IC	Source / Cas A	p.e.	Flux Density 10^{-26}w $m^{-2}(c/s)^{-1}$	$m_{68.2}$
253	0.0015	0.0001	9.5	8.1
342*	.0032	.0004	20.2	7.3
598	.0005	.0002	3.4	9.3
1613*	.0013	.0004	8.2	8.3
2403	.0004	.0001	2.5	9.7
3034	.0018	.0001	11.4	7.9
4258	.0004	.0001	2.7	9.5
5194/5	.0010	.0002	6.3	8.6
5236	.0018	.0002	11.4	7.9
5457	.0003	.0002	1.9	9.9
278	< .001		< 6.3	> 8.6
4631	< .001		< 6.3	> 8.6
4826	< .001		< 6.3	> 8.6
6822	< .002		<12.6	> 7.8
6946	< .001		< 6.3	> 8.6
7331	< .001		< 6.3	> 8.6

TABLE 4

40 CM MEASUREMENTS

NGC *IC	Source / Cas A	p.e.	Flux Density 10^{-26}w $m^{-2}(c/s)^{-1}$	m_{40}
253	0.0013	0.0003	5.4	8.3
342*	.0021	.0001	8.8	7.7
598	.0007	.0004	3.0	8.9
2903	.0005	.0001	2.2	9.3
3034	.0019	.0001	8.0	7.8
4258	.0004	.0001	1.8	9.5
4490	.0006	.0001	2.7	9.0
4631	.0008	.0001	3.4	8.8
4826	.0004	.0001	1.7	9.5
5194/5	.0007	.0001	2.8	9.0
5236	.0018	.0001	7.5	7.9
5457	.0003	.0001	1.3	9.8
2403	< .0006		< 2.7	> 9.0
4594	< .0006		< 2.7	> 9.0
6946	< .0006		< 2.7	> 9.0

TABLE 5

21.4 CM MEASUREMENTS

NGC *IC	Source / Cas A	p.e.	Flux Density 10^{-26}w $m^{-2}(c/s)^{-1}$	$m_{21.4}$
253	0.0020	0.0002	5.0	7.8
342*	.0010	.0001	2.5	8.5
598	.0012	.0002	3.0	8.3
2403	.00040	.00007	1.0	9.5
4258	.00028	.00007	0.7	9.9
4490	.00025	.00010	0.7	9.9
4631	.00045	.00010	1.1	9.4
4826	.00020	.00008	0.5	10.3
5194/5	.0015	.0003	3.8	8.1
5236	.0013	.0001	3.2	8.2
5457	.00025	.00009	0.7	9.9
6946	.00074	.00008	1.8	8.8
10*	< .0003		< 0.8	> 9.8
55	≤ .0003		≤ 0.8	≥ 9.8
185	≤ .0004		≤ 1.0	≥ 9.5
221	≤ .0006		≤ 1.6	≥ 9.0
278	< .0003		< 0.8	> 9.8
300	< .0003		< 0.8	> 9.8
891	< .0003		< 0.8	> 9.8
1052	< .0002		< 0.5	>10.3
1613*	< .0002		< 0.5	>10.3
2623	< .0003		< 0.8	> 9.8
2841	< .0003		< 0.8	> 9.8
3031	< .0006		< 1.5	> 9.1
3115	< .0002		< 0.5	>10.3
3368	< .0002		< 0.5	>10.3
4214	< .0002		< 0.5	>10.3
4236	< .0002		< 0.5	>10.3
4244	< .0002		< 0.5	>10.3
4278	< .0002		< 0.5	>10.3
4449	< .0002		< 0.5	>10.3
4736	< .0002		< 0.5	>10.3
5866	< .0002		< 0.5	>10.3

TABLE 6

10 CM MEASUREMENTS

NGC *IC	Source / Cas A	p.e.	Flux Density 10^{-26}w $m^{-2}(c/s)^{-1}$	m_{10}
55	0.00015	0.00002	0.2	10.4
253	.0024	.0001	3.3	7.4
342*	.00052	.00007	0.7	9.1
2403	.0002	.0001	0.3	10.0
3031	.00016	.00005	0.2	10.3
3034	.0046	—	6.2	6.7
4258	.0006	.0001	0.8	8.9
4490	.0003	.0001	0.4	9.8
4594	.00008	.00005	0.1	11.0
4631	.0006	.0001	0.9	8.9
4826	.00015	.00008	0.2	10.4
5194/5	.00017	.00011	0.2	10.3
5236	.0012	.0002	1.6	8.2
6946	.0006	.0001	0.8	8.9
598	≤ .00009		≤ 0.1	≥10.9
2683	< .00015		< 0.2	>10.4
2903	≤ .00006		≤ 0.08	≥11.4
5055	< .00015		< 0.2	>10.4
5457	< .00015		< 0.2	>10.4

small compared to the antenna beamwidth at the wavelength in question. Corrections to the measured values to obtain total fluxes and magnitudes are discussed in section IV.

The measurements of NGC 3034 at 10 cm and 40 cm wavelengths were made at the NRAO by C. R. Lynds (1961b). I am indebted to him for the use of these observations prior to publication.

III. ACCURACY OF OBSERVATIONS

All of the objects observed in this program are very weak radio emitters. The observations therefore may have large uncertainties due to receiver noise fluctuations and zero line instability, confusion, and perhaps systematic effects.

The probable errors given in Tables 3 to 6 are measures of the purely internal uncertainties due to receiver noise and zero line instability, and to measuring errors. They range from about 10 per cent to, in a few cases, greater than 50 per cent, depending on the strength of the source. While these uncertainties could be decreased by longer observing times, or better receivers, it is hardly worthwhile doing so with the 85-foot telescope. Except at the shortest wavelength the internal uncertainties are already equal to or smaller than the confusion limit, as will be discussed below. Thus in general the accuracy of the observations is limited by the telescope resolution rather than by sensitivity.

The effects of confusion due to unresolved sources have been discussed by a number of authors, and most recently by von Hoerner (1961). Von Hoerner takes as the resolution limit of a telescope a flux density equal to five times the r. m. s. background "noise" due to unresolved sources. This corresponds to 75 beam areas per source, a more stringent criterion than that usually adopted. Von Hoerner shows that at this flux density the probability of a complete misinterpretation is 1/20. At a flux level three times the confusion "noise" the probability of a complete misinterpretation is 1/4.

Following von Hoerner, we find the values listed in Table 7 for the resolution limits of the 85-foot telescope. The limits are given in the table in terms of source/Cas A ratios and radio magnitudes, as well as in flux densities.

TABLE 7

RESOLUTION LIMITS OF THE 85-FOOT TELESCOPE

Wavelength (cm)	Flux Density $[w\ m^{-2}(c/s)^{-1}]$	Source/Cas A	m_λ
68.2	8.2×10^{-26}	.0013	8.3
40	2.7×10^{-26}	.00066	8.9
21.4	7.0×10^{-27}	.00028	9.8
10	1.4×10^{-27}	.0001	10.8

We can now compare the observations at various wavelengths with the values in Table 7 and get at least some estimate of the uncertainties due to confusion.

68.2 cm. Table 3: At this wavelength five of the ten sources observed — NGC 598, 2403, 4258, 5194/5 and 5457 — are well below the resolution limit. The results for these objects must be very uncertain and, from von Hoerner's study, one would expect one or two complete misinterpretations in the sense that the observed flux may not be associated with the galaxy at all. The other objects observed are all close to the resolution limit and therefore should have, on the average, uncertainties of about 20 per cent due to confusion. Since the internal probable errors are considerably smaller than the resolution limit, the accuracy at this wavelength is limited almost entirely by confusion.

40 cm. Table 4: Four of the sources — NGC 2903, 4258, 4826 and 5457 — are below the resolution limit, and four others are at or near it. The results for these objects must also be considered very uncertain. Again the internal probable errors are generally smaller than the resolution limit, so the accuracy is limited largely by confusion.

21.4 cm. Table 5: Only one source, NGC 4826, is below the resolution limit, with three others right at the limit. Confusion is less serious at this wavelength, and the probability of large errors is small. Confusion is still a major source of uncertainty, however.

10 cm. Table 6: All of the objects gave results above the resolution limit. Internal

probable errors are of the same order as the resolution limit.

It is apparent that many of the observations at 68.2 and 40 cm may have considerable errors due to confusion. In some cases the interpretation of the observed flux as originating in the galaxy may be in error. Since confusion is a statistical uncertainty, the error in a given source observation may be greater, or smaller, than the average uncertainty due to confusion. Probably for only the four strongest sources, NGC 253, 3034, 5236 and IC 342, can one be reasonably certain of no large error due to confusion.

At 21.4 and 10 cm the uncertainty due to confusion is considerably less than at the longer wavelengths. A few of the observations, however, may have appreciable errors from this cause.

Observations of some of these galaxies have also been made at Harvard at a wavelength of 22 cm (Goldstein 1961; Roberts 1961). The agreement between the Harvard and the NRAO observations is in general quite good.

Perhaps the best test possible at present of the reliability of the observations is in the degree of consistency of the results for a given object at different wavelengths, on the reasonable assumption that the radio emission is a smooth function of frequency. Spectra derived from these observations and those by others at longer wavelengths are discussed in detail in section V. It is shown there that the data are in general quite consistent, within the limitations described above.

Any interpretation of the data shown in Tables 3 to 6 brings in another large source of uncertainty, not discussed above. These observations refer to peak intensities and are not measures of total flux unless the radio emitting regions are small compared to the antenna beamwidth. It is not at all certain that this is the case, particularly at 10 cm wavelength, where the antenna beamwidth is of the same order as, and in some cases smaller than, the optical size of the objects. This problem is discussed in detail in the following section.

IV. CORRECTIONS FOR SOURCE SIZE

Except in one instance, which will be discussed later, radio diameters were not measured in the observations described here. Thus, if corrections are to be applied to the observations to obtain total flux densities, the corrections must be based on some adopted relationship between radio diameter, optical diameter, and perhaps frequency. Unfortunately, relatively few data are available with which to determine such a relationship.

Mills (1955) has observed the distribution of radio emission from the Magellanic Clouds at a wavelength of 3.5 meters. He finds that in both Clouds the distribution of radio emission is very similar to that of the interstellar gas and early-type stars. In the case of the Small Cloud the radio distribution may be somewhat more extensive than the stellar distribution.

Observations of M 31 and M 33 at 158 mc and 237 mc by Brown and Hazard (1959) indicate a rather different type of brightness distribution for these two objects. The radio emission comes primarily from a corona with maximum extent about 3 times the maximum visual extent of the galaxies. In the case of M 31 a disk component was also observed, which contributes about 10 per cent of the total flux. The dimensions of the disk component appear to be smaller than the visual disk. Observations of M 31 at 400 mc by Seeger, Conway and Westerhout (1957) and by Large, Mathewson and Haslam (1959) also show a corona of greater extent than the visual extent.

Observations of NGC 253 at 10 cm wavelength by the writer gave a total width to half-power of 12 minutes of arc in right ascension, after correction for antenna smoothing. On the other hand, interferometer observations by Maltby (1961) at 960 mc gave a width in R.A. of only 2-3 minutes of arc. Taking for the galaxy an inclination of 88° and a position angle of about 45° the radio brightness distribution in R.A. would have a total half-power width of about 4 minutes of arc if the distribution is like that of the visual disk. If the distribution is like that of M 31 at 158 mc, the half-power width in R.A. would be about 20 minutes of arc. The radio observations at both 10 cm and 960 mc are probably too uncertain to decide whether either of these two extremes is more nearly correct or whether the actual distribution is intermediate between them, but they suggest that the narrower, disk, distribution is more likely. Both of the observations, however, could easily have missed an extensive low surface-brightness halo.

The only observations of the radio dimensions of other galaxies are those by Leslie (1960). She observed eleven galaxies at 178 mc, and found that in general the total widths to half-brightness were comparable to the maximum visual dimensions, consistent with the coronal distribution found in M 31.

It appears that, at least at long wavelengths, most of the radio emission from normal galaxies is distributed in a corona — with dimensions two to three times the visual dimensions of the galaxies. In the case of the Magellanic Clouds this coronal distribution does not seem to be present, and the dimensions of the radio distribution are more comparable to the visual dimensions. Whether the relative strengths of the disk and halo contributions are a function of galaxy type or whether they vary in galaxies of a given type is not known. Nor is it known whether the relative strength of disk and halo changes with frequency.

It is not possible, from the material discussed above, to make any quantitative estimate of a relation between optical and radio size which might apply to the observations presented in this paper. Hence, any corrections for source size will necessarily be rather arbitrary. We shall therefore make corrections on the basis of an assumed relation between radio and optical dimensions, and examine both the corrected and uncorrected results to see what conclusions can be drawn and how these conclusions may be influenced by the uncertainties in the corrections.

It will be assumed that the radio brightness distribution of a normal galaxy is circular and gaussian, with a total width to half-brightness equal to the maximum visual extent of the galaxy as given by de Vaucouleurs (1953). The correction to the observations then is

$$S_{tot} = S_{obs}(1 + x^2)^{1/2}$$

where S_{obs} is the flux density derived from an observation on the assumption that the source is a point source, and x is the ratio of source half-brightness width to antenna beamwidth. This assumption is not inconsistent with the results at long wavelengths described above. The adopted dimensions and corrected flux densities are given in Table 8. The accuracy of these corrections is undoubtedly very low. The assumed relation between radio and optical dimensions may be greatly in error for any given galaxy. The maximum visual dimensions are also very uncertain. The values used, for example, are in general smaller than those given by Holmberg (1958), in some cases by a factor of two.

TABLE 8

FLUX DENSITIES CORRECTED FOR SOURCE SIZE

NGC *IC	Corrected flux density (10^{-26}w m^{-2}(c/s)$^{-1}$) 10	21.4	40	68.2	Adopted Diameter
55	0.4	——	——	——	25'
253	5.6	5.8	5.7	9.7	22
342*	1.3	3.0	9.4	20.6	25
598	$\leq$ .4	5.7	4.0	3.9	20
1613*	——	<0.5	——	8.4	60
2403	.4	1.1	<2.8	2.5	16
2903	$\leq$ .1	——	2.2	——	11
3031	.3	——	——	——	16
3034	6.8	——	8.0	11.4	7
4258	1.3	0.8	1.9	2.7	20
4490	.4	.7	2.7	——	4
4954	.1	——	<2.7	——	7
4631	1.1	1.2	3.4	< 6.3	12
5194	.25	4.0	2.8	6.3	12
4826	.21	.5	1.7	< 6.3	8
5236	1.9	3.3	7.5	11.4	10
5457	< .3	0.8	1.4	1.9	22
6946	.9	1.8	<2.7	< 6.3	8

V. SPECTRA

The radio spectra of the galaxies are given in Figures 1 through 14. Each figure is a logarithmic plot of flux density versus frequency for a particular galaxy. Open circles are the data of Tables 3 through 6, uncorrected for size effects, and the results, listed in Table 9, obtained by other observers. The results, corrected for size, given in Table 8 are plotted as filled circles when they differ from the uncorrected values. Solid lines are meant to represent the spectra as defined by the open circles. The spectra modified by size corrections are shown by the dashed lines. The slope or spectral index, x, of each spectrum, defined by the relation

$$S \alpha \nu^{x},$$

is also given in each figure.

Inspection of the figures shows that for two of the sources — NGC 598, and 5194/5 — there are large inconsistencies between the observations at different frequencies. In

TABLE 9

RESULTS OF OTHER OBSERVERS

FLUX DENSITY — 10^{-26}w m^{-2}(c/s)$^{-1}$

NGC *IC	M S H 86 mc	H B H 159 mc	Leslie 178 mc	Goldstein 1420 mc
55	4.8			
253	29	20		4.8
598		18.2	10	
342*		27.5		
2403		< 9.6		
2903			4.0	
3031				
3034		12. **		8.4
4258		7.9	6.5	
4490		6.7	5.5	
4631		6.6	< 4.5	
5194		10.5	< 5.0	
4826		7.9	< 3.0	
5236	36	30.2		3.3
5457		6.6	19.0	
6946		6.6		
1613*		10.5		
4594		< 5.0		

** - value from 3C catalog - 3C 231
M S H = Mills, Slee and Hill 1960.
H B H = Brown and Hazard 1961.
Leslie = Leslie 1960.
Goldstein = Goldstein 1960.

each case, either one or more of the observations is in error by a large amount or the spectrum is very different from the spectra of the other galaxies. These are among the weakest galaxies observed and, as noted in section IV, both are below the resolution limit of the 85-foot telescope at 68.2 cm. In addition, NGC 598 is the galaxy of largest angular diameter in the list, and the uncertainties in the total fluxes are undoubtedly large. For the other twelve galaxies the observations are in reasonable agreement, and in some cases the agreement is excellent.

Comments on some of the individual spectra follow:

NGC 253 (Fig. 2): This is one of the more intense normal radio galaxies. It has been observed at six wavelengths, with relatively high accuracy. The observations are all in excellent agreement, but the spectrum at short wavelengths is uncertain because of the

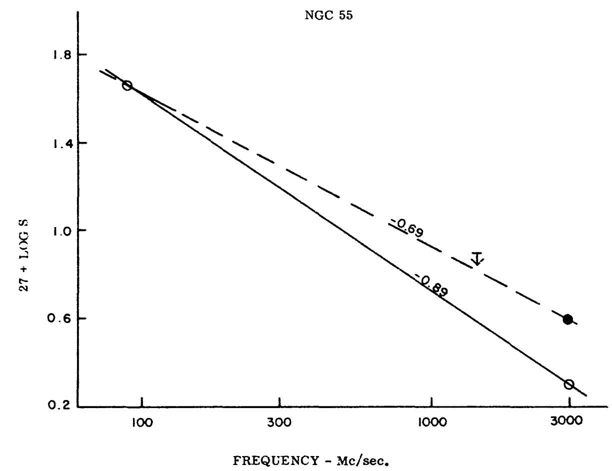

Figure 1. The spectrum of NGC 55. In this and following figures through figure 14 open circles represent observed flux densities, filled circles represent flux densities corrected for source size, and horizontal bars and arrows represent upper limits.

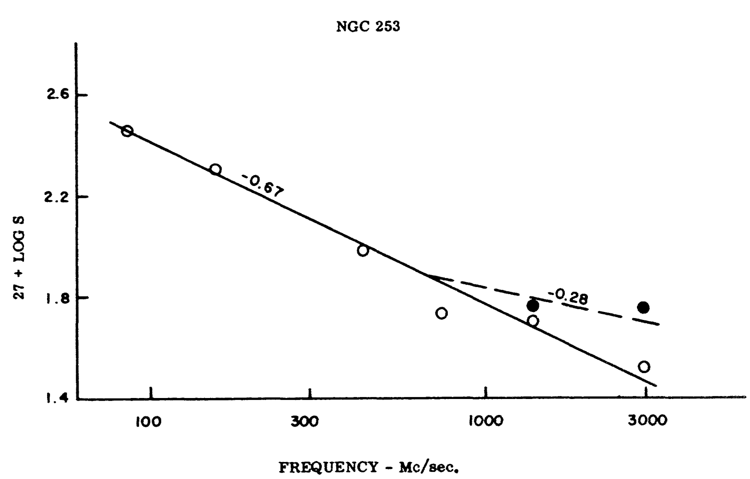

Figure 2. The spectrum of NGC 253.

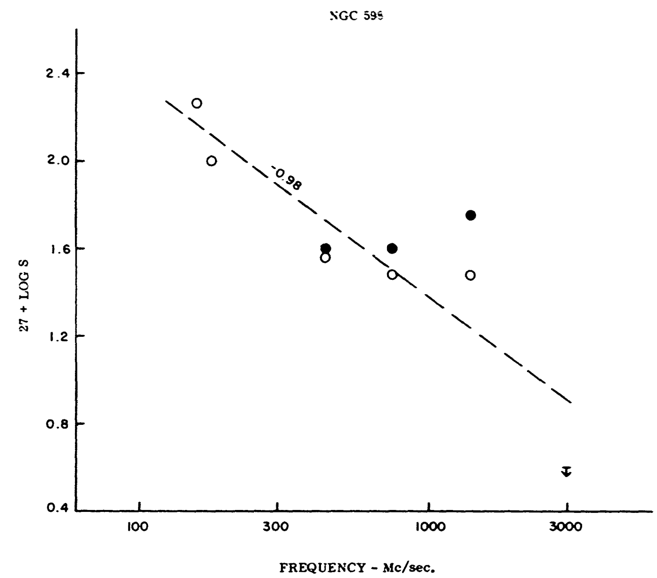

Figure 3. The spectrum of NGC 598.

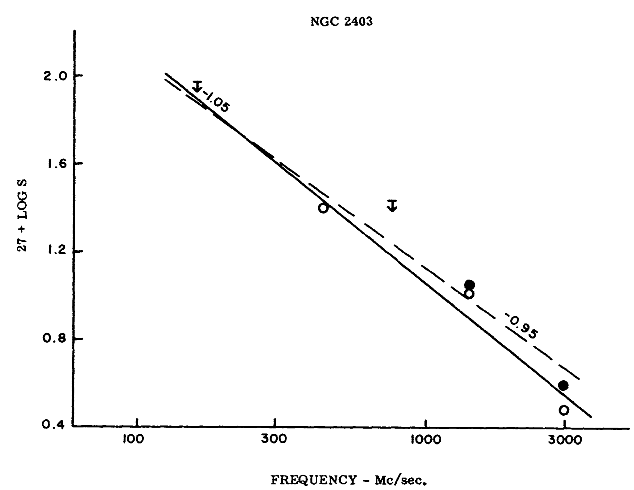

Figure 4. The spectrum of NGC 2403.

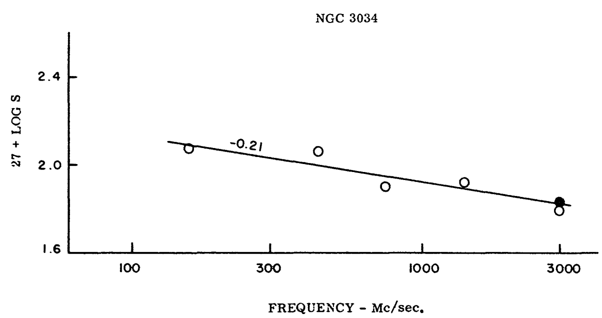

Figure 5. The spectrum of NGC 3034.

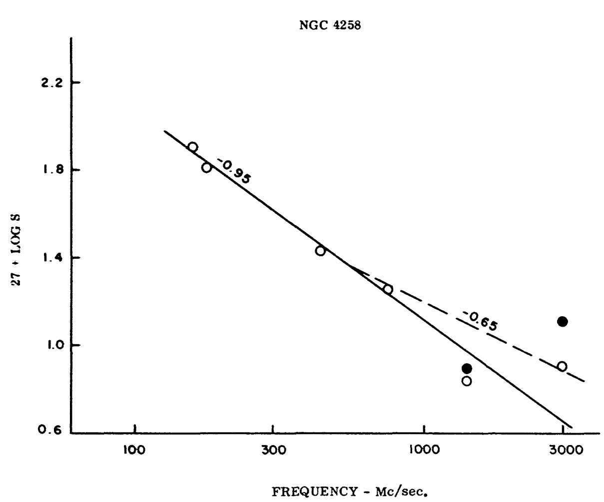

Figure 6. The spectrum of NGC 4258.

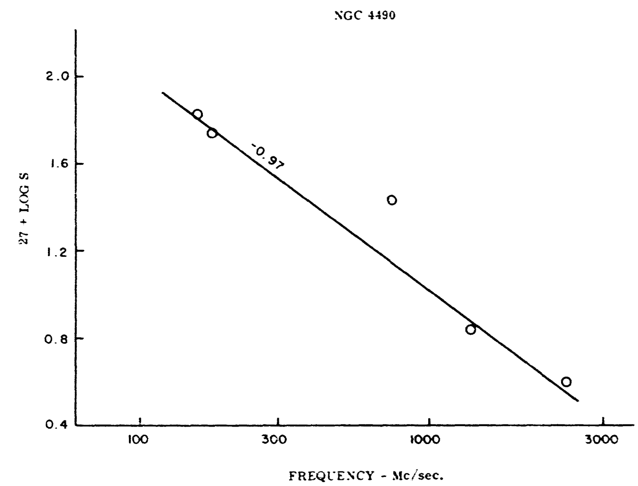

Figure 7. The spectrum of NGC 4490.

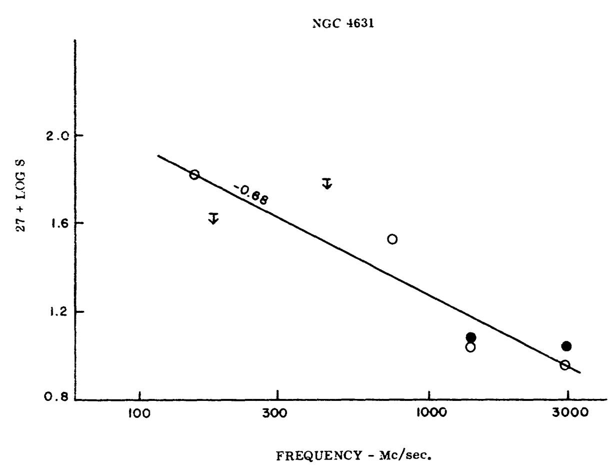

Figure 8. The spectrum of NGC 4631.

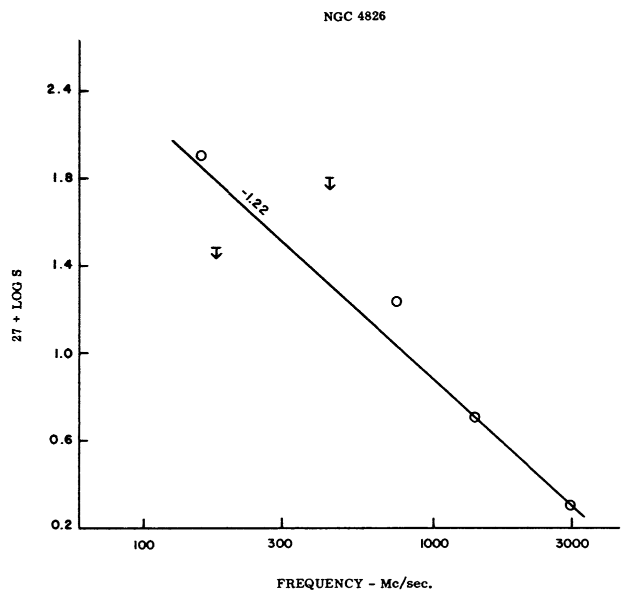

Figure 9. The spectrum of NGC 4826.

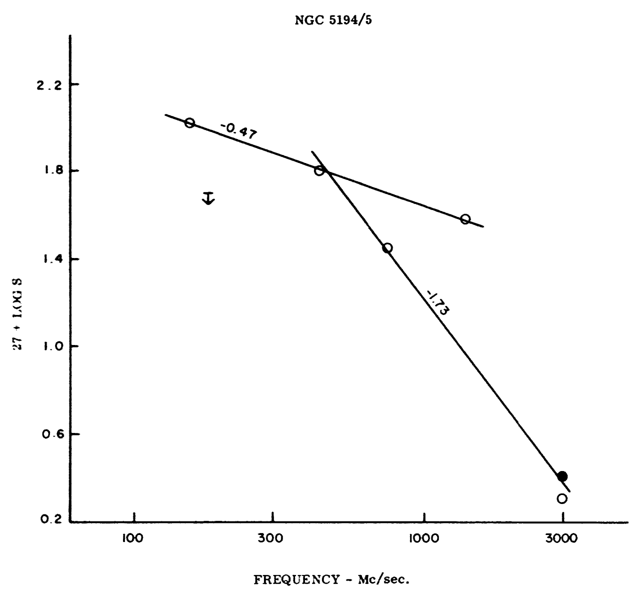

Figure 10. The spectrum of NGC 5194/5.

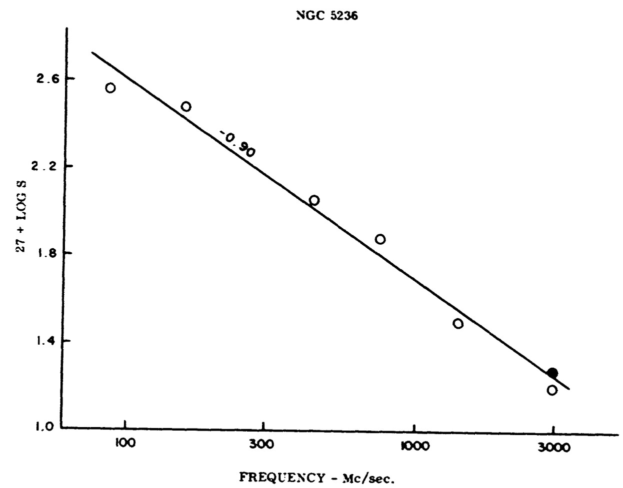

Figure 11. The spectrum of NGC 5236.

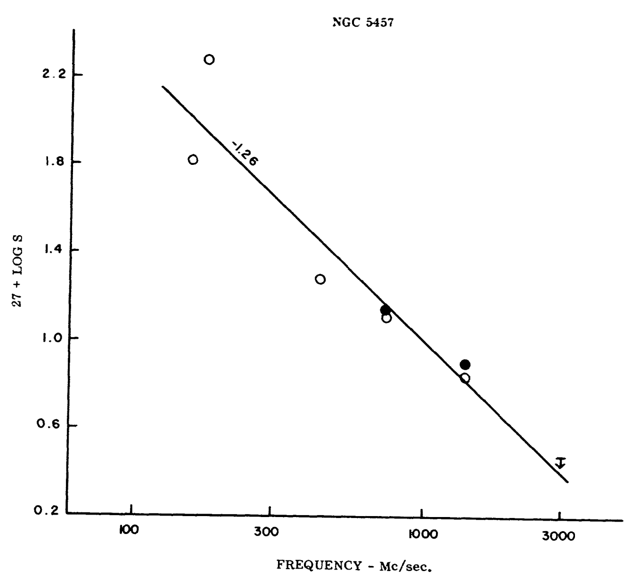

Figure 12. The spectrum of NGC 5457.

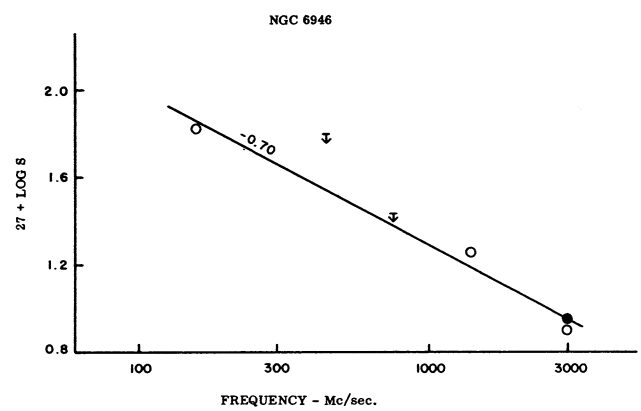

Figure 13. The spectrum of NGC 6946.

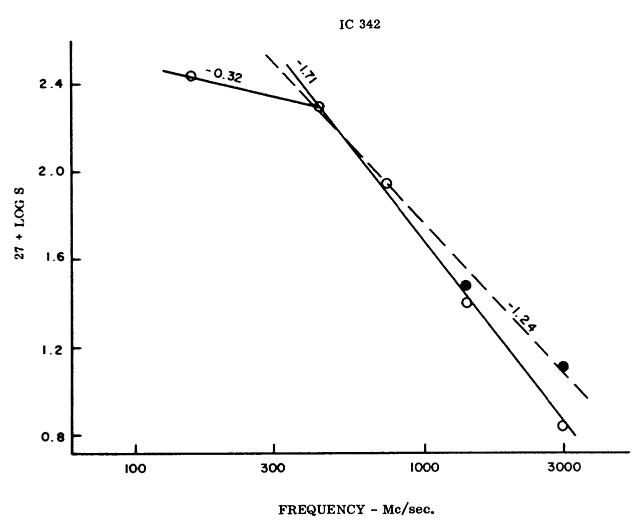

Figure 14. The spectrum of IC 342.

uncertainty in correcting for source size. The spectral index is about -0.9 at frequencies below 500 mc/sec. At higher frequencies the spectral index may be anywhere from -0.9 to about -0.2, depending on what the radio brightness distribution is.

NGC 598 (M 33, Fig. 3): The upper limit at 3000 mc/sec shown in the figure has been corrected for source size. The observations at different frequencies are not at all consistent with one another. If it is assumed that the 21.4 cm measurement, or correction for size, is incorrect, a reasonable spectrum may be drawn to represent the observations at wavelengths longer than 21 cm. The negative result at 10 cm suggests that at short wavelengths the spectrum may become very steep.

NGC 3034 (M 82, Fig. 5): This galaxy has the flattest radio spectrum which has been found thus far in a galaxy. The observations are in very good agreement and are not subject to the uncertainties of size corrections. The galaxy is classified as an irregular of type II, but is a somewhat peculiar object (Sandage 1961). It is the only irregular galaxy, aside from the Magellanic Clouds, from which radio emission has definitely been detected. Both its radio and its optical characteristics suggest that perhaps it should not be classified as a normal radio galaxy. Its ratio of radio to light emission and its absolute radio magnitude are intermediate between the corresponding values for normal galaxies and the weaker of the peculiar radio galaxies such as NGC 1068 and NGC 4038-39. The 1400 mc flux density plotted in the figure is from Goldstein (1961).

NGC 4258 (Fig. 6): The spectrum appears to be well determined for frequencies lower than 750 mc, but the higher frequency observations are not in good agreement. The high frequency observations suggest, after correction for source size, a flattening similar to that mentioned above in the case of NGC 253. A 22 cm measurement made at Harvard is higher than the NRAO result at 21.4 cm by a factor of two (Roberts 1961). If the Harvard result is more nearly correct, which seems likely by comparison with observations at other wavelengths, the evidence for flattening at short wavelengths is still stronger.

NGC 4631 (Fig. 8): The observations are in only moderate agreement. If the negative result at 178 mc/sec is correct, rather than the positive result at 158 mc/sec, the spectrum may be flatter than indicated at low frequencies, and steeper at high frequencies.

NGC 4826 (M 64, Fig. 9): The observations are reasonably consistent, and indicate a rather steep spectrum. Again, if the negative result at 178 mc is correct, the spectrum may be flatter than shown at low frequencies, and steeper at high frequencies.

NGC 5194/5 (M 51, Fig. 10): The observations are not in good agreement, and it is not possible to determine the spectrum with any reliability. Several interpretations besides the one represented by the lines in the diagram are equally likely. However, unless several of the observations are in error by large amounts, the spectrum must be relatively flat at low frequencies and quite steep at high frequencies. It is not possible at present to determine whether the radio emission comes from NGC 5194 or NGC 5194, or both. NGC 5194 is a normal Sc, similar to most of the other galaxies from which radio emission has been observed. NGC 5195 is a type II irregular, very similar to NGC 3034 (Sandage 1961). If the radio emission from NGC 5195 were similar to that from NGC 3034, it would appear somewhat brighter at 21.4 cm and much brighter at 10 cm than was actually observed. We shall assume for later sections that the radio emission comes from NGC 5194.

However, if both are radio emitters, it is possible that some of the inconsistencies in the observations are due to varying contributions from the two objects at different wavelengths, because of differences in telescope resolution or observing techniques, even though they are separated by only a few minutes of arc.

IC 342 (Fig. 14): The centimeter wavelength observations are very consistent and indicate a steep spectrum. The spectrum is somewhat uncertain, however, because of the corrections for source size. The meter wavelength observation is not in agreement with the spectrum at centimeter wavelengths. If this observation is correct, the spectrum must be relatively flat to about 500 mc, and then become much steeper at higher frequencies.

The spectral indices obtained from the solid curves of figures 1 to 14 are listed in column 2 of Table 10. NGC 598 and NGC 5194/5 have been omitted because of their very large uncertainties. These indices roughly represent the spectra at lower frequencies, below about 500 mc, irrespective of the uncertainties at higher frequencies due to corrections for source size. The mean spectral index is -0.93. The total range

TABLE 10

SPECTRAL INDICES

NGC *IC	x	x_c
55	- .89	- .69
253	- .67	- .28
342*	-1.71	-1.24
2403	-1.05	- .95
3034	- .21	- .21
4258	- .95	- .65
4490	- .97	- .97
4631	- .68	- .68
4826	-1.22	-1.22
5236	- .90	- .90
5457	-1.26	-1.26
6946	- .70	- .70

in index is 1.5, from -0.21 to -1.71. However, ten of the twelve galaxies in the list have indices within $\pm$ 0.3 of the mean, a remarkably small range considering the uncertainties in the data. The spectral indices of the dashed curves are given in column 3. The mean is -0.81. Thus the mean spectral index of these normal galaxies is similar to that of peculiar extragalactic sources.

These spectra suggest three possible phenomena, which are not conclusively shown by the available material but which, if real, would be of some interest:

1. The spectra of NGC 253 and NGC 4258 appear to flatten out at frequencies above about 1000 mc/sec. This is suggestive of a thermal contribution from ionized hydrogen. If one-half of the total flux at 10 cm from these galaxies is due

to ionized hydrogen, the mean density of H II must be of the order of 1 to $2/cm^3$, if the H II is distributed throughout a disk 200 parsecs thick. The flattening, however, depends almost entirely on the corrections for source size, which in turn are based on the assumption of a large non-thermal contribution from a halo. The true situation is probably quite complex, and can not be resolved until observations of brightness distribution at several wavelengths are available.

2. In contrast to the flattening at high frequencies discussed above, the spectra of several galaxies suggest a marked and abrupt steepening at higher frequencies. In addition to the galaxies already mentioned — NGC 598, 4631, 4826, 5194/5 and IC 342 — two other galaxies for which only two or three observations are available also suggest this steepening. They are NGC 2903 IC 1613. In every case, however, the suspected steepening is the result of an observation at only one frequency and must be considered very uncertain.

3. Although the range of spectral indices of the galaxies with the best determined spectra all lie within $\pm$ 0.3 of their mean value, there is an indication in the present material that indices of some galaxies lie well outside this range, and that the total range of spectral indices of normal galaxies may be rather large. The spectrum of NGC 3034 is well determined, and, with a spectral index of -0.2, is the flattest spectrum observed thus far in any extragalactic source. The limit at the other end, if one exists, is much more uncertain. Unless many of the low frequency observations are systematically too high, or many high frequency observations systematically too low by large amounts, spectra with indices greater than -1.5 seem to be indicated.

VI. RELATION BETWEEN RADIO EMISSION AND OPTICAL PROPERTIES

Radio and optical data for the galaxies observed are given in Table 11. Photographic magnitudes have been taken from de Vaucouleurs (1953). Distance moduli were obtained from the Hubble Atlas (Sandage 1961), or from van den Bergh (1960), and, where necessary, have been corrected to an assumed Hubble constant of 100 km/sec/mpc. In three instances — NGC 55, IC 342 and NGC 300 — the distance moduli were derived by assuming an absolute photographic magnitude of -18.5 for the galaxies. The spectral indices, x_c, and the radio magnitudes at 21.4 cm were taken from the dashed line spectral curves of Figures 1 through 14. In the case of undetected galaxies the lower limits given are based on observations at two or more wavlengths.

In Figure 15 the ratio of light to radio emission at 21.4 cm, $m_{21.4} - m_{pg}$, is plotted against galaxy type. The absolute radio magnitude at 21.4 cm is plotted against galaxy type in Figure 16. In neither case is there evidence for, or against, a correlation with type of galaxy. The sample is too small and the observations do not extend to faint enough limits to allow any conclusions to be drawn.

From an investigation of sixteen Sb and Sc galaxies at 1.9 meters (158 mc), Brown and Hazard (1961) found a value of $m_r - m_{pg} = + 1.3$ with an r.m.s. deviation of $\pm$ 0.8. The mean value of $m_{21.4} - m_{pg}$ for the thirteen Sb and Sc galaxies investigated in this paper is + 0.7, with an r.m.s. deviation of $\pm$ 1.0. The difference in the results at the

TABLE 11

ADOPTED OPTICAL AND RADIO DATA

NGC *IC	Type	m_{pg}	$m_{21.4}$	$m_{21.4} - m_{pg}$	m-M	$M_{21.4}$	M_{pg}	x_c
55	Sc	7.8	9.8	+ 2.0	26.3	-16.5	-18.5	- .69
253	Sc	7.6	7.4	- 0.2	28.0	-20.6	-20.4	- .28
342*	Sc	8.2	8.2	0.0	26.7	-18.5	-18.5	-1.24
598	Sc	6.0	8.8	+ 2.8	24.5	-15.7	-18.5	- .98
2403	Sc	8.8	9.4	+ 0.7	27.1	-17.6	-18.3	- .95
3034	Ir	9.0	7.2	- 1.8	27.1	-19.9	-18.1	- .21
4258	Sb	9.1	8.2	- 0.9	28.2	-20.0	-19.1	- .65
4490	Sc	9.7	9.7	0.0	28.2	-18.5	-18.5	- .97
4631	Sc	9.6	9.0	- 0.5	28.2	-19.1	-18.6	- .68
5194/5	Sc/Ir	8.5	9.5	+ 1.0	27.5	-18.0	-19.0	-1.73
5236	Sc	7.5	8.0	+ 0.5	27.5	-19.5	-20.0	- .90
5457	Sc	8.1	9.8	+ 1.7	27.0	-17.2	-18.9	-1.26
6946	Sc	8.4	9.0	+ 0.6	27.6	-18.6	-19.2	- .70
4826	Sb	9.2	10.2	+ 1.0	27.8	-17.6	-18.6	-1.22
185	Epec	7.8	> 9.5	> + 1.7	24.5	> -15.0	-16.7	
278	Sb	10.8	> 9.8	> - 1.0	29.7	> -19.9	-18.9	
300	Sc	9.6	> 9.8	> + 0.2	28.1	> -18.3	-18.5	
891	Sb	10.7	> 9.8	> - 0.9	28.4	> -18.6	-17.7	
1052	E3	11.7	>10.3	> - 1.4	30.8	> -20.5	-19.1	
1613*	Ir	8.9	>10.3	> + 1.4	24.0	> -13.7	-15.1	
2683	Sb	9.8	>10.3	> + 0.5	27.3	> -17.0	-17.5	
2841	Sb	10.2	> 9.8	> - 0.4	29.2	> -19.4	-19.0	
2903	Sc	9.5	>10.3	> + 0.8	28.6	> -18.3	-19.1	
3031	Sb	7.8	> 9.1	> + 1.3	27.1	> -18.0	-19.3	
3115	E7	10.2	>10.3	> + 0.1	28.1	> -17.8	-17.9	
3368	Sa	9.7	>10.3	> + 0.6	29.2	> -18.9	-19.5	
4214	Ir	10.1	>10.3	> + 0.2	28.2	> -17.9	-18.1	
4236	Sc	9.5	>10.3	> + 0.8	26.5	> -16.2	-17.0	
4244	Sc	10.5	>10.3	> - 0.2	27.0	> -16.7	-16.5	
4278	El	10.9	>10.3	> - 0.6	29.6	> -19.3	-18.7	
4449	Ir	9.4	>10.3	> + 0.9	28.2	> -17.9	-18.8	
4594	Sa/Sb	8.9	> 9.0	> + 0.1	30.6	> -21.6	-21.7	
4736	Sb	8.6	>10.3	> + 1.7	28.2	> -17.9	-19.6	
5055	Sb	9.4	>10.4	> + 1.0	28.2	> -17.8	-18.8	
5866	SO	11.1	>10.3	> - 0.8	30.0	> -19.7	-18.9	

two wavelengths is attributable to the different values of photographic magnitudes used. If we use the corrected photographic magnitudes given by Brown and Hazard, we obtain

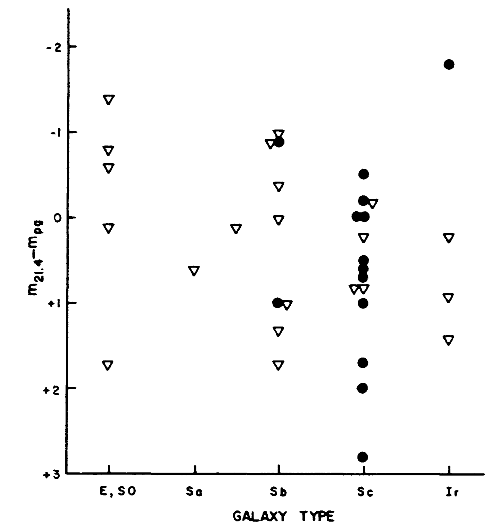

Figure 15. The ratio of light to radio emission at 21.4 cm, $m_{21.4} - m_{pg}$, vs. galaxy type. Filled circles are observed values; open triangles represent upper limits.

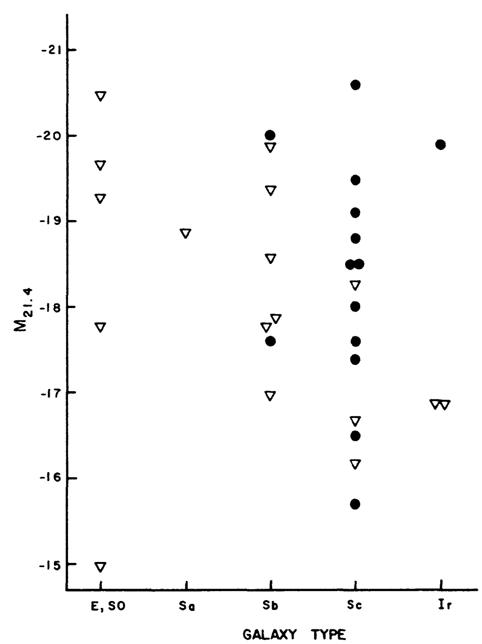

Figure 16. Absolute radio magnitude at 21.4 cm vs. galaxy type.

$m_{21.4} - m_{pg} = +1.1 \pm 0.8$, in excellent agreement with their result at 1.9 meters. Our results also lend support to Brown and Hazard's conclusion that the observed deviation in $m_r - m_{pg}$ is not due entirely to observational errors, but represents a real dispersion in the properties of the galaxies.

The mean absolute photographic magnitude of the galaxies observed is about - 19, with a total range of $\pm$ 1 magnitude. The range in absolute radio magnitude, on the other hand, is $\pm$ 2.5 magnitudes. Thus the dispersion in $m_{21.4} - m_{pg}$ is due primarily to the dispersion in $M_{21.4}$. This is shown in figure 17, where $M_{21.4}$ is plotted against M_{pg}. The filled circle represents the irregular galaxy NGC 3034. Open circles represent the Sb and Sc galaxies observed. The slant line in the diagram is a line of constant ratio of light to radio emission, $m_{21.4} - m_{pg} = 0$. The diagram shows that for galaxies in the range Mpg = -18 to -19 the radio luminosity may vary over a relatively wide range. In addition, there is a suggestion that in the case of brighter galaxies the ratio of light to radio luminosity is approximately constant. There are not enough observations, however, to draw any definite conclusion. While the ratio of light to radio emission is a useful parameter in differentiating between the intense peculiar extragalactic radio sources and normal galaxies, and may also ultimately prove useful in describing the radio properties of different types of galaxies, some other parameter seems to be needed to describe the radio emission properties of Sc galaxies.

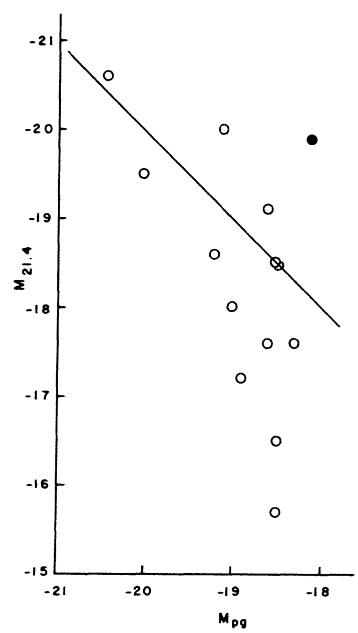

Figure 17. Absolute radio magnitude at 21.4 cm vs. absolute photographic magnitude. The filled circle is the irregular galaxy NGC 3034. Open circles give the values for the Sb and Sc galaxies observed.

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