ON THE RADIO EMISSION FROM SOME PECULIAR GALAXIES

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Summary

Radio observations have been made of 18 galaxies whose spectra and colours in their central regions are abnormal for their morphological types (Markarian 1963). Observations at 1410 and 2650 Mc/s were made with the CSIRO 210 ft steerable telescope at Parkes, and at 408 Mc/s with the east–west arm of the Mills Cross at the Molonglo Observatory of the University of Sydney. Radio emission was detected from the central regions of 13 of these galaxies. For these 13 the radio index ($m_r - m_{pg}$) is about $1 \cdot 2$ and differs by about two magnitudes from that of normal spirals. Absolute radio magnitudes of the galaxies are about $-21 \cdot 0$. In most cases the presence of radio emission is accompanied by emission lines in the optical spectra. It is concluded that the enhanced radio emission of the galaxies investigated is due to the production of relativistic electrons in their active nuclei.

I. Introduction

Markarian (1963) has pointed out that some E, SO, Sa, and Sb galaxies have unusually early spectral classes A and F, which are more characteristic of Sc and Magellanic galaxies. In these galaxies of abnormal spectral class, the central parts are bluer than normal galaxies of the same morphological type. Markarian has suggested that the colour is due to the presence of an additional blue and ultraviolet continuum and that this emission, associated with activity within the nucleus, is possibly of non-stellar and perhaps even non-thermal origin.

If the nature of this additional radiation is due to synchrotron radiation from relativistic electrons, then a similar enhancement of radio emission might be expected. The present observations were undertaken to investigate this possibility. Two of the southern galaxies in Markarian's list (NGC 1068 and NGC 5128) have long been known as prominent radio emitters, and radio emission has been found from a third (NGC 1097) by Mathewson and Rome (1963). In addition, radio emission has been detected from six of nine of these galaxies observed by Heeschen and Wade (1964) in their radio survey of northern galaxies.

Additional observations have now been made of a further 18 galaxies in Markarian's list, which could be observed with the Australian radio telescopes at Parkes and Molonglo.

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II. Observations

The initial observations were made at 1410 Mc/s with the 210 ft reflector and the radiometer described by Gardner and Milne (1963). At this frequency the beamwidth of the telescope is $\sim$ 14 min of arc. The i.f. bandwidth of the radiometer is 10 Mc/s and the system noise temperature 100°K. With the 2 sec time constant used in the observations, peak-to-peak noise fluctuations were $0 \cdot 15$ degK. A backward-looking sky horn provided the reference.

The observations consisted of scans of $\pm 30'$ through the position of the galaxy in both right ascension and declination. At least 2 scans were made in each coordinate and in some cases up to 10. By integration of such scans, sources as weak as $0 \cdot 1$ flux units (10^{-26} W m^{-2} (c/s)$^{-1}$) could be detected. Approximately once each hour the receiver was calibrated by injecting a known noise signal through a directional coupler into the line between the aerial feed and the r.f. switch. Overall calibration of the system was made several times each day by observation of sources that are adopted as flux density standards at Parkes.

Observations were made at a frequency of 2650 Mc/s on the galaxies that were detected at 1410 Mc/s. At 2650 Mc/s the beamwidth of the 210 ft telescope is $7' \cdot 5$. The degenerate parametric receiver described by Cooper, Cousins, and Gruner (1964) has an i.f. bandwidth of 40 Mc/s and a system noise temperature of 150°K. It also employs a backward-looking sky horn as reference. With a 2 sec output constant, peak-to-peak noise fluctuations are $\sim 0 \cdot 15$ degK. The method of observation was similar to that at 21 cm, except that the scan range and scan rate were reduced. Integration of a number of scans enabled detection of signals as low as $0 \cdot 1$ flux units.

At 408 Mc/s some of the galaxies were further investigated by observing their transits through the beam of the 1 mile east–west arm of the Mills Cross. These observations provided a more accurate estimate of right ascension and a flux density from which the spectral indices in the range 408–2650 Mc/s could be determined. The beam is $1' \cdot 5$ in right ascension and 4° in declination. Calibration was made by observation of some standard sources and also by injection of a standard noise signal into one of the system preamplifiers.

The accuracy of the flux density measurements is estimated at $\pm 30\%$. The direct pointing accuracy of the 210 ft telescope is $\sim 0' \cdot 6$ (Bolton, Gardner, and Mackey 1964). In the present observations the low signal-to-noise ratio considerably influences the accuracy of position measurements. The estimated accuracy of the position measurements in declination is $\pm 2'$. Where observations were made at 75 cm the accuracy is probably $0' \cdot 5$ in right ascension, otherwise it is $2'$. Fairly good agreement was obtained between the measurements at the different wavelengths.

III. Results

The list of the 18 galaxies observed, their types, apparent magnitudes (de Vaucouleurs and de Vaucouleurs 1964), and positions are presented in Table 1. NGC 3351, NGC 3628, and NGC 7469 have also been observed by Heeschen and Wade (1964) and NGC 1097 by Mathewson and Rome (1963). The table also contains the measured flux densities at the various frequencies, and the differences between the measured radio positions and the optical positions. The detected radio source was considered identified with the corresponding galaxy provided the declination differences did not exceed 2′ and provided the right ascension differences did not exceed 2′ for the 2650 and 1420 Mc/s observations or 1′ for the 408 Mc/s observations. On this basis 13 out of the 14 sources may be identified with the galaxies. In the other case, the radio source is 5′ north-west of NGC 3351 and is most likely a chance coincidence. An examination of the Palomar Sky Survey print and a plate by Kolloglian at Byurakan did not suggest any outer extension of NGC 3351 that might be associated with the source.

Table 1

MEASURED POSITIONS AND FLUX DENSITIES FOR OBSERVED GALAXIES

NGC No.	Type	m_{pg}	R.A. (1950)		Δ R.A.	Dec. (1950)		Δ Dec.	Flux Density (flux units)*		
			h	m	m	°	′	′	21 cm	11 cm	75 cm
23	Sb	13·1	00	07·3	0	25	39	−1·5	0·22 (4)	0·15 (6)	—
1097	SBb	10·3	02	44·3	−0·7	−30	29	+0·2	0·57 (2)	0·42 (6)	1·1 (1)
2911	SOp	13·4	09	31·0	+0·5	10	22	+1·9	0·27 (10)	0·19 (6)	<1·0 (2)
3185	SBa	12·7	10	14·9	+0·8	21	56	−0·5	0·16 (5)	<0·10 (7)	—
3227	Sb	11·9	10	20·7	−0·9	20	07	0	0·16 (6)	0·10 (8)	<1·0 (1)
3351	SBb	11·0	10	41·3	+4·7	11	58	+2·6	0·35 (8)	0·20 (6)	1·1 (1)
3593	SOp	12·0	11	12·0	−1·0	13	06	+1·2	0·25 (6)	0·10 (13)	1·25 (2)
3628	Sb	10·6	11	17·7	−0·7	13	53	−1·6	0·61 (5)	0·35 (4)	1·5 (2)
4179	E7	12·2	12	10·3	—	01	35	—	<0·10 (2)	—	—
4479	SO	13·9	12	27·8	—	13	51	—	<0·10 (4)	—	—
5548	Sa	13·4	14	15·7	+2·0	25	22	−0·1	0·14 (5)	<0·10 (4)	—
5713	Sb	12·1	14	37·6	−0·2	−00	05	+0·5	0·30 (4)	0·19 (5)	<1·0 (2)
6814	Sb	12·3	19	39·9	0	−10	25	+0·9	0·15 (4)	<0·10 (2)	<0·7 (3)
6954	Sb	14·2	20	41·5	—	03	01	—	<0·10 (2)	—	—
7469	Sa	13·3	23	00·7	0	08	36	−0·3	0·29 (5)	0·19 (5)	<1·0 (1)
7576	Sa	14·1	23	14·9	−2·0	−05	01	−2·0	0·34 (5)	0·26 (5)	—
7625	SOp	13·2	23	18·0	—	16	57	—	<0·10 (2)	—	—
7771	SBb	13·4	23	48·9	−2·0	19	50	0	0·20 (4)	<0·10 (4)	—

* Number of observations shown in parentheses after each value.

The general question of chance coincidence between weak radio sources and galaxies will be considered in detail in a forthcoming paper by the author. However, we may note that only 1 of 50 galaxies, of the same apparent magnitude but with type 3 nuclei (Kolloglian and Tovmassian 1964), observed in the same manner had apparent radio emission. Thus the possibility of chance coincidence in 13 out of 18 in the present study is extremely remote.

The scans of the observed source showed no sign of beam broadening at 11 cm, so that these diameters are less than 2–3′. Thus the flux densities calculated on the basis of peak deflections might be underestimated at the most by 7–16% at 11 cm and 2–5% at 21 cm. Only NGC 1097 was slightly resolved at 75 cm and its dimensions in right ascension are less than 2′—less than the value given by Mathewson and Rome (1963) from 21 cm observations.

IV. Discussion

(a) *Radio Emissions of Peculiar Galaxies*

In 13 out of the 18 cases the detected radio sources coincide within the limits of error to the centres of the corresponding galaxies. If we add the 5 previously known radio emitters (NGC 1068, NGC 2146, NGC 2903, NGC 4151, and NGC 5128), we see that 18 out of 23 observed from Markarian's (1963) list of 41 galaxies have appreciable radio emission. The percentage of systems in which radio emission is detectable ($\sim 70\%$) is much higher than amongst normal galaxies of the same apparent magnitude (see for example, Heeschen and Wade 1964; Tovmassian, in preparation).

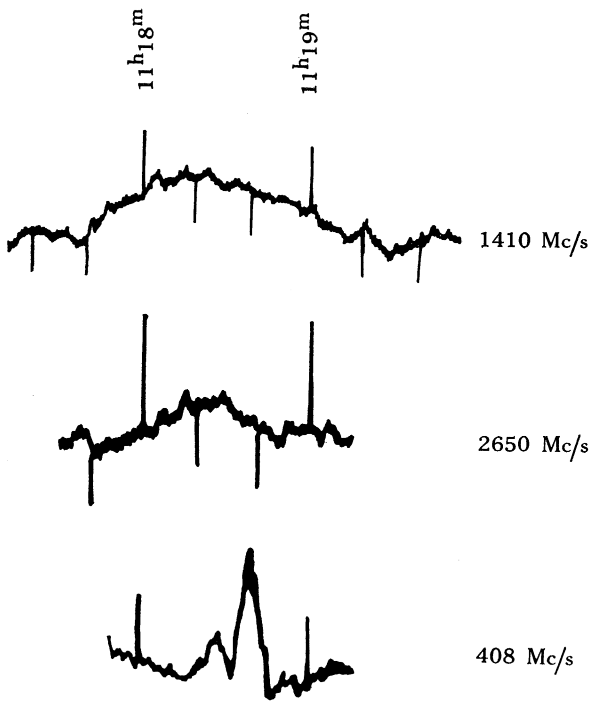

Fig. 1.—Scans in right ascension of NGC 3628 at 1410, 2650, and 408 Mc/s.

It is interesting to note that the radio dimensions of the 13 galaxies studied in the present investigation are not larger than their optical dimensions—in contrast to the results of Hanbury Brown and Hazard (1959) for normal galaxies. This means that the radio emission must originate in the central regions only and not throughout the entire volume. An example is shown in the records of NGC 3628 in Figure 1, which show no detectable beam broadening. In this case the dimensions of the radio source do not exceed 30 sec of arc in right ascension (from the 75 cm record) and 2–3 min of arc in declination. The major axis of NGC 3628 extends 14′·5 in right ascension (de Vaucouleurs and de Vaucouleurs 1964). (The stronger source to the right of NGC 3628 on the 75 cm record is some distance away in declination and thus is not seen on the 11 or 21 cm records.)

(b) *Spectral Indices*

The spectral indices of the detected radio sources are given in Table 2 and their spectra are shown in Figure 2. For three of the galaxies that were detected at 75 cm, the spectra have simple power laws for the range 11–75 cm. The distributions of spectral indices are shown in Figure 3, and it can be seen that most of the indices lie between $-0\cdot4$ and $-0\cdot9$ with a maximum between $-0\cdot6$ and $-0\cdot7$. NGC 3593 with a spectral index of $-1\cdot3$ is an exception.

TABLE 2

OPTICAL AND RADIO MAGNITUDES AND RADIO INDICES FOR OBSERVED GALAXIES

NGC No.	Spectral Index a	m'_{pg}	m_{1410}	m_{158}	R_{1410}	R_{158}	M_{158}
23	−0·60	12·5	13·2	11·8	+0·7	−0·7	−22·2
1097	−0·56	9·9	12·1	10·8	+2·2	+0·9	−20·4
2911	−0·51	12·9	12·8	11·6	−0·3	−1·3	−21·4
3185	—	12·2	13·5	12·0	+1·3	−0·2	−21·0
3227	−0·73	11·4	13·5	11·8	+2·1	+0·4	−19·5
3351	—	10·5	>14·0	>12·5	>+3·5	>+2·0	>−17·2
3593	−1·32	10·8	13·1	9·9	+2·3	−0·9	−18·9
3628	−0·86	9·1	12·1	10·0	+3·0	+0·9	−20·1
4179	—	10·9	>14·0	>12·5	>+3·1	>+1·6	>−18·6
4479	—	13·6	>14·0	>12·5	>+0·4	>−1·1	>−20·0
5548	—	13·2	13·7	12·1	+0·5	−1·1	−22·0
5713	−0·71	11·8	12·9	10·1	+1·1	−1·7	−22·0
6814	—	11·5	13·5	12·1	+2·1	+0·6	−19·5
6954	—	13·6	>14·0	>12·5	>+0·4	>−1·1	>−21·2
7469	−0·65	12·8	12·9	11·4	+0·1	−1·4	−22·7
7576	−0·42	13·7	12·7	11·7	−1·0	−2·0	−21·8
7625	—	12·8	>14·0	>12·5	>+1·2	>−0·3	>−20·6
7771	—	12·1	13·3	11·7	+2·1	−0·4	−22·2

(c) *Radio Index*

The most interesting parameter is the *radio index* ($R = m_r - m_{pg}$). Values for the galaxies were computed for 1410 and 158 Mc/s and are given in Table 2. The radio magnitudes were determined from the relation

$$m_r = -53\cdot45-2\cdot5\log_{10}S,$$

as defined by Hanbury Brown and Hazard (1961). The photographic magnitudes are those of Table 1, corrected for absorption in our Galaxy by $\Delta m = -0\cdot25\operatorname{cosec} b$ and internal absorption within the systems themselves by using the results of Holmberg (1957). For the radio magnitude at 158 Mc/s, the flux density at 158 Mc/s was estimated from the flux density at 1410 Mc/s and the spectral index (assumed constant over that frequency range). Where the spectral index was not known a value of $-0\cdot65$ was used. R_{1410} and R_{158} together with the radio magnitudes m_{1410} and m_{158}, the corrected photographic magnitude m'_{pg}, and the absolute radio magnitude at 158 Mc/s, M_{158}, are given in Table 2.

At 1410 Mc/s we may compare our results with those of Mathewson and Rome (1963). For 16 normal spiral galaxies they found $R_{1410} = +3 \cdot 3$. For the 13 spirals with abnormal spectra and colour in the nuclei we obtain $R_{1410} = 1 \cdot 2$ with an r.m.s.

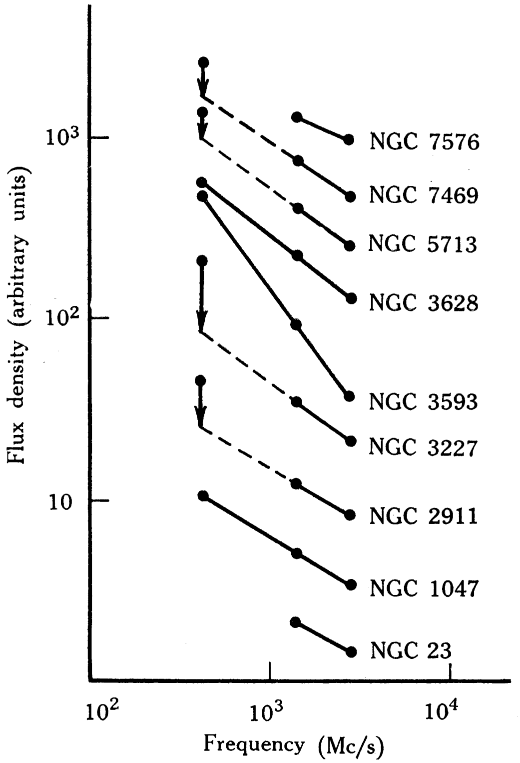

Fig. 2.—Spectra of nine of the observed galaxies plotted with displaced flux density origins.

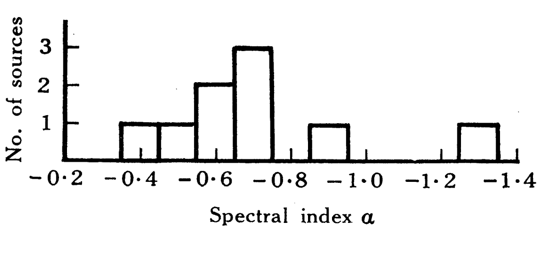

Fig. 3.—Distribution of the spectral indices for nine of the observed galaxies.

deviation of $1 \cdot 3$. One of the abnormal galaxies, NGC 1907, is included in Mathewson and Rome's list and this lowers their mean R_{1410}.

The mean value of R_{158} for the 13 galaxies studied is $-0 \cdot 5$ with an r.m.s. deviation of $0 \cdot 9$. The corresponding value for 32 normal spirals studied by Hanbury Brown and Hazard (1961) and by Mathewson and Rome (1963) is $+1 \cdot 5$ with an r.m.s. deviation of $0 \cdot 8$.

The radio indices at 1410 Mc/s for the four galaxies (NGC 1068, NGC 2146, NGC 2903, and NGC 4151) have been estimated from the peak deflections D_{1410} of the observations of Heeschen and Wade (1964) and are given in Table 3. (NGC 5128 is omitted because of the complexity of its radio distribution.) The addition of these data does not materially change the results.

TABLE 3

OPTICAL AND RADIO MAGNITUDES AND RADIO INDICES FOR GALAXIES OBSERVED BY HEESCHEN AND WADE (1964)

NGC No.	m'_{pg}	D_{1410}	m_{1410}	R_{1410}
1068	9·9	4·9	9·8	−0·1
2146	10·4	1·3	11·2	+0·8
2903	9·3	0·4	12·5	+3·2
4151	11·1	0·4	12·5	+1·4

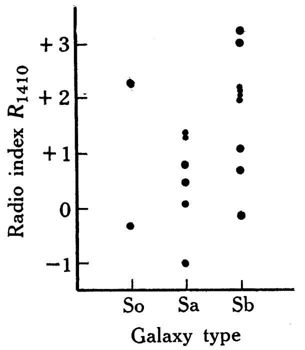

Fig. 4.—Radio indices for 17 peculiar galaxies.

The radio indices of the galaxies whose nuclei have abnormal spectra and are bluer in colour than would be expected from their morphological types are on the average two magnitudes less than that of normal spiral systems. The radio emission is thus six to seven times greater for these systems than for normal spirals.

In Figure 4 the distribution of radio indices is shown as a function of the type of galaxy. Sa galaxies are perhaps stronger emitters than Sb galaxies, but the difference is not statistically significant.

(*d*) *Strong Emission Lines*

It is interesting to note that out of the 41 galaxies studied by Markarian (1963) 11 have strong emission lines in their spectra and 7 of these (NGC 1068, NGC 3227, NGC 4151, NGC 5548, NGC 5713, NGC 6814, and NGC 7469) have enhanced radio emission. Of the remaining 4, 3 were not observed and for 1, NGC 4051, no radio emission was found. However, in the majority of cases strong line emission is accompanied by enhanced radio emission (as was also noted by Heeschen and Wade 1964).

(*e*) *Radio Magnitude*

The mean value of the absolute radio magnitude for the 13 galaxies determined from the known radial velocities and a Hubble constant of 75 km sec^{-1} Mpc^{-1} is −21·0. In this respect the systems are intermediate between the normal galaxies and the radio galaxies.

V. Conclusions

The present investigation has shown that, in comparison with normal spirals, systems whose spectra and colour are abnormal for their morphological types have enhanced radio emission in their central regions. Activity in the nuclei of these regions is probably responsible for the production of relativistic electrons, which in turn are responsible for some of the abnormal emission at both optical and radio emissions.

The scale of the radio emission is probably related to the scale of activity in the nucleus at any given moment (Ambartsumian 1956, 1958, 1962). Further investigations at both radio and optical wavelengths are required to properly understand the phenomena.

VI. Acknowledgments

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