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6 cm observations of LBDS radio sources. Radio properties of blue radio galaxies

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Summary. We present results of 6 cm observations of sources detected at 21 cm in the Leiden-Berkeley Deep Survey [LBDS] (Windhorst et al., 1984a). Most observations were made with the Westerbork 3 km Synthesis Radio Telescope (WSRT), but six sources were mapped at high (0$''$.4) resolution with the VLA in the *A*-configuration.

The main purpose of the project discussed in the current paper, is to study the radio spectra of blue radio galaxies. The radio galaxies selected have total flux densities measured at 21 cm, 50 cm, and in many cases also at 92 cm. In addition to the 22 blue radio galaxies, the sample presented contains 7 "red" elliptical radio galaxies and 10 unidentified, $m_F > 22^{\mathrm{m}}.5$, radio sources.

The median spectral index between 6 and 21 cm of the sources in our sample is steep, regardless of optical type which confirms the results found by Donelly et al. (1987) from a complete sample with a somewhat lower median flux density than the sources presented here.

The blue radio galaxies observed almost all fall in either of two classes: those with radio morphologies resembling that of the classical red radio galaxies, and those which are very compact (largest angular size $<1''$). The latter class frequently shows variability on timescales of a few years and/or exhibit a turnover in spectral index at a few hundred MHz. Both traits can be interpreted as being characteristics of small optically thick non-thermal cores, no more than a few parsec in size. This is not characteristic of radio galaxies undergoing active star formation, which show diffuse extended emission.

Throughout this paper $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0$ will be used.

Key words: radio galaxies – radio morphologies – radio spectral indices

1. Introduction

The radio sky below 50 mJy (at $\lambda = 21$ cm) is very different from that above this flux level. At high flux densities the main body of the identified radio sources consists of radio ellipticals with mostly extended radio emission, and quasars which show both very compact and extended radio morphologies.

Below 50 mJy, these classically known classes constribute less to the total radio source population. Between 1 and 50 mJy the majority of identified radio sources are the intrinsically less (radio) powerful radio ellipticals and the "blue" types of radio galaxies. The latter class consists locally ($z < 0.3$) mainly of radio spirals and to a lesser extent Seyfert galaxies. Above a redshift of ~ 0.3, a different type of blue radio galaxy is observed, which optically shows peculiar morphologies and might be the product of interaction or merging (Kron et al., 1985). The radio luminosities of these blue radio galaxies are, on average, 10 times higher than those of local spirals, and only a small percentage have Seyfert-like emission lines in their spectra (Windhorst et al., 1986). Not much is known about the nature of these blue radio galaxies.

Oort et al. (1987), have mapped many of these blue radio galaxies at high resolution (1$''$) with the VLA *A*-array. The galaxies have morphologies of two different kinds: Those resembling the morphology of the elliptical radio galaxies (classical doubles, or resolved one-component sources), and those that are unresolved with the VLA *A*-array beam. The latter morphology is very rare for radio ellipticals.

In this paper we study the blue radio galaxies, and in particular the unresolved ones, in more detail. Our 6 cm observations, when combined with fluxes at other radio frequencies provide a tool for determining whether the intrinsic size of the unresolved radio galaxies is on the kilo-parsec or on the parsec scale. In Sect. 4 we will discuss the evidence available for these radio galaxies that they are dominated by a very small non-thermal nucleus.

Because the sources observed do not form an unbiased subsample of the radio sources in the sky between 1 and 50 mJy, no firm statements on the spectral index distribution in general between 6 and 21 cm can be made. Our results, however, are in agreement with the findings of Donnelly et al. (1987): The spectral index distribution is narrow with a steep ($\langle\alpha\rangle = 0.8$) median spectral index, irrespective of optical type.

2. Observations and reduction

2.1. Observations

The 6 cm maps of LBDS radio sources were obtained in three observation periods. First of all, two 12 h full synthesis observations were made with the WSRT 3 km array in 1984, centered on two of the LBDS 21 cm fields.

The field Lynx. 3 – at $\alpha = 8^{\mathrm{h}}45^{\mathrm{m}}30^{\mathrm{s}}$, $\delta = 44°36'00''$ (1950) – was observed on April 23, 1984. The field SA 68.1 – at $\alpha = 0^{\mathrm{h}}14^{\mathrm{m}}53^{\mathrm{s}}$, $\delta = 15°36'48''$ – was observed on April 24. The shortest spacing of the WSRT was 72 m in both cases. The observations were made with the WSRT digital continuum backend, using 8 channels, each

10 MHz wide, centered on $(4839+10^*n)$ MHz ($n=0,\ldots,7$). One of the fixed telescopes was out of commission, and two channels (4839 and 4889 MHz) were not used because of excessive interference. The effective frequency is 4877 MHz. The observations were calibrated by observing 3C48, 3C147, and 3C286 (fluxes from Baars et al., 1977) before and after each 12 h period.

A second (short) set of observations was made with the VLA in the A-configuration (shortest spacing: 0.8 km, longest spacing: 36.6 km) on April 11, 1986. Seven 10-min snapshots were made of blue radio galaxies known to be smaller than 1″ from previous 21 cm A-array observations (Oort et al., 1987). The typical flux at 21 cm of these objects is 10–50 mJy. A total bandwidth of 100 MHz (two 50 MHz channels centered on 4835 and 4885 MHz) was used at an effective frequency of 4860 MHz. The source 3C286 was used as a primary flux calibrator, taking into account the fact that 2% of the flux is resolved out at this configuration. Nearby sources from the VLA calibrator list were also observed for 5 min every half hour.

Finally, selected blue radio galaxies and unresolved ($\psi < 1''$) red radio galaxies were mapped with short WSRT observations in September–November 1986. Each source was observed at five or six different hour angles for 20 min each time. As in the full synthesis WSRT observations, eight 10 MHz wide channels were observed using the digital continuum backend. Because all channels were interference-free, the effective frequency is slightly different: 4874 MHz. During the last 15% of the observation period, four fixed telescopes were out of commission. However, no serious interference was present. Again, 3C48, 3C147, and 3C286 were used as flux calibrators.

2.2. *Reduction*

Because the three sets of observations were made under different circumstances and with different instruments, the details of the reduction in each case are somewhat different.

Of the WSRT observations only the forty standard interferometers were used to produce the maps. No redundancy corrections were applied. The visibilities from each frequency channel were Fourier transformed with the line data transform routine LINEMAP (Harten, 1980). The full synthesis maps have a pixel size of two points per beamwidth, the short observations three points per beamwidth. The individual frequency channel maps were combined with weights proportional to the inverse square of the noise in each channel. Grating rings were removed via a cleaning algorithm (Högbom, 1974) on the Leiden IBM 3083. The restoring beam has a full width at half maximum of $3''.5 \times 3''.5/\sin\delta$. The noise in the full synthesis maps is 80 μJy, in the short observation maps somewhat higher, 0.1–0.15 MJy.

The VLA observations were reduced on the VLA site, using the AIPS reduction package on a VAX 11/780. The maps have a pixel separation of four points per beamwidth. The inner quarter of each map was cleaned (Clark, 1980), and components were restored with a Gaussian beam with a $0''.4$ half power beamwidth. The noise in each map is typically ~ 0.25 mJy. The cleaned maps were then exported to Leiden for further analysis.

A search for candidate sources was restricted to the positions where a source from the complete LBDS 21 cm radio sample (Windhorst et al., 1984a) is present. A minimum detection threshold of 3.5σ was applied. The fundamental parameters of the sources thus found, the peak flux, S_p, the total flux, $S_{\rm tot}$ and the largest angular size, ψ, were determined using a two-dimensional Gaussian fitting routine (Brinks, private communication). For sources with extended emission, the total flux was computed directly from the data by summing the pixel intensities inside the $^1/_2\,\sigma$-contour. If possible, the source is divided into components, for which the flux is calculated separately. The angular size of the entire source is determined from the distance between the outermost peaks.

In the full synthesis maps (and occasionally in one of the short WSRT observation maps) the peak-, and total-flux had to be corrected for attenuation of the beam, using the relation $\mathrm{ATT} = \cos^{-6}(301.323\varrho)$, where ϱ is the distance from the field center in degrees (Lugtenborg, 1981, private communication).

Because this correction becomes very large at large distances, only sources within a radius of $0^\circ.134$ (ATT = 5) in the WSRT observations were included in the final source list. Because bandwidth smearing is more severe in the VLA maps, only the central VLA source was included in the source list.

3. The source list

The source list, presented in Table 1, contains all LBDS sources within the field of view of the 6 cm maps. Sources not detected were assigned an upper limit to their peak flux of $3^1/_2\,\sigma$. Because in most cases a VLA 21 cm high resolution (1″) map is available, the extent of the source is known, making it possible to make a reliable estimate of the upper limit to the total flux. The total flux of each source is transformed to 4875 MHz for consistency, using the 6–21 cm spectral index found. Errors in position and flux were computed using the following realtions:

$$\sigma^2_{\alpha,\delta} = [C_{p\alpha,\delta}(RN/S_p)]^2 + C^2_{\alpha,\delta} \qquad \text{(arcsec)}$$

$$\sigma^2_S = S^2_{\rm tot}\,[(N/S_p)^2 + F_0^2 + (\Delta\varrho\,\Delta\tau)^2] \qquad \text{(mJy)},$$

where S_p/N is the signal-to-noise ratio, R is defined as the number of uncorrelated beam areas covered by the source, $\Delta\varrho$ is the average pointing error of the individual dishes, and $\Delta\tau = dAtt(r)/dr$. The value of the constants, $C_{p\alpha,\delta}$, $C_{\alpha,\delta}$, F_0, and $\Delta\varrho$ have been determined emprically by Oort and Windhorst (1985) for 21 cm WSRT observations and have been scaled to 6 cm: $C_{p\alpha} = {}^1/_2\,\mathrm{HPBW}_\alpha$, $C_{p,\delta} = {}^1/_2\,\mathrm{HPBW}_\delta$, $C_\alpha = 0.04\,\mathrm{HPBW}_\alpha$, $C_\delta = 0.03\,\mathrm{HPBW}_\alpha$, $F_0 = 0.03$, and $\Delta\varrho = 0^\circ.006$ (HPBW_α = Half Power Beam Width in the right ascension direction).

Table 1 is organized as follows:

Column 1: The source name in the LBDS (Windhorst et al., 1984a)

Columns 2 and 3: The right ascension and declination of the source at 6 cm for equinox 1950. Errors are given directly below.

Column 4: The total flux transformed to 4875 MHz, using the spectral index found in the current paper. For sources not detected, an upper limit to the total flux is given (see text). The uncertainty in the flux is given directly below.

Column 5: For resolved and extended sources, the largest angular size ψ (full width at half maximum) in arcseconds. For unresolved (<) sources, no upper limit is given. A general first order upper limit can be used, equal to $^3/_4$ HPBW for a 5σ source, $^1/_2$ HPBW for a 10σ source, and $^1/_4$ HPBW for a 25σ source.

Column 6: The peak flux-to-noise ratio.

Column 7: The attenuation factor at the position of the source.

Column 8: The 6–21 cm spectral index. The error is given below.

Table 1. The 6 cm source list

Name	RA (1950)	Decl. (1950)	S(4875 MHz)	ψ	Sp/N	Att.	α	Type	Notes
	h m s	° ′ ″	(mJy)	(″)					
54W051	–	–	< 0.53	–	< 3.5	2.01	> 1.532	U	wsrt
			0.18				.282		
54W053	–	–	< 0.82	–	< 3.5	3.08	> 0.991	U	* wsrt
			0.27				.294		
54W059	0 15 16.72	15 39 25.5	0.99	<	5.0	2.61	0.460	U	* wsrt
	.02	.8	0.39				.338		
55W010	8 32 49.46	45 07 47.5	23.18	4.0	92	1.00	0.280	BG	C scan
	.01	.1	0.74				.047		
55W034	–	–	< 0.49	–	< 3.5	1.00	> 1.766	BG	scan
			0.17				.325		
55W036	8 34 15.61	45 15 46.0	3.11	< 3.1	19	1.00	0.576	BG	scan
	.01	.2	0.19				.065		
55W046	8 35 24.06	45 32 07.1	4.36	4.9	19	1.00	0.663	?G	C scan
	.01	.2	0.27				.130		
55W049	8 35 35.85	44 50 52.1	3.43	<	33	1.00	0.275	BG	vla
	.01	.1	0.18				66 .059		
55W066	8 36 52.16	45 16 16.9	9.30	9.2	23	1.00	0.748	BG	C scan
	.02	.4	0.76				.077		
55W077	8 37 30.47	44 55 18.7	3.16	0.3	17	1.00	0.842	BG	vla
	.01	.1	0.23				.067		
55W102	8 38 46.89	45 04 53.0	2.12	3.1	15	1.00	1.224	BG?	scan
	.01	.2	0.07				.052		
55W103	8 38 47.65	45 23 15.0	40.5	12.2	134	1.09	0.972	U	C scan
	.01	.1	1.8				.071		
55W105	8 38 48.56	45 21 31.4	1.42	<	11	1.00	0.755	RG	scan
	.01	.1	0.13				.089		
55W144	–	–	< 0.55	–	< 3.5	1.00	> 1.325	BG	scan
			0.15				.234		
55W166	–	–	< 0.40	–	< 3.5	1.00	> 1.473	RG?	* V scan
			0.13				.204		
55W171	8 43 43.30	44 33 46.7	1.92	<	14	1.00	0.418	BG	V vla
	.01	.1	0.15				.071		
55W175	8 44 10.59	44 15 13.3	26.20	<	71	1.00	0.366	BG	V vla
	.01	.1	1.22				.047		
55W188	8 45 03.01	44 51 35.7	3.74	3.3	23	1.00	1.030	BG?	scan
	.01	.2	0.20				.049		
55W190	8 45 14.10	44 40 47.6	3.75	2.4	21	2.11	0.816	RG	wsrt
	.01	.1	0.19				.097		
55W191	8 45 16.56	44 13 03.6	4.27	<	32	1.00	0.961	BG	scan
	.01	.1	0.18				.045		
55W199	8 45 42.86	44 32 30.6	0.84	7.6	4.5	1.51	1.119	BG	wsrt
	.02	.5	0.19				.191		
55W226	8 47 35.73	44 34 39.6	2.83	<	19	1.00	0.459	BG	V vla
	.01	.1	0.18				.170		
52W005	13 04 27.47	29 31 18.6	3.61	9.6	5.7	1.00	1.061	BG	C scan
	.10	.3	0.64				.176		
52W007	13 04 59.52	29 17 16.1	11.58	8.4	27	1.04	1.124	U	C scan
	.02	.4	0.56				.086		
52W008	13 05 02.21	29 18 27.1	13.97	<	99	1.00	0.196	U	* scan
	.01	.1	0.44				.043		
52W012	13 05 23.82	29 19 03.1	3.35	4.2	20	1.00	0.884	BG	scan
	.01	.2	0.20				.096		
52W013	13 05 26.36	29 41 48.2	1.05	<	7.3	1.00	0.809	BG	scan
	.02	.5	0.15				.121		

Table 1 (continued)

Name	RA (1950)	Decl. (1950)	S(4875 MHz)	ψ	Sp/N	Att.	α	Type	Notes
	h m s	° ′ ″	(mJy)	(″)					
52W014	13 05 27.19	29 18 42.0	2.96	4.5	18	1.02	0.707	U	scan
	.01	.3	0.19				.121		
53W027	17 15 11.79	50 27 03.6	2.35	23.8	5.8	1.00	0.942	BG	CH scan
	.06	1.2	0.60				.211		
53W026	17 15 12.25	49 50 24.4	5.27	3.1	13	1.00	1.052	BG	C scan
	.03	.5	0.62				.102		
53W031	17 15 30.60	49 59 54.8	40.3	2.7	169	1.49	0.803	RG	scan
	.01	.1	1.2				.036		
53W065	17 18 24.66	50 00 36.1	1.31	3.5	9.5	1.00	1.131	BG	scan
	.02	.3	0.14				.089		
53W071	17 18 56.82	50 20 13.0	0.91	<	11	1.00	1.163	BG	V vla
	.01	.1	0.11				.107		
53W072	17 19 15.31	50 25 32.0	2.28	<	18	1.00	0.758	BSp	scan
	.09	.2	0.14				.059		
53W079	17 20 08.03	50 13 21.9	14.31	<	106	1.00	−0.119	RG	* scan
	.01	.1	0.45				.034		
53W083	17 20 33.89	50 05 29.0	1.75	<	15	1.00	0.883	BG	vla
	.01	.1	0.12				.067		

Column 9. The optical identification (Windhorst et al., 1984b), preceded – in the case of galaxies – by its color-type (Kron et al., 1985). If an identification was deemed unreliable on the basis of a high resolution map (Oort et al., 1987), the source is classified as unidentified.
N.B.: BG = blue galaxy, RG = red galaxy, BSp = spiral galaxy, U = unidentified, ? = classification uncertain.

Column 10: Notes: *: A separate note is given in the text. V: The source is known to be variable on the basis of previous observations. H: Low surface brightness emission may be present, which is resolved out at 6 cm. C: A contour plot is given in Fig. 4. vla: Source is observed with the VLA at 0.″4 resolution. wsrt: Source found in WSRT full synthesis. scan: Source observed with WSRT short scans.

Notes to individual sources:

52W008: Small angular size found by Oort et al. (1987) is confirmed. The identification is probably incorrect.

54W053: The LBDS identification is not correct (Oort et al., 1987).

54W059: The source is not in the complete optical sample, i.e. it is fainter than 22.^{m}5.

55 W 034: The source is not detected at 6, 50, and 92 cm. It is only 5.04σ in the 21 cm map. It is probably a spurious source.

55W166: Not detected in our map, but detected by Donnelly et al. (1987) at a level which should have made it show up in our map. There are no indications from WSRT surveys that the source is variable.

53W079: WSRT observations at 21 cm list this source as being resolved ($\psi \approx 6''$), but VLA high resolution observations (Oort et al., 1987) and the current 6 cm observations show only an unresolved component. If diffuse flux is present, it contains less than 5% of the total flux of the source at 21 cm.

4. The spectral index distribution

We can now use the data from the current sample to study the spectral index distribution between 6- and 21 cm, and compare it to the distribution seen at lower frequencies. Because our observations were carried out primarily to map blue radio galaxies, the current sample is not a representative subset of the different radio source populations at low flux densities. One is referred to Donnelly et al. (1987) for a discussion of the median high frequency spectral index for the general source population at flux densities below 10 mJy. It suffices to say that the distribution of 6–21 cm spectral index in our sample – shown in Fig. 1 – confirms their finding: the median spectral index is steep, irrespective of optical type.

The blue galaxy spectral index distribution is a bit broader than that of the other radio sources. The median spectral index lies at $\alpha = 0.83 \pm 0.19$. For the red radio galaxies and the unidentified radio sources, the median lies at 0.87 ± 0.07 for both types. Note that this distribution is composed of spectral indices of randomly detected sources with a large spread in flux.

We will primarily use the data from the current sample to study the radio spectra of individual objects. In particular, a levelling off, or even an inversion of the spectral index can give information about the extent of the region from which the radio emission is originating. To this end, we will in this section combine all the radio and optical information available on the radio galaxies in the LBDS.

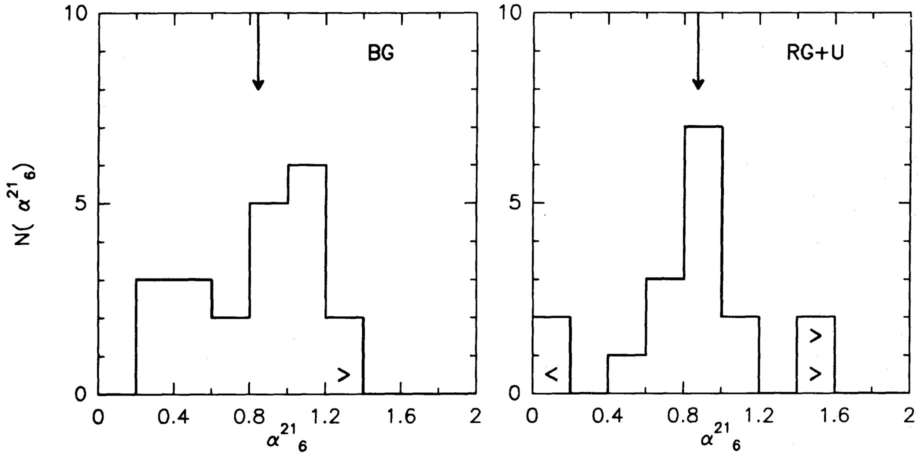

Fig. 1. The 6–21 cm spectral index distribution of blue radio galaxies (left), and red radio galaxies and unidentified sources (right). The arrow denotes the median on the distribution

Our sample contains 22 blue radio galaxies (one of which is a spiral galaxy), 7 red (elliptical) radio galaxies, and 10 unidentified (presumably $F \geqq 22^{\mathrm{m}}5$) radio sources. The optically identified sources have accurate magnitude estimates in at least two colors, and in some cases a measured spectroscopic redshift (Kron et al., 1985). A large amount of radio information is available as well. All sources have a 21 cm flux from the LBDS (Windhorst et al., 1984a). In addition, a number of sources have a second 21 cm WSRT flux from either Oort and Windhorst (1985), Oort (1987a) or Oort and van Langevelde (1987). A third 21 cm flux – as well as high resolution morphological information – is available from 1″ resolution VLA *A*-array maps (Oort et al., 1987). These flux determinations are averaged to arrive at a weighted mean 21 cm total flux density. Variable sources are assigned a rough mean flux by averaging fluxes from observations separated in time by more than a few months.

Low frequency total flux densities are available as well. Fluxes at 608.5 MHz have been determined from a 50 cm deep survey by Windhorst and Oppe (1987, in preparation). Sources from the 55 W-survey in Lynx have a flux measured at 327 MHz as well, from a deep WSRT 92 cm survey by Oort et al. (1987b).

We will now proceed to discuss the radio properties of two major populations of radio sources at flux densities below 50 mJy (at 1412 MHz): the red and blue radio galaxies. The former class consists of the classical population of elliptical radio galaxies. The latter class appears primarily at lower flux densities, and becomes increasingly more numerous as the relative contribution of the red galaxies to the radio source counts decreases. They are distinguished from the red radio galaxies by their optical morphology, specifically their bulge-to-disk ratio (Kron et al., 1985). An empirical distinction can be made between the two classes of radio galaxy via a separation in the color-magnitude ([$J-F$] vs. F) diagram, hence the terms "red" and "blue". It turns out that this empirical separation of optical morphology is accompanied by a difference in radio properties as well.

4.1. *Red radio galaxies*

The population of elliptical radio galaxies is very homogeneous. They have a small spread in absolute magnitude at all flux densities ($\Delta M \approx 0^{\mathrm{m}}4$), which makes it possible to estimate photometric redshifts quite accurately. The radio sources associated with these ellipticals, are almost without exception resolved or extended doubles. They show a nearly unchanging distribution of spectral index over a large range in frequency (Oort et al., 1987b).

There are some notable exceptions to these rules. Six red radio galaxies out of 37 are unresolved at 1″ resolution (Oort et al., 1987; Oort, 1987b). From photometric redshift estimates of these sources one can show that their size does not exceed 10 kpc. The question arises whether these sources are intrinsically small or are just unresolved because they are at too large a distance to see the source as an extended double.

We have sufficient information on all of these radio galaxies to attempt to answer this question. We will discuss these six "elliptical" galaxies individually:

53 W045: This source has been observed only at 21 cm, but at three different epochs. The total flux has decreased by a factor of four between the first two observations, separated by 1650 days. Between the second and the third observation, seperated by 450 days, the total flux has risen again by a factor of two. The source seems to be variable on a scale of a few years. This implies that the emission emanates from a small region of a few parsecs.

55 W105: This source has a normal steep spectrum between 6 and 50 cm, but is not detected in the 92 cm map (see Fig. 2). This indicates a steep inverted spectrum with $\alpha \leqq -0.7$ ($S \propto \nu^{-\alpha}$). If this cutoff at low frequencies is due to synchrotron self absorption, this indicates that the source is no larger than 10 pc (see next section).

55 W166: This source shows a beginning of convexity at 92 cm (Fig. 2). It resembles the spectrum of many unresolved blue radio galaxies (see next section). It is very faint optically, and its colors suggest that it might be a blue galaxy after all.

53 W079: This source has a concave spectrum, with a minimum at 21 cm (Fig. 2). The upper limit in angular size gives an upper limit of the linear diameter of the source of 8.5 kpc ($H_0 = 50\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0$). It may consist of a strong, small non thermal core and a more extended diffuse, optically thin region. No high resolution evidence for this is available, however.

52 W013: This source lacks a 92 cm flux, which makes it impossible to distinguish whether this source is similar to 55W105, and therefore very small, or just a distant extended source. Its spectrum is straight over the frequency range observed (Fig. 2). If the source has extended emission, its linear size must be less than 5 kpc, as estimated from the 1″ size upper limit.

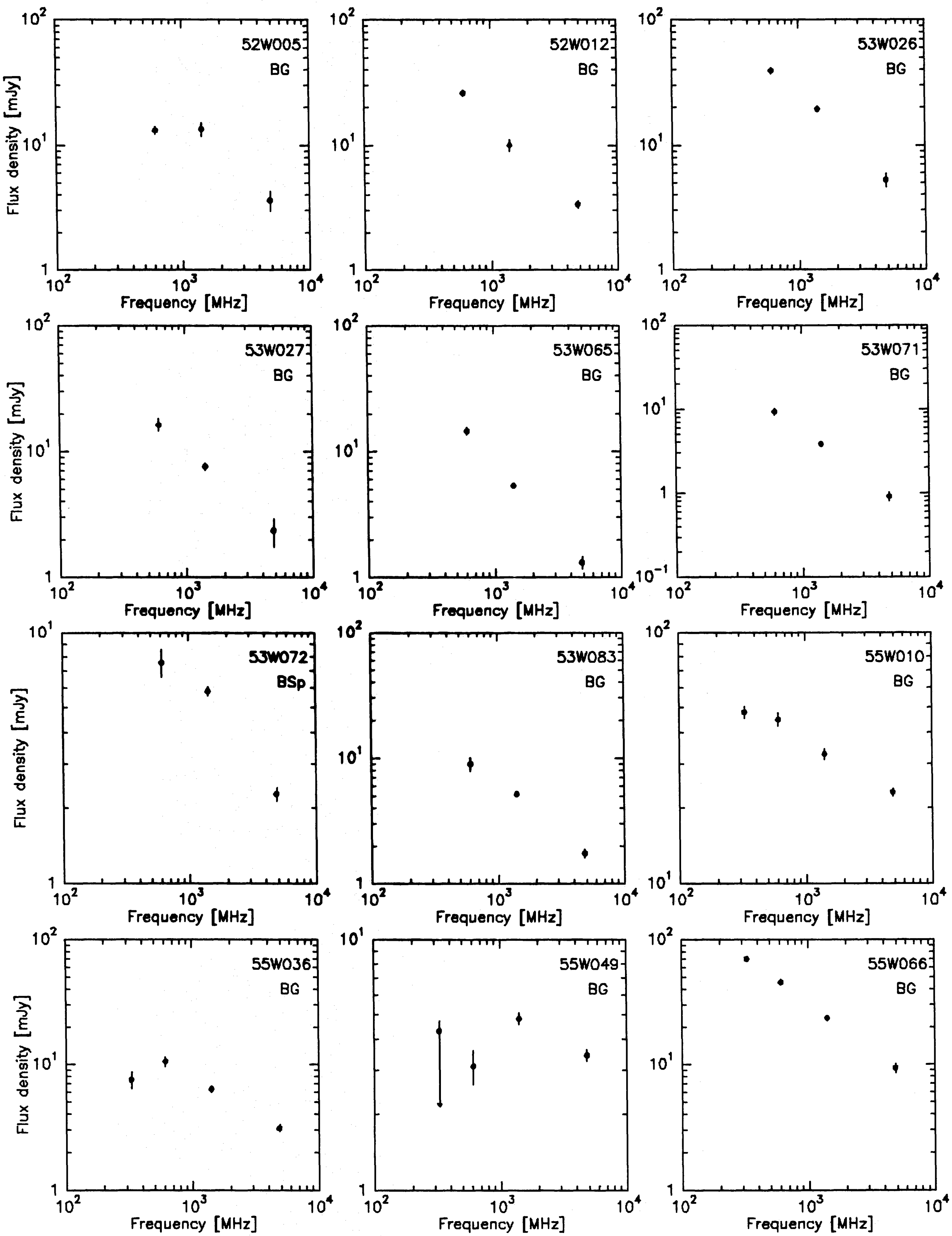

Fig. 2. The radio spectra of the sources in the current sample. For references to the flux densities at 21, 50, and 92 cm, see the text

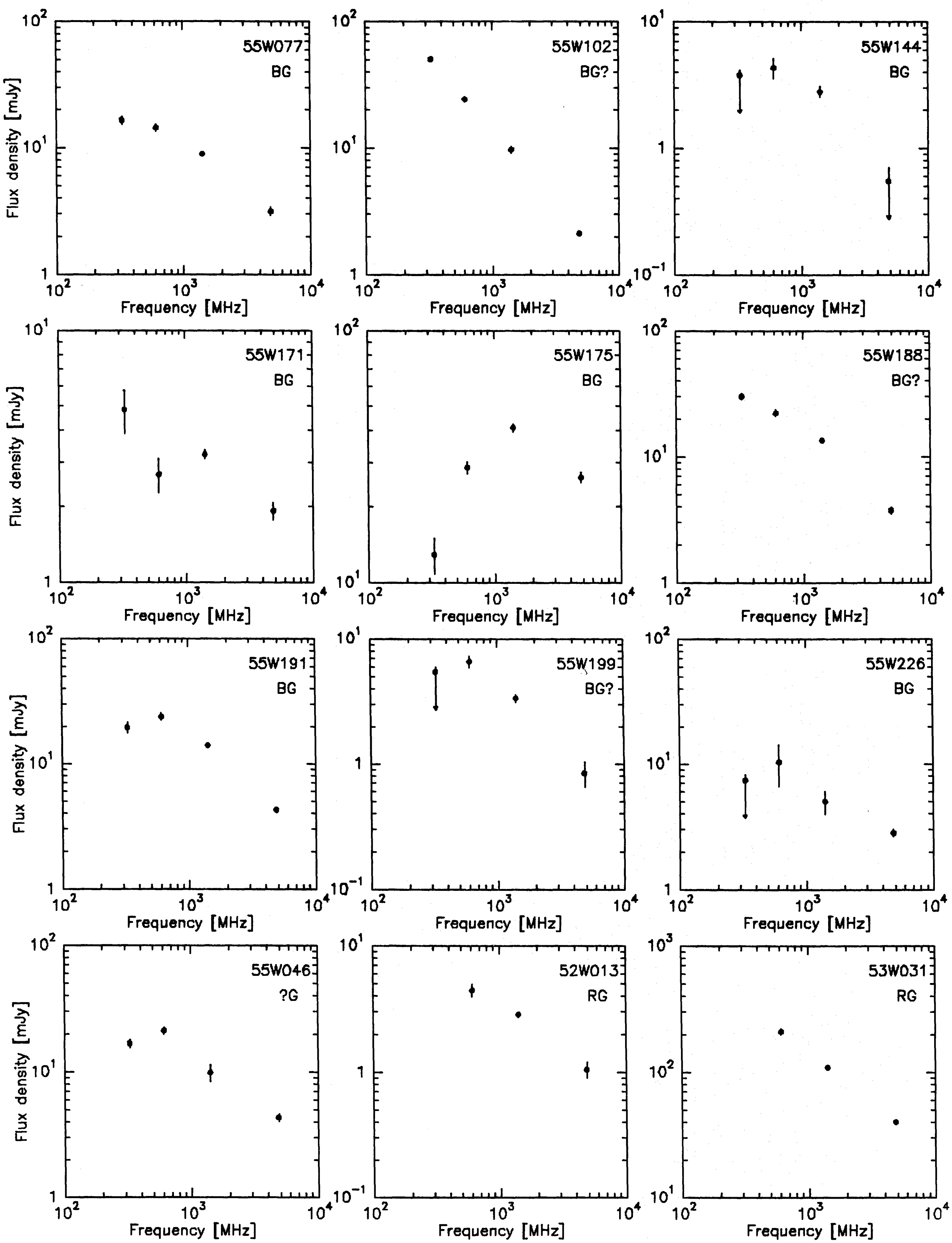

Fig. 2. (continued)

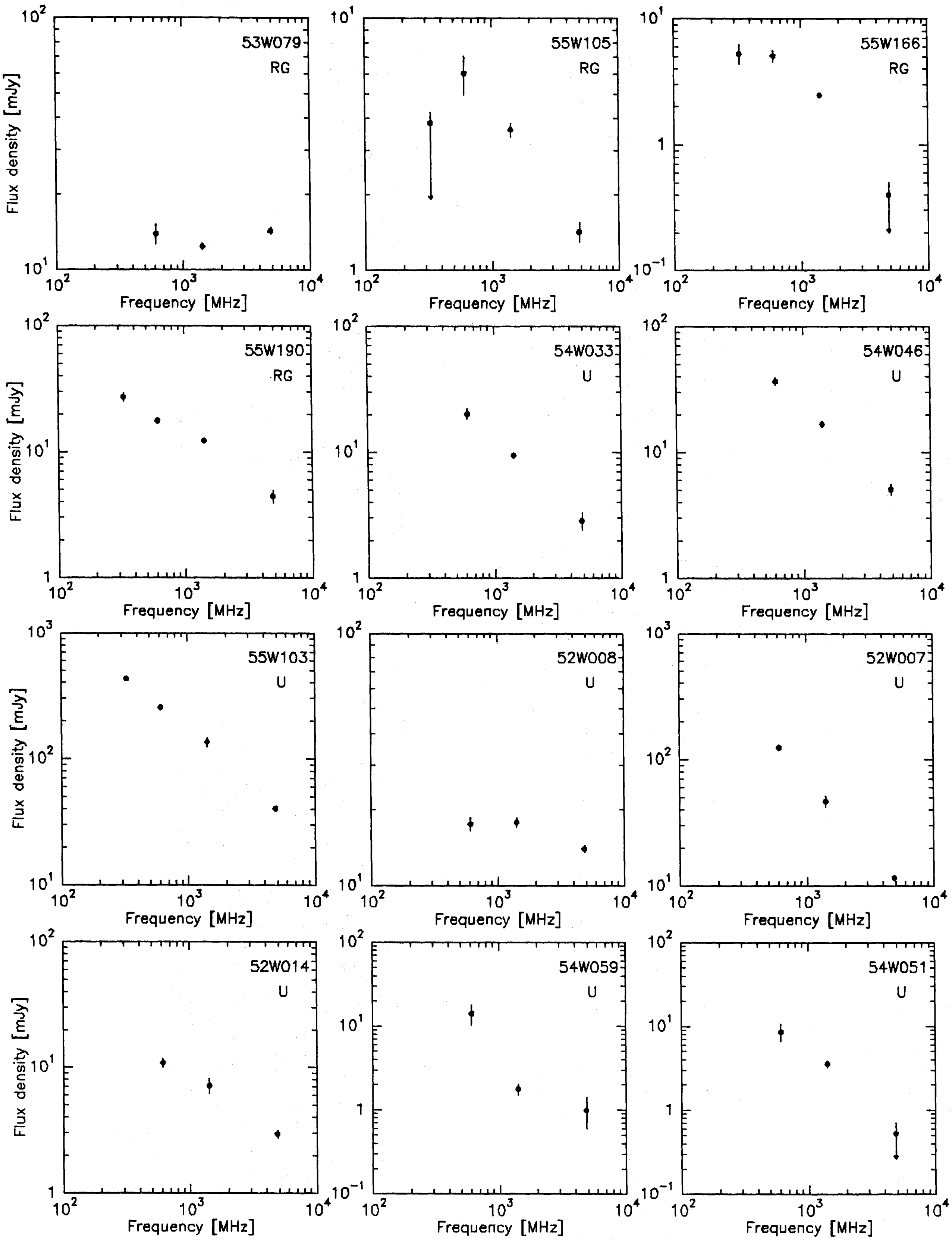

Fig. 2 (continued)

53 W030: This source has been observed only at 21 cm (there is an upper limit at 50 cm, suggesting that $\alpha \leqq 0.6$), but at three different epochs. No variability has been detected. It is a very distant radio galaxy ($z=0.628$, Kron et al., 1985) and may well be only unresolved due to its large distance. The upper limit in angular size suggests that $D < 10$ kpc.

The discussion above shows that not all unresolved red radio galaxies are merely distant sources with extended emission, too small to be resolved at 1″ resolution. Truly compact radio sources in elliptical radio galaxies are fairly rare (2 out of 37). The next section will show that this is not the case with blue galaxies.

4.2. *Blue radio galaxies*

In contrast to the red radio galaxy population, the blue radio galaxies are a very heterogeneous class of objects. There is still little known about their nature, because they are very rare locally (there are only two known with $z < 0.3$). Optically, blue radio galaxies have peculiar morphologies, and might be in the process of interaction or merging. They are unlikely to be associated with blue populations of galaxies known locally, spirals and Seyferts. Their radio luminosity is a factor of 10–100 higher than local spirals, and their space density is such that it would require enormous density evolution for them to be Seyferts. Moreover, only one in thirty blue radio galaxies have Seyfert-like spectra.

The optical morphology and colors of the blue radio galaxies suggest active star formation. There could be a number of possible origins for the radio emission: Thermal emission, non-thermal emission from a small steep spectrum core, or non-thermal emission from a large number of super novae. The high resolution morphology and radio spectra of the blue radio galaxies can give indications as to which process is dominant.

The angular size distribution at 21 cm of the blue radio galaxies is very different from that of the red radio galaxies (Oort et al., 1987). Of the 22 blue radio galaxies in the LBDS complete sample observed at high resolution, about half (10) are smaller than 1″. The other half (10) resembles the radio morphology of the radio ellipticals. The rest shows only irregular low surface-brightness emission.

As already remarked by Oort et al. (1987), the extended blue radio galaxies occur mainly at higher flux densities, with the blue galaxies which resemble the classical double most occuring at the highest fluxes. These are probably intrinsically the most powerful blue radio galaxies as well.

The unresolved blue galaxies occur mainly at low flux densities, there are none brighter than 50 mJy. Of the blue galaxies between 20 and 50 mJy about 35% (4 out of 11) is unresolved. The fraction rises steadily to ~60% at a median flux of 2.5 mJy. There are clear indications that these unresolved blue radio galaxies contain a very small non-thermal cores. First of all, of the six blue galaxies observed at 6 cm with the VLA, five are smaller than 0″.2. This gives an upper limit of 1–2 kpc to the size of the source for the redshift range where the blue galaxies are mainly found (0.3–0.7).

Secondly, most of the *unresolved* blue radio galaxies show variability on a time scale of a few years. We have flux densities at 21 cm at three different epochs of six blue radio galaxies. Four of these show definite variability under the strict criterium that the flux difference at two epochs is more than $2^1/_2$ times the combined flux error σ_S. Another has a flux difference of $1^1/_2\,\sigma_S$, and may be variable as well. Only one source is definitely not seen to be variable. The variability occurs on a time scale of years, rather than months or shorter, because flux measurements made with a time difference of two months for three of the variable sources, agree to well within $1\,\sigma_S$.

The variability found for the *unresolved* blue radio galaxies suggests that the radio emission originates from a small region, no more than a few parsec in diameter. Radio emission from multiple supernova bursts be expected to show variability on time scales of a few days, indicative of random large-event processes, if at all.

A third factor in favour of the emission coming from a small active nucleus is the fact that many *unresolved* blue galaxies show a turnover in their spectral index at a few hundred MHz (Oort et al., 1987b). If the source of radio emission is by synchrotron radiation of relativistic electrons, the electrons become optically thick to their own emission at some frequency. If the turnover is due to synchrotron self absorption, the turnover frequency and the flux at this position determine an angular size of the source (Moffet, 1975):

$$\theta \approx 5.2\,(S_*)^{1/2}\,(\nu_*/\text{MHz})^{-1.25}\,(B/10^{-4})^{0.25}\ \text{(arcsec)}$$

or, assuming $H_0 = 50\,\text{km s}^{-1}\,\text{Mpc}^{-1}$, $q_0 = 0$, $B = 10^{-4}$ G,

$$D = \frac{0.85\,z\,(1+\frac{1}{2}z)}{(1+z)^2}\,(S_*/\text{mJy})^{1/2}(\nu_*/\text{GHz})^{-1.25}\,[\text{pc}],$$

where S_* and ν_* are defined in the following manner: Let us assume that the flux density of a source varies with frequency as $S_> \propto \nu^{-\alpha}$ far above the turnover frequency, where the source is still optically thin. Below the turnover frequency the synchrotron self-absorption causes the spectrum to have the following shape: $S_< \propto \nu^{+2.5}$. The turnover frequency ν_* is then defined as the frequency where $S_<$ is equal to $S_>$. The turnover flux is defined as $S_* = S_>(\nu_*)$. Figure 3 shows the theoretical linear size for $S_* = 10$ mJy with respect to cutoff frequency and redshift. A cutoff at a frequency of a few hundred MHz for total fluxes and redshifts in the general range of the blue radio galaxies in the current sample corresponds to a linear size of 0.5–5 pc.

Of the ten *unresolved* blue radio galaxies, all of the ones with four-point spectra show a turnover (Fig. 2). One of these, the

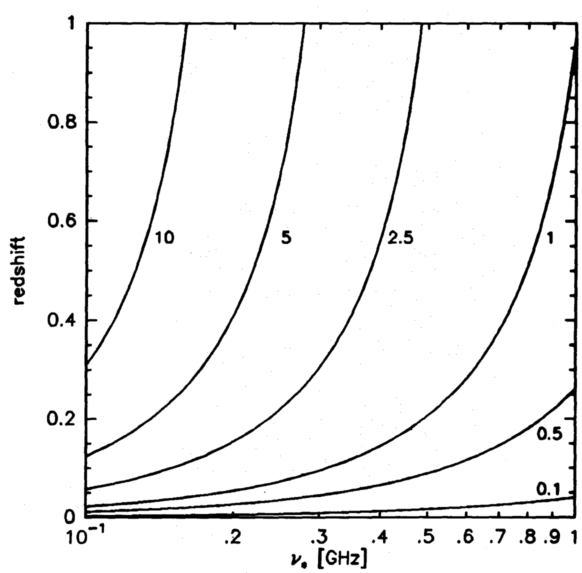

Fig. 3. The linear size in parsec of a source with a turnover in its spectrum due to synchrotron self-absorption as a function of turnover frequency and redshift. The flux density at the turnover frequency is assumed to be 10 mJy. ($H_0 = 50\,\text{km s}^{-1}\,\text{Mpc}^{-1}$, $q_0 = 0$)

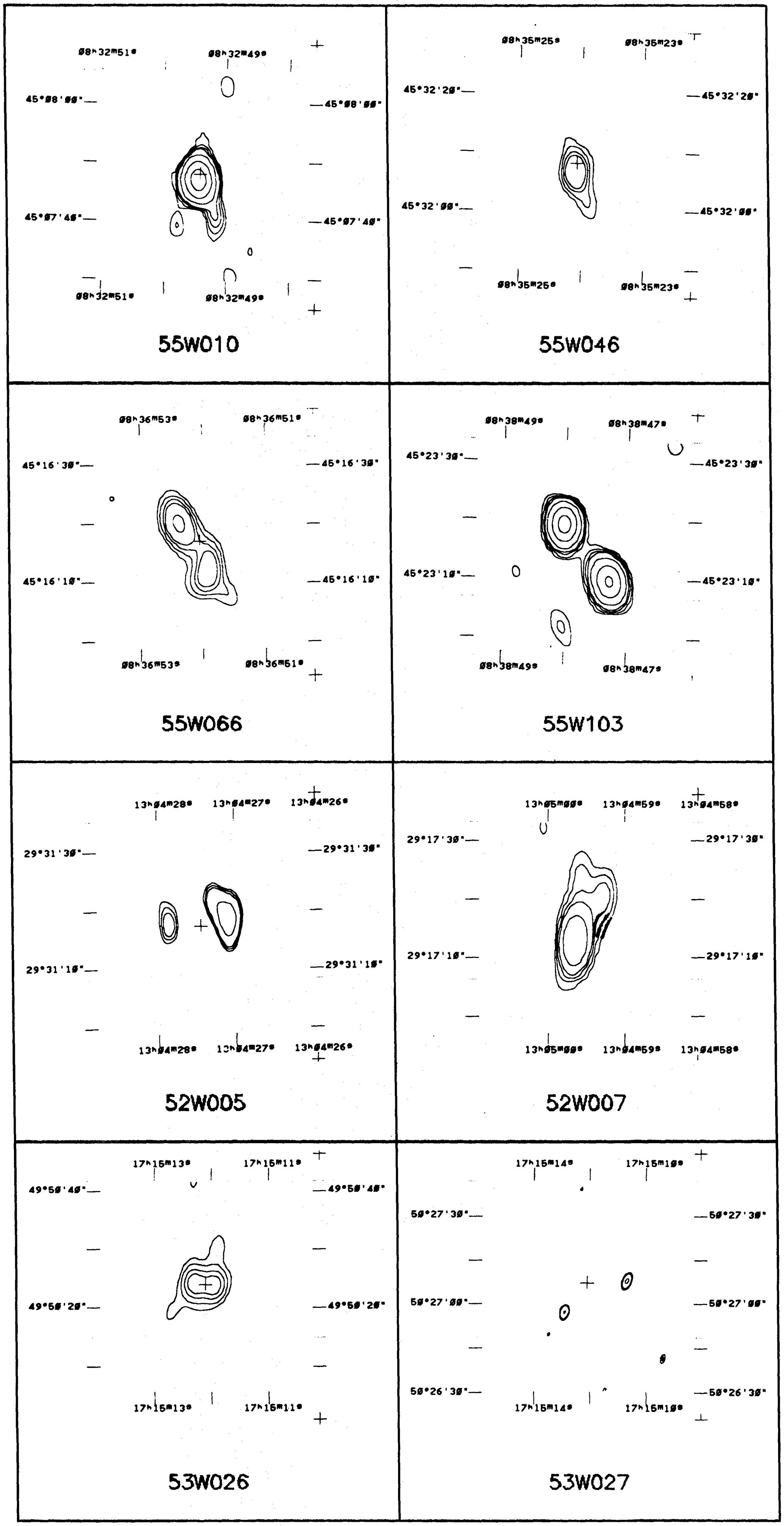

Fig. 4. Contour plots of selected sources in the sample. The lowest contour lies at 3σ. A cross denotes the position of the optical identification

variable source 55W171, turns over twice. It may have a very low surface brightness halo, which is visible only at 92 cm. The three unresolved blue radio galaxies which show no turnover have no 92 cm flux available, so they may have a turnover as well, at frequencies lower than 600 MHz.

The conclusion is therefore that at least a large fraction of the flux of an unresolved ($\psi < 1''$) blue radio galaxy originates from a compact core, no more than a few parsec in size.

Three (out of 10) *resolved* blue radio galaxies show a turnover as well. One has a component which may be compact which would account for the turnover. Two of these are the only blue radio galaxies with very irregular, low surface brightness radio structure, for which fluxes are less well determined.

The presence of a dominant small non-thermal core in many blue radio galaxies makes them different from most radio galaxies with active star formation, which exhibit disk emission associated with super nova bursts. A small fraction of startburst galaxies do show only a core in the radio, such as IC 4553, but in this case the core is resolved, corresponding to a spatial size of a few hundred parsec. The *unresolved* blue galaxies may be the bright distant counterparts of IC 4553, if the variability and the turnover in the spectrum of the *unresolved* blue radio galaxies is caused by a compact nucleus embedded in a more diffuse region of a few hundred parsec in size.

The wide range in radio morphologies, from radio elliptical type morphologies to compact radio cores, show that the blue galaxies form a very heterogeneous population. It may not be possible to tie the blue radio galaxies to any one locally known population.

5. Conclusions

1. The 6–21 cm median spectral index of radio sources at flux densities above 1 mJy is steep ($\alpha_{\rm med} = 0.85$) regardless of optical type. The distribution of α is somewhat broader for blue radio galaxies ($\sigma_\alpha \approx 0.2$) than for red radio galaxies and unidentified ($F > 22\overset{\rm m}{.}5$) sources ($\sigma_\alpha \approx 0.1$).

2. The radio emission of blue radio galaxies fall into two categories. Half exhibit morphologies which resemble those of the radio ellipticals. The other half is unresolved at 1″ resolution. We have presented three pieces of evidence that these unresolved radio galaxies consist of a compact (a few parsec in size) non-thermal nucleus:

A: Of the six blue radio galaxies observed at 0″.4 resolution, five are unresolved. This puts an upper limit of ~1.5 kpc to their size.

B: Many blue radio galaxies exhibit variability on timescales of a few years.

C: Many blue radio galaxies show a turnover in radio spectral index at a few hundred MHz. If this turnover is caused by synchrotron self-absorption, the size of the radio core is only a few parsec.

The presence of a small non-thermal core would seem to be at odds with a simple picture for galaxies with active star formation.

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