

WSRT observations of elliptical galaxies from the B2 catalogue

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Summary. We present 4995 MHz observations of 22 radio galaxies from the B2 catalogue. The most frequent type of radio structure found in this sample is the classical double, with linear sizes ranging from tens to hundreds of kpc. Detected degrees of polarized flux density range from 2% to 23%. The orientation of the projected magnetic field is mostly perpendicular to the source major axis.

Key words: radio galaxies – radio structures – polarization

1. Introduction

In the past years two samples of elliptical galaxies, mainly of intermediate or low radio power ($\text{Log } P(408) \lesssim 25.5 \text{ W/Hz}$), selected from the B2 catalogue of radio sources (Colla et al., 1970, 1972, 1973), have been studied at several frequencies. The first sample (Colla et al., 1975, hereafter referred to as sample I), containing 54 objects, results from the identifications of B2 radio sources with galaxies in the Catalogue of Galaxies and Clusters of Galaxies (Zwicky and Herzog, 1963). The selection criteria were:

$$S_{408} \gtrsim 0.2 \text{ Jy}, \quad m_{pg} \leq 15.7, \quad 24^\circ < \delta < 40^\circ.$$

The second sample (Fanti et al., 1978, hereafter referred to as sample II) was obtained by searching for identifications between B2 radio sources and fainter galaxies, with $m_r \leq 16.5$, and contains 49 objects.

Sample I has been studied in detail at several frequencies with the Westerbork Synthesis Radio Telescope (WSRT): 40 galaxies were observed at 610, 1415, and 4995 MHz with the short cut technique (Fanti et al., 1977), while the extended sources were mapped with 12-h synthesis (see e.g. Ekers et al., 1981 and references therein). So far sample II has been satisfactorily studied only at 1415 MHz (Fanti et al., 1978). Polarization data at 1415 MHz of 66 sources are presented in Gioia and Gregorini (1979).

Here, we present new observations of 10 radio galaxies from sample I and 12 radio galaxies from sample II, made with the WSRT at 4995 MHz. The sources of sample I were reobserved at 4995 MHz to obtain maps with better sensitivity. This allows a more detailed study of their radio structures and linear polarization.

The aim of the present observations is to study the radio structures of some interesting sources and to derive the spectral

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index of individual radio components between 1415 and 4995 MHz. Moreover, the data give information on the linear polarization and allow to compute the physical parameters of the sources for which linear polarization has been detected at 1415 MHz.

Section 2 describes the radio observations and the reduction technique. Section 3 presents total intensity and linear polarization data, while comments on individual galaxies are given in Sect. 4. Section 5 briefly discusses the results.

We use $H = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ throughout this paper.

2. Radio observations and data reduction

The radio observations were made at 4995 MHz with the WSRT. A description of the instrument can be found in Weiler (1973), Högbom and Brouw (1974), and Casse and Muller (1974). The observations were made with 10 fixed and 4 movable antennas, producing 40 interferometers with a maximum baseline of 1440 m. For each source five to seven short observations (each not less than ten minutes) were made at widely spaced hour angles. The calibrated data were Fourier transformed to produce a two dimensional map, $5' \times 5'$ in size, for all Stokes parameters. The Clean and Restore technique (Högbom, 1974) was applied to remove the effects of side and grating lobe responses from the maps. The half power beam width (HPBW) in the resulting maps is $6.7'' \times 6.7'' / \sin \delta$. The r.m.s. noise level, including dynamical range effects, is 2 mJy almost constant in all fields. The “Cleaned” U and Q maps were then combined to obtain the intensity of the polarized flux, $P = (U^2 + Q^2)^{1/2}$ and the position angle of the electric vector $\Phi = (1/2) \arctan U/Q$.

In order to compare the new 4995 MHz data with the older at 1415 MHz, maps were made with equivalent spacings in wavelengths, cleaned and restored with the same gaussian beam.

3. The data

The results of the observations are presented in Table 1. They are arranged as follows:

Column 1: B2 Name. The numbers I and II in parentheses denote sources of the two samples.

Column 2: component designation (G means optical galaxy; c : radio core; T : total flux; A, B, C : individual components).

Column 3, 4: right ascension and declination at 1950.0 of the radio centroid or of the optical galaxy.

Column 5: redshift taken from: Colla et al. (1975), Fanti et al. (1978), and Ulrich et al. (1980).

Table 1. Radio data

NAME	R.A. h m s	DEC. ° ' "	z	S mJy	$\theta_1 \times \theta_2$ " " (pA)	LAS (pA)	P mJy	ϕ °	m %	Type
0206+35 (I)	G c T	020639.3 39.2 42	.0375	90 1000						
					60x26(130)		57.2	-45	5.7+0.5	HC
0331+39 (I)	G c T	033101.0 00.9 23	.0202	270 570						
					24x12(170)		12.7	-47	2.2+0.2	HC
0828+32AB (II)	G A B	082820.6 12.5 2841 27.9 3035	.0507	410 436	65x58 67x51	280(50)	28.3 53.2	72 84	6.9+0.8 12.2+1.1	D
0836+29 (I)	G A B	083659.1 58.0 24 59.3 49	.0650	148 105	12x 8(30) 24x 7(35)	30(35)	7.1 5.7	22 -21	4.8+0.6 5.4+0.8	D
0908+37 (II)	G c A B	090845.4 45.3 35 45.3 19 45.6 50	.1040	50 102 122						
					11 (90) 13 (91)	31(7)	4.0 9.2 6.5		(8) 9.0+1.0 5.3+0.8	D
0913+38 (II)	G A B	091339.1 38.4 42 40.2 44	.0711	81 63	11x10 12x10	21(85)	9.7 (2.0)	-86	12.0+0.8 (3)	D
1040+31 (I)	G c T	104031.0 31.2 48	.0360	55 415						
					30x17(60)		8.5	-45	2.0+0.2	HC
1102+30 (I)	G c A B	110239.7 39.6 55 35.4 38 43.5 2608	.0720	26 80 90						
					45x19(88) 40x23(75)	144(75)	13.0 15.2 16.2		(11.5) 19.0+1.2 18.0+1.1	D
1113+29 (I)	G c A B	111353.4 53.5 41 51.9 37 55.9 50	.0489	70 520 380						
					18x14(90) 25x23	54(76)	3.5 44.8 26.6	70 85 45	5.0+1.1 8.6+0.2 7.0+0.2	D
1141+37 (II)	G A B	114150.0 41.8 2343 57.2 2656	.115	274 355						
					8 (4) 8 (106)	300(45)	7.9 15.3	-36 74	2.9+0.2 4.3+0.2	D
1204+34 (II)	G c A B	120500.5 00.5 21 0458.9 32 0501.5 13	.0788	37 105 100						
					14x11(170) 15x 8(170)	37(120)	2.0 8.7 2.8		(5) 8.3+0.5 2.8+0.5	D
1422+26 (I)	G c A B	142226.5 26.5 03 23.4 5058 29.5 5102	.0370	25 214 223						
					40x30(93) 40x30(83)	120(87)	1.0 28.1 24.3		(4.0) 13.1+0.5 10.9+0.5	D
1441+26 (II)	G A B C	144153.9 48.3 42 54.0 1415 59.0 32	.0621	22 9 41						
					49 (90) 49 (90)	180(71)	2.0 1.0 15.0		(9) (11) (12)	D
1457+29 (II)	G c A B	145734.4 34.4 32 35.5 41 35.5 13	.0825	20 62 83						
					20x11(1) 27x13(179)	54(137)	3.8 10.6 12.2	-36 -28 -29	19.0+3.0 17.1+1.0 14.7+1.0	D
1521+28 (II)	G c A B	152121.4 21.5 07 21.1 53 23.1 4643	.0825	70 82 88						
					27x25(91) 40x17(7)	140(170)	3.6 10.7 20.2	47 62 -43	5.1+0.7 13.0+0.7 23.0+0.8	D
1525+29 (I)	G T	152539.6 39.8 28	.0653	102						
					17x 8(22)		3.0		(3)	D
1609+31 (II)	G A B	160942.3 42.2 31 42.3 46	.0944	26 44						
					7 (91) 8 (85)	15(5)	1.5 4.9		(6) 11.0+1	D
1621+38 (I)	G c T	162116.9 16.8 17	.0310	50 200						
					30x11(87)	50(87)	4.0		(2)	HT
1637+29 (II)	G c A	163722.2 22.3 45 20.9 5750	.0875	13 115						
					60x37(177)	*	0.5 6.0		(4) (5)	C
1658+30 (II)	G c A B	165848.9 48.9 31 46.6 15 52.1 55	.0351	84 160 141						
					35x31 40x38	120(60)	3.8 20.3 17.9	80 67 83	4.5+0.6 12.7+0.5 12.7+0.6	D
1752+32B (II)	G c T	175244.5 44.4 47	.0449	21 91						
					46x29(25)		3.0		(3)	HC
2116+26 (I)	G c T	211620.7 20.8 09	.0164	57 120						
					45x10(20)		4.8	3	4.0+1.0	HC

* : Complex source. See Fig. 1

Column 6: flux density at 4995 MHz in mJy, corrected for the primary beam attenuation.

Column 7: width at half maximum, along the major and minor axis, of the elliptical gaussian used to fit the brightness distribution (in arcsec). In parentheses the position angle of the major axis in degrees.

Column 8: largest angular size of the source in arcsec. In parentheses the position angle of the source in degrees.

Column 9: flux density of the polarized radiation in mJy, corrected for the primary beam attenuation.

Column 10: position angle of the electric vector in degrees (N through E)

Column 11: polarization percentage

Column 12: morphological type. HC = halo + core, D = double, HT = head-tail, C = complex.

The total intensity data on sample I galaxies, obtained here with better sensitivity, are generally in good agreement with those previously measured by Fanti et al. (1977), except, in some cases, for a better flux estimate of the core component. The polarization data are in most cases new: in the case of 0836 + 29 and 1102 + 30, we detect a polarized flux, while Gioia and Gregorini (1979) gave an upper limit.

In Fig. 1 we present the contour maps of the total and of the polarized intensity for sources with interesting structure. Maps of sample I sources are given only for sources whose map was not published in Fanti et al. (1977).

4. Comments on individual sources

0828 + 32 AB: The trend of the spectral index between 1415 and 4995 MHz has been derived along the source. A value $\alpha = 0.8^1$ is found to be almost constant through the source, except in the hot spot of the western component, where the spectrum flattens considerably ($\alpha \approx 0.4$). The polarized flux, given in Table 1, has been determined from a map convolved to a lower resolution (HPBW = 20"), where the signal to noise ratio is better.

1113 + 29: The source has been studied by Riley (1975).

1141 + 37: The outer components have a steep spectrum $\alpha \sim 0.85$. The source has been studied by Ulrich et al. (1980) who propose an optical identification with a tight chain of galaxies which are probably gravitationally bound. A radio map has been presented in Katgert-Merkelijn et al. (1980).

1422 + 26: The outer components show a multiple structure (Fig. 1). This source has been mapped at 1415 MHz by Ekers et al. (1981).

1457 + 29: The S shaped structure may indicate a rotating beam (see for example NGC 326, Ekers et al., 1978). At present no redshift measurement is available for this galaxy.

1521 + 28: The spectrum is very flat in the nucleus ($\alpha \approx 0$) and steepens going to the outer regions ($\alpha = 1.2$ at the end).

1621 + 38: The total intensity distribution of this source at 610, 1415, and 4995 MHz has been studied by Ekers et al. (1978).

1637 + 29: This radio galaxy is very asymmetric (Fig. 1); a jet like structure points from the nucleus to the extended northern feature, marked with A. A second extended region (B), more evident in the convolved map, is present on the north of the galaxy close to the first one. Using a WSRT 12-h synthesis map at 1415 MHz (Ekers et al., in preparation) we derived the trend of the spectral index. In the extended structures it is almost constant with a value $\alpha = 0.7$, while in the nuclear source it is flat ($\alpha = 0.1$).

1 $S(\nu) \propto \nu^{-\alpha}$; α is always between 1415 MHz and 4995 MHz

1658 + 30: The spectrum in the nucleus is flat ($\alpha = 0.0$) and steepens rapidly to a spectral index $\alpha \approx 0.5$ in the outer regions.

5. Results

The most frequent type of radio structure (15/22) found here is the classical double (D). Eight of these double sources also have an unresolved core coinciding with the center of the galaxy.

Five sources can be classified as halo-core (HC): they show an unresolved component, coincident with the center of the galaxy, surrounded by an extended low brightness region, which in some cases is elongated. This could be an indication of a double structure on a smaller scale.

There are also two peculiar sources in the sample: one of them, 1621 + 38, is a well known head-tail source; the other source, 1637 + 29, displays a complex structure (Fig. 1).

The linear size of the sources ranges from 10 to 370 kpc; we note that 12 sources have a size smaller than 50 kpc, and therefore, their radio emitting region is completely or almost completely embedded within the optical galaxy. Among them, 6 show a well defined D structure and 4 have an elongated HC structure, which suggests their possible double structure.

Therefore, we do not find relevant morphological difference between small and extended sources. In fact the most common type among the small radio galaxies is the classical double just as found for the larger ones (see also Ekers et al., 1981).

By adding the present data to those already published by Gioia and Gregorini (1979), we have a sample of 24 radio galaxies, for 18 of which significant polarization is detected at 4995 MHz. The degree of polarization, m , ranges from 2% up to 23%. Its median value at 4995 MHz, evaluated by taking into account the upper limits, is $\sim 7.0 \pm 2.0\%$. This value is consistent with the median value found in a sample of 4C radio galaxies (Conway et al., 1977; Padrielli and Conway, 1977); for these stronger radio galaxies we find a median value of $4.5^{+4.5}_{-2.5}\%$.

There are no obvious correlations between the degree of polarization and the physical source parameters like maximum linear size, component diameter, source brightness, spectral index.

A possible correlation between the degree of polarization and the radio structure has been searched for by computing the median values of polarization for the two classes of radio sources, D and HC, defined above. We obtained $7.5^{+3.0}_{-3.5}\%$ and $3.0^{+2.0}_{-1.0}\%$ respectively. There is, therefore, a marginal evidence for a difference between the polarization properties of the two classes. This can be understood by considering that the halo-core sources are core-dominated and the total polarization reflects the properties of the core itself.

Individual components of the same source may show rather different percentages of polarization, m (see 0913 + 38, 1204 + 34, 1521 + 28, 1609 + 31, and 2236 + 35).

Using data from Tabara and Inoue (1980) we have estimated the foreground rotation measure in the direction of each source and determined the intrinsic position angle of the electric vector and therefore the direction of the projected magnetic field.

We have examined the mean orientation of the magnetic field (θ_H) with respect to the source's major axis (θ_S) for the sources of our sample and for the radio galaxies of a sample of 94 3C sources (Conway et al., 1983). The two distributions of $|\theta_H - \theta_S|$ are different, in fact the first one is peaked around 80° while the second one is peaked around 0° . Therefore there is the indication that in powerful radio sources the magnetic field tends to be parallel to the source axis, while in the weak sources it is roughly perpendicu-

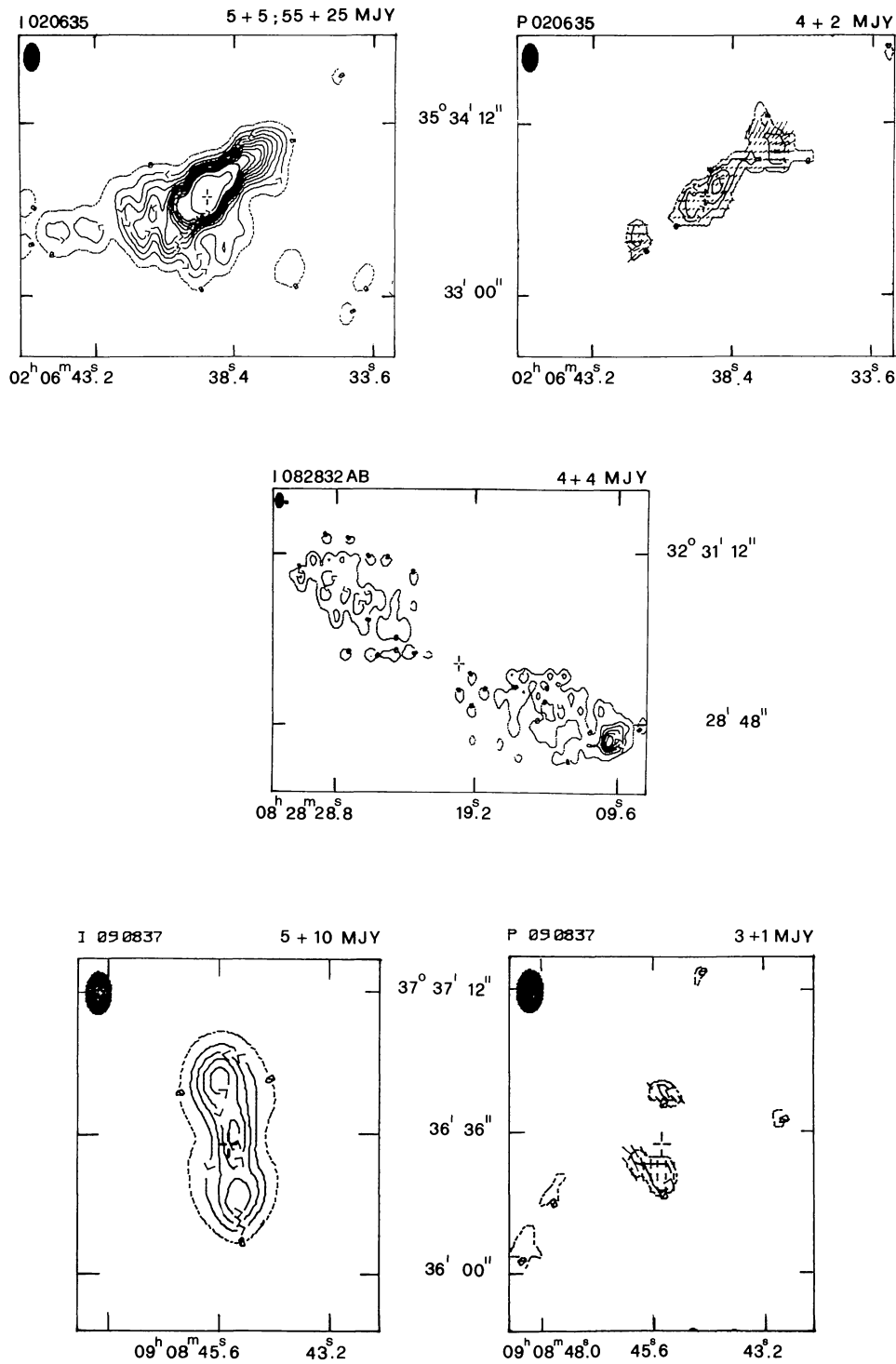


Fig. 1. Contour maps at 4995 MHz of interesting radio galaxies. The values in mJy per beam area of the first contour level and that of the constant increment between levels are given at the top of each map. The half power beam is drawn in each map. A cross indicates the optical galaxy. "I" denotes total intensity maps and "P" polarized intensity maps. In the latter, polarization position angles are represented by line segments whose length is proportional to the percentage of polarized flux. The maps are not corrected for primary beam attenuation

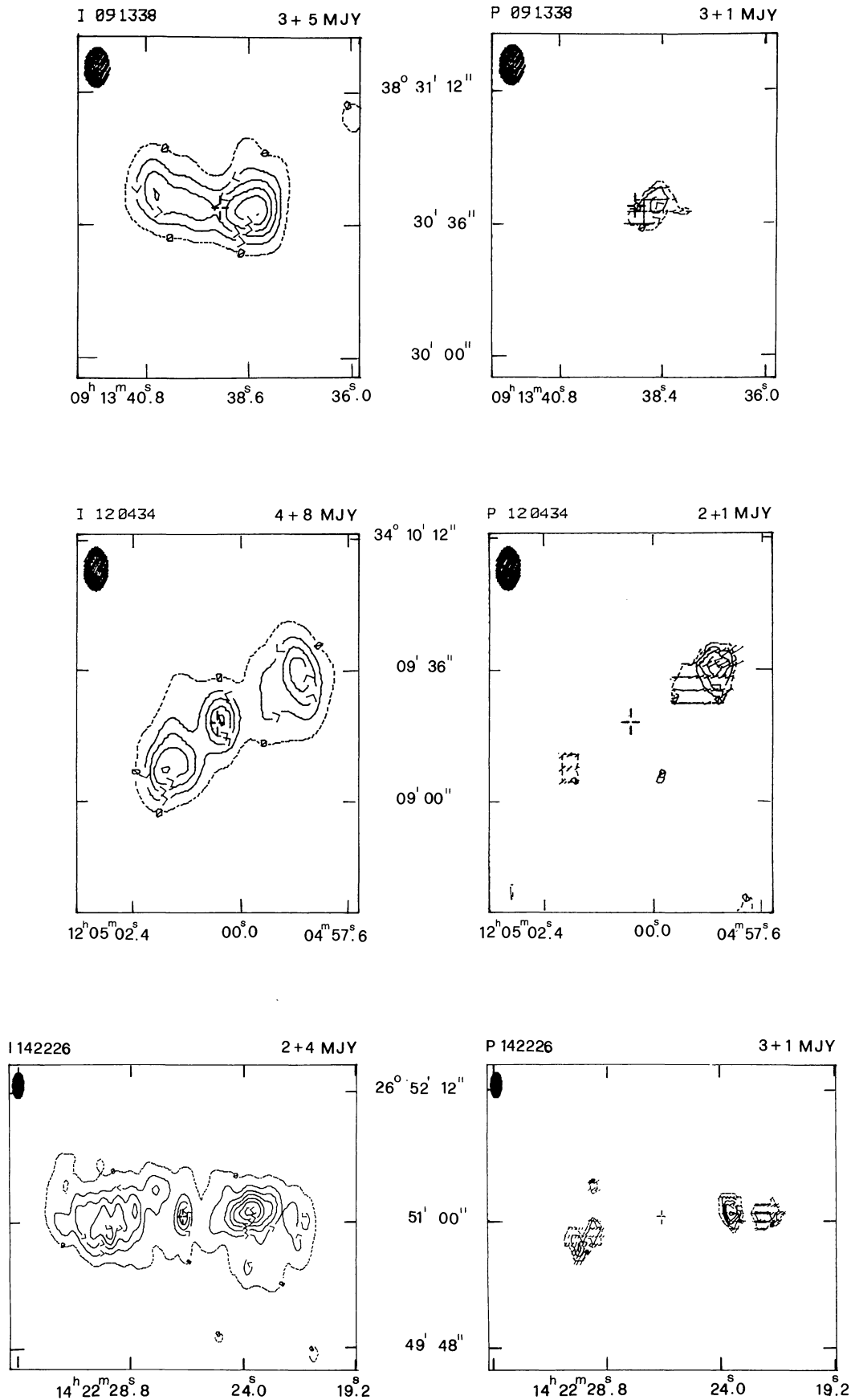


Fig. 1 (continued)

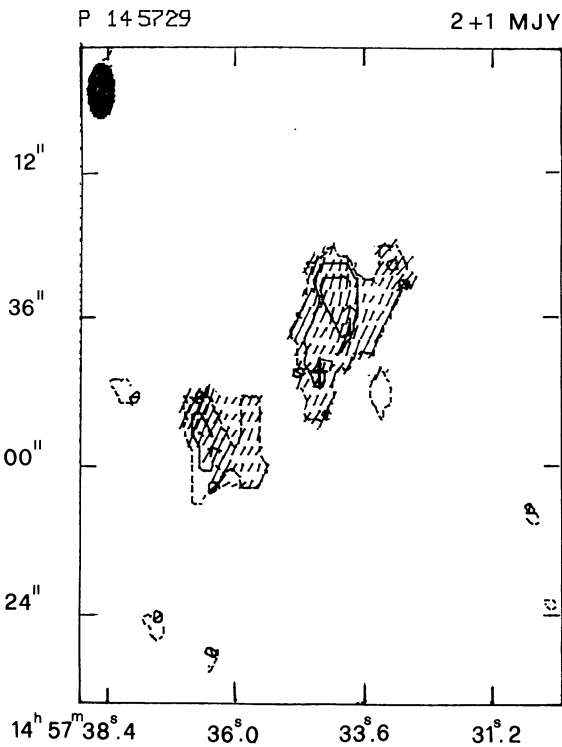
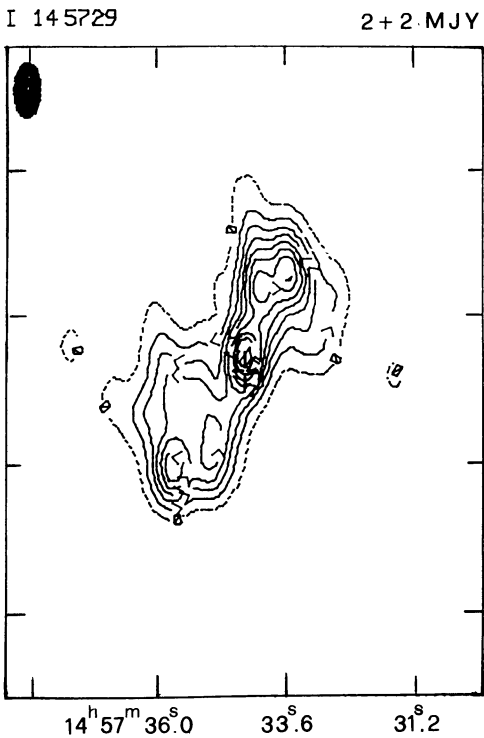
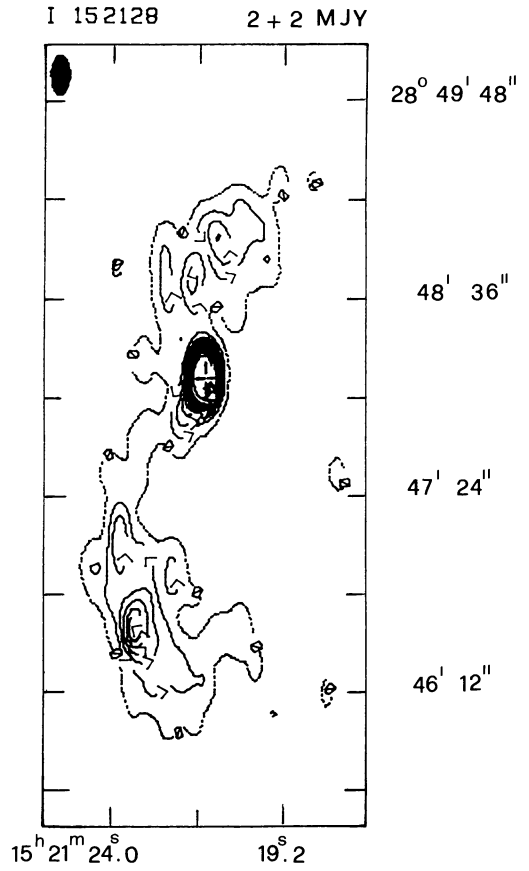
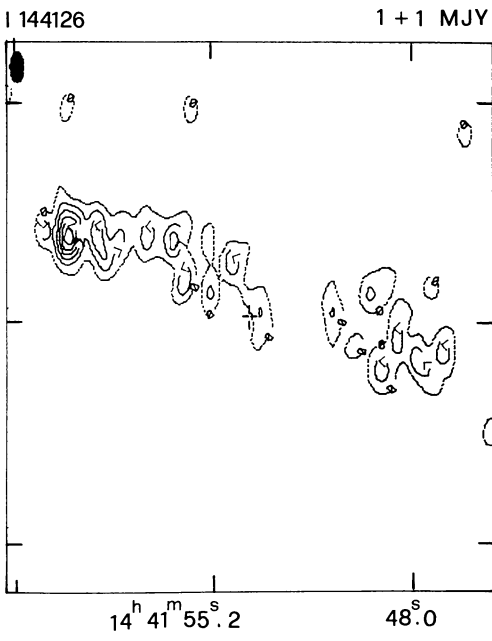


Fig. 1 (continued)

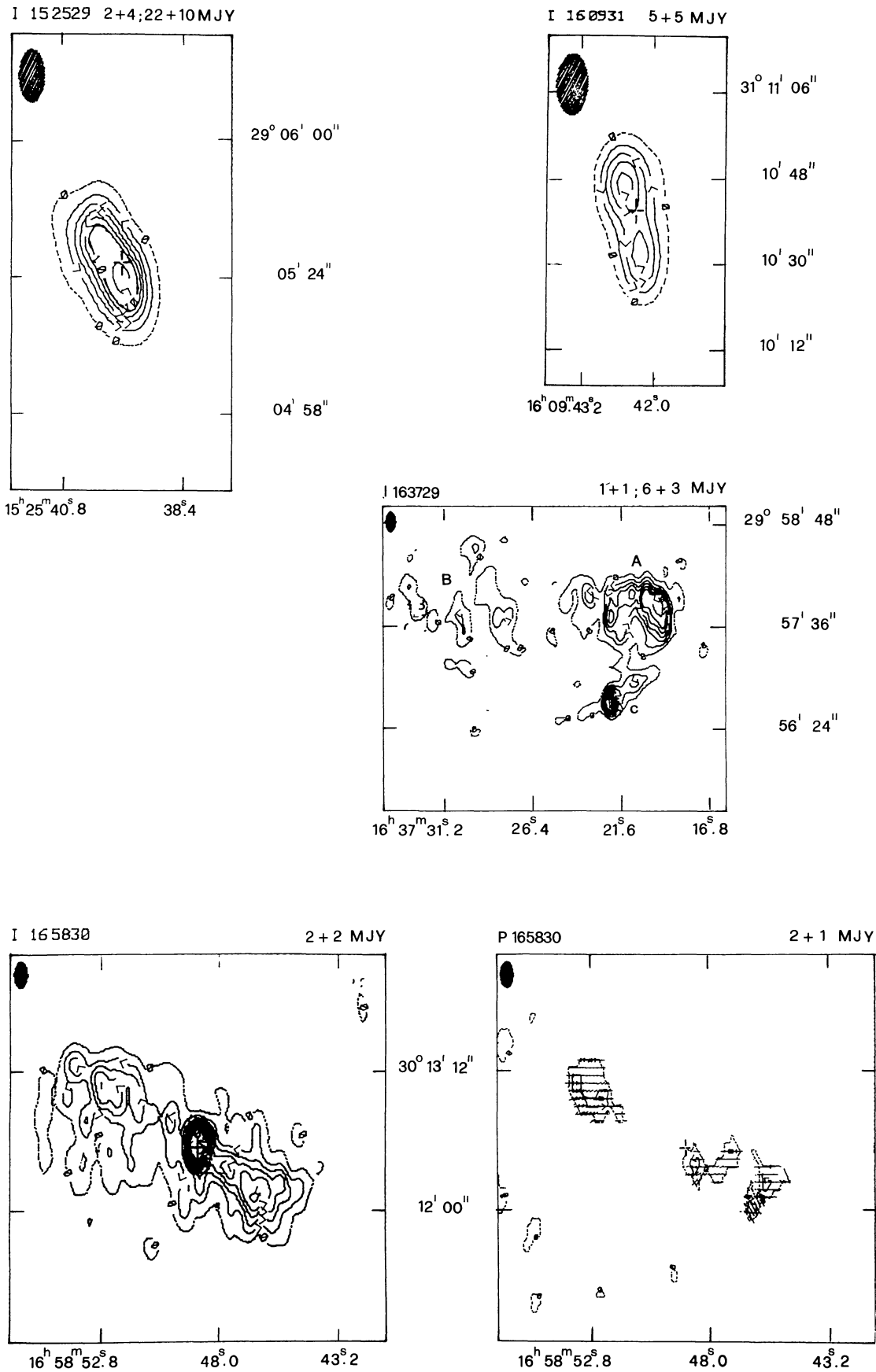


Fig. 1 (continued)

Table 2. Physical parameters obtained from the polarization data

NAME	$m_{1.4} / m_{5.0}$	$H_{ } n_e l$ ($\times 10^{14}$) cgs units	l kpc assumed	$H_{ }$ (10^{-6} gauss) assumed	n_e ($\times 10^{-3} \text{ cm}^{-3}$) calculated	M ($\times 10^7 M_{\odot}$)
0206+35 T	0.7	1.3	11	2.6	1.5	11.0
0331+39 T	1.0*	<0.06	2	4.2	<0.2	<0.01
0828+32 A	0.9	0.7	44	1.4	0.4	93.0
B	1.0	<0.2	39	1.8	<0.1	<19.0
0836+29 T	1.0	<0.2	20	1.6	<0.2	<1.3
0908+37 T	0.8	1.0	19	>6.0	<0.3	<5.3
0913+38 T	1.0	<0.2	21	2.7	<0.1	<3.4
1102+30 A	1.0	<0.2	21	0.6	<0.6	<32.0
B	0.8	1.0	25	0.7	1.9	130.0
1113+29 A	1.0	<0.2	10	2.3	<0.3	<1.0
B	0.6	1.4	17	1.6	1.7	22.0
1141+37 A	1.0	<0.2	14	1.7	0.3	2.0
B	0.8	1.0	14	3.4	0.7	4.7
1204+34 T	0.9	0.7	5	6.0	0.1	0.3
1422+26 A	1.0	<0.2	4	3.6	<0.5	<0.5
B	0.6	1.4	11	3.7	1.1	5.9
1521+28 B	0.4	1.7	21	1.7	1.5	81.0
1609+31 T	0.9	0.7	10	>6.0	<0.4	<1.7
1658+30 A	1.0	<0.2	11	3.0	<0.2	<1.1
B	1.0	<0.2	20	2.4	<0.1	<2.1
2116+26 T	1.0	<0.2	10	2.1	<0.3	<3.3

*This value has been derived between 2700 MHz and 4995 MHz.

lar to it (see e.g. Clarke et al., 1980). This could reflect the fact that most of the weak sources have a jet with a transversal magnetic field (Bridle, 1981).

The difference between the directions of the magnetic field in the individual components of double sources in our sample is $\leq 40^\circ$, except for two cases (1141+37 and 1521+28), while it has no preferred value in the sample of Conway et al. (1983). No conclusions can be drawn due to the poor statistics.

Combining the present data with those by Gioia and Gregorini (1979) and Ekers et al. (1981) we have derived the depolarization ratios between 4995 MHz and 1415 MHz. For the source 0331+39 the depolarization was computed using the 2700 MHz data by Parma and Weiler (1981), since no 1415 MHz data are available.

If we interpret the depolarization as being due to internal Faraday rotation and assume a slab model (Burn, 1966), we can derive the internal rotation measure and, therefore, the internal plasma density n_e . For double sources only a total value may be found in some cases, due to the lower resolution of the 1415 MHz maps.

Table 2 gives the physical parameters of the sources as follows:

Column 1: B2 name.

Column 2: radio component designation, as in Table 1.

Column 3: depolarization ratio.

Column 4: value of the quantity ($H_{||} n_e l$) in units of 10^{14} cgs units, where the parameters are the same as in columns 5, 6, and 7.

Column 5: depth of the source in kpc.

Column 6: magnetic field component along the line of sight in unit of 10^{-6} gauss. It has been taken equal to 0.4 of the equipartition magnetic field from geometrical considerations.

Column 7: internal plasma density in units of 10^{-3} cm^{-3} .

Column 8: mass of the thermal plasma in units of 10^7 solar masses.

Thermal electron densities are in the range $10^{-4} - 10^{-3} \text{ cm}^{-3}$. We do not find any systematic difference of the plasma density among small and large radiogalaxies, as might be expected if the stopping distance of the radio components would be determined by the ratio of internal to external plasma density (blob model). This could be due to the uncertainty associated with the computation of physical parameters as well as to the small number of radio galaxies used for the comparison.

Assuming that the thermal plasma is produced in the galaxy and is swept out by the explosive phenomena which produce the radio source and that the mass loss rates in elliptical galaxies is $0.1 - 1 M_{\odot}/\text{yr}$ we can deduce an accumulation time of the gas of $10^7 - 10^9 \text{ yr}$ between successive outbursts or for continuous activity.

The intrinsic degree of polarization P is related to the ratio between the ordered component (H_o) of the magnetic field and the random component (H_r) (Burn, 1966):

$$P = \frac{3\alpha + 3}{3\alpha + 5} \frac{H_o^2}{H_o^2 + H_r^2},$$

where α is the spectral index. Taking the fractional polarization at 4995 MHz as representative of the intrinsic degree of polarization we obtain: $H_o/H_r=0.2-0.5$. This is in agreement with values found in the literature.

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