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VLBI study of 57 flat spectrum radio sources at 5 GHz

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Summary. A sample of 57 flat spectrum radio sources has been observed with a VLBI array at 5 GHz. Compact structure on the milliarcsecond scale was detected in 56 of them. The data for most of the sources can be described by simple models for the brightness distribution. The fraction of the total flux density contained in compact components is correlated with the type of optical identification and is higher for quasars and BL Lac objects than for galaxies.

Key words: radio sources – VLBI

1. Introduction

Compact radio structure on the milliarcsecond scale has been found in many sources showing flat or inverted radio spectra (i.e. $\alpha \gtrsim 0$, flux density $S_\nu \propto \nu^\alpha$) (Kellermann and Pauliny-Toth, 1981). These sources are usually identified with quasars, BL Lac-objects and active galaxies. Very long baseline interferometry (VLBI) is the only direct method of obtaining information about their milliarcsecond structure. In order to obtain statistical results on the structural properties of such flat spectrum sources we have defined a homogeneous sub-sample of the sources found in the MPIfR-NRAO 5 GHz-surveys. We observed this sample with a 3-station VLBI network including transatlantic baselines at 5 GHz and interpreted the visibility data in terms of simple gaussian-component models for the source brightness distributions. On the basis of these models it is possible to give a measure of the "compactness" of each source and to use this as a statistical parameter to study possible correlations between the source structure and other properties.

In this paper we describe the sample and the observations, present the results, and give a brief discussion, with emphasis on statistical implications.

2. The sample

The sources were chosen from the MPIfR-NRAO 5 GHz surveys (Kühr et al., 1981; references therein) using the following selection criteria:

1) $S_{5\,\mathrm{GHz}} > 1$ Jy,
2) spectral index $\alpha > -0.5$ (measured between 2.7 GHz and 5 GHz or between 5 GHz and 10.7 GHz),
3) declination $10° < \delta < 70°$ and galactic latitude $|b^{\mathrm{II}}| > 10°$.

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These criteria were fulfilled by 108 sources. Out of these we chose 58 which could most easily be scheduled for a VLBI experiment of 60 h observing time. From these we excluded 3C84 because it has been observed extensively in other experiments (e.g. Romney et al., 1982) and its structure is too complex for meaningful observation by our technique.

3. The observations

For the VLBI observations we used the 100 m telescope of the Max-Planck-Institut für Radioastronomie (MPIfR) at Effelsberg near Bonn, Federal Republic of Germany and two instruments in USA: the 43 m dish of the National Radio Astronomy Observatory[1] (NRAO) in Green Bank, West Virginia and the 40 m dish of the Owens Valley Radio Observatory (OVRO) at Big Pine, California. The date of the experiment was July 8–11, 1978, and part of it was repeated April 2–4, 1979. The observing frequency for the first epoch was 4850 MHz with linear polarization (North-South) and for the second epoch 5010 MHz with linear polarization (East-West), all sites being equipped with hydrogen-maser frequency standards. For both sessions we used the Mark II VLBI recording system with 2 MHz bandwidth (Clark, 1973). The cross-correlation of the data to derive the amplitude of the visibility functions was done with the Mark II processor of the MPIfR at Bonn.

The individual sources were observed in several scans of approximately 6 min duration, these cuts being spread over a range of hour angle, resulting in 15–20 points in the UV-plane for which we obtained visibility amplitudes. The data were calibrated following Cohen et al. (1974) using the measured gains and system temperatures of the telescopes as functions of elevation, together with flux densities for all sources measured in both sessions at Effelsberg simultaneously with the VLBI observations. Typical values for the rms-noise in a 1 min-integration were 15–30 mJy on the baselines MPI-NRAO, MPI-OVRO and 60–70 mJy on the baseline NRAO-OVRO. The fringe spacings of the baselines range from 1.5 to 3.5 milliarcsec.

4. Results

With one exception (0945 + 66) all sources were detected in our VLBI measurements, indicating that a significant part of the emission originates in regions milliarcseconds in extent.

1 The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation

Table 1

(1) SOURCE	(2) NAMES	(3) opt. ident.	(4) $\alpha^{5}_{2.7}$	(5) $S^{5\,GHz}_{Total}$ (Jy) I	(6) II	(7) epoch	(8) $S^{5\,GHz}_{VLBI}$ (Jy) N-O	(9) M-N	(10) M-O	(11) type	(12) C(%)	(13) VLBI-model a x b(mas)	(14) p.a.(°)	(15) Comments
0010+40	4C40.01	G	-0.19	1.07	1.10	I	0.50	0.39	0.34	E	55	1.5 x 0.5	-8	
0026+34		G	-0.28	1.28	1.22	II	0.37	0.11	0.13	CH	100	3.5 x 2.4	50	
0108+38		E	0.49	1.27	1.28	I	0.78	0.17	0.19	D	78	1.0 x 0.5	66	unres. comp. sep. 1 mas, p.a. 59°
0133+47		B	0.65	2.00	2.06	I	1.39	0.87	0.55	E	85	1.3 x 0.9	165	
0248+43		Q	0.38	1.25	1.38	I	0.86	0.66	0.57	E	74	1.0 x 0.6	-4	
0602+67		E	0.41	0.70	0.69	I	0.55	0.31	0.24	E	84	0.9 x 0.6	34	
0710+43		G	-0.22	1.62	1.59	II	0.63	0.37	0.25	D	99	3.8 x 1.3	-4	unres. comp. sep. 2.9 mas, p.a. 39°
0723+67	3C179	Q	-0.30	1.05	0.94	I	0.23	0.13	0.10	D	38	1.6 x 0.5	57	unres. comp. sep. 1.2 mas, p.a. 99°
0755+37	3C189	G	-0.58	1.04	1.06	II	0.26	0.12	0.12	E	26	1.0 x 0.5	71	
0804+49		Q	0.49	0.53	0.79	II	0.69	0.57	0.57	C	87	<0.5		
0814+42		Q	-0.45	1.76	1.54	II	1.18	1.14	0.98	CH	89	1.7 x 0.5	-48	
0828+49		Q	-0.20	1.35	1.57	II	1.30	0.57	0.35	E	100	1.3 x 0.6	62	
0831+55	4C55.16	G	-0.46	5.61	5.56	I	0.40	0.09	0.12	CH	17	3.1 x 2.2	43	
0833+58		Q	1.30	1.23	1.23	I	1.00	0.78	0.68	C	86	0.6		
0850+58	4C58.17	Q	0.78	1.18	1.18	I	0.84	0.81	0.50	E	80	1.0 x 0.5	-23	
0859+47	4C47.29	Q	-0.09	1.55	1.64	II	0.89	0.55	0.48	E	71	2.0 x 0.6	-2	
0906+43	3C216	Q	-0.46	1.77	1.90	II	0.76	0.76	0.76	CH	37	3.7 x 1.1	-27	
0923+39	4C39.25	Q	1.0	7.55	7.54	II	2.46	4.91	3.35	D	100	1.1x(<0.5)	102	unres. comp. sep. 1.8 mas, p.a. 98°
0945+40	4C40.24	Q	0.08	1.56	1.15	II	0.60	0.54	0.50	C	52	<0.5		
0945+66	4C66.09	E	-0.46	1.18	1.15	I	not detected							
0954+65		B	0.30	0.59	0.70	I	0.39	0.29	0.25	E	73	0.8x(<0.5)	-54	
1030+41		Q	0.19	0.72	0.66	II	0.48	0.44	0.46	C	68	<0.5		
1031+56		G	-0.30	1.31	1.24	I	0.36	0.20	0.18	CH	48	2.6 x 2.6		
1252+11		Q	-0.08	0.99	1.06	I	0.56	0.23	0.13	C	57	1.1		
1308+32		B	-0.05	2.54	2.48	I	1.98	1.81	1.54	E	100	1.3 x 0.6	-30	
1345+12	4C12.50	G	-0.41	2.89	2.81	I	0.38	0.12	0.11	CH	27	6.7 x 2.9	162	
1354+19	4C19.44	Q	-0.15	2.13	2.07	I	1.17	0.98	0.81	C	53	0.5		
1404+28	OQ208	G	0.75	2.98	2.94	I	2.20	1.20	0.95	E	85	1.8 x 0.8	-8	
1502+10	4C10.39	Q	0.48	1.99	1.84	I	1.50	0.96	0.76	C	78	0.8		
1504+37		E	0.19	1.06	0.95	II	0.57	0.21	0.22	E	53	1.4 x 0.7	13	
1538+14	4C14.60	B	0.61	1.28	1.27	I	0.71	0.53	0.45	C	56	0.6		
1606+10	4C10.45	Q	-1.03	1.14	1.67	I	0.83	0.56	0.51	C	75	0.6		
1611+34		Q	0.10	2.25	2.20	I	1.39	1.03	0.83	C	64	0.6		
1624+41	4C41.32	E	-0.29	1.16	1.14	II	0.45	0.28	0.21	CH	96	4.0 x 1.3	69	core size 0.6 mas
1633+38	4C38.41	Q	0.77	1.72	1.86	II	1.03	0.99	0.85	E	58	0.5x(<0.5)	-63	
1638+12	4C12.60	E	-1.03	1.10	1.04	I	0.28	0.14	0.16	CH	33	2.0 x 2.0		
1638+39	NRAO512	B	0.13	0.39	0.48	II	0.42	0.32	0.32	CH	94	1.2 x 1.2		
1641+39	3C345	Q	-0.53	7.90	8.00	II	3.13	1.56	1.45	D	51			both comp.unres. sep. 1 mas, p.a.-97°
1652+39	4C39.49	B	-0.20	1.35	1.25	II	0.40	0.45	0.40	C	34	<0.5		
1732+38		G	0.88	1.12	1.22	II	1.08	0.92	0.91	C	89	<0.5		
1751+44		Q	0.93	0.90	0.95	II	0.78	0.62	0.57	C	84	0.5		
1800+44		Q	0.73	0.96	0.81	II	0.63	0.50	0.55	E	77	0.7x(<0.5)	25	
1828+48	3C380	Q	-0.53	6.35	6.07	II	0.97	1.01	0.73	E	21	1.3x(<0.5)	153	
2113+29		Q	0.17	0.82	0.89	II	0.74	0.67	0.69	C	80	<0.5		
2136+14		Q	-0.08	1.38	1.37	II	1.05	0.79	0.68	C	80	0.6		
2150+17		G	0.40	0.83	0.76	II	0.43	0.31	0.25	C	58	0.7		
2200+42	BL Lac	B	-0.15	3.02	1.99	I	1.80	0.55	0.82	CH	83	3.2 x 0.8	3	
2201+31	4C31.63	Q	0.23	2.23	2.10	II	1.31	1.14	1.00	CH	95	5.5 x 1.2	40	
2230+11	CTA102	Q	-0.05	3.29	3.20	II	0.46	0.64	0.50	C	31	<0.5		poor data, complex?

Table 1 (continued)

(1) SOURCE	(2) NAMES	(3) opt. ident.	(4) $\alpha^{5}_{2.7}$	(5) $S^{5\ GHz}_{Total}$ (Jy) I	(6) II	(7) epoch	(8) $S^{5\ GHz}_{VLBI}$ (Jy) N-O	(9) M-N	(10) M-O	(11) VLBI-model type	(12) C(%)	(13) a x b(mas)	(14) p.a.(°)	(15) Comments
2234+28		Q	-0.50	1.34	1.26	II	1.26	1.18	1.20	C	99	<0.5		
2251+15	3C454.3	Q	0.50	9.21	7.94	II	4.03	3.02	2.31	CH	66	1.4 x 1.4		
2319+27	4C27.50	G	-0.12	0.86	0.86	II	0.40	0.33	0.39	CH	69	7.7 x 1.5	11	
2323+43		G	-0.47	1.01	0.93	I	0.22	0.08	0.10	CH	31	4.0 x 1.6	27	
2324+40	3C462	G	-0.50	1.04	0.95	I	0.22	0.08	0.10	CH	31	3.1 x 1.7	25	
2328+10	4C10.73	Q	-0.07	1.17	1.17	II	0.85	0.80	0.54	C	79	0.6		
2351+45	4C45.51	G	-0.07	1.31	1.24	I	0.34	0.16	0.16	E	22	1.0 x 0.6	38	
2352+49		G	-0.34	1.68	1.65	I	0.57	0.25	0.21	CH	48	2.4 x 0.5	12	

Since the amount of data for individual sources is limited, we fitted simple gaussian component models for the brightness distribution to the calibrated amplitudes, and did not attempt to use more sophisticated schemes for the data interpretation. The procedure used to obtain a final model always started with a point source. If no satisfactory fit was obtained we gradually increased the complexity of the model to improve the fit. The sequence we used was: circular gaussian, elliptical gaussian, core-halo (extended component and a compact core in its center) and then two separated components. In this way we always assumed the simplest model to be the best one. The data for only five sources (0108+38, 0710+43, 0723+67, 0923+39, 1641+39) required models with two separated components. The majority of the sources show structure which can be described by a core-halo model or only one component. These models, though crude, give a description of the basic properties of the source structure, such as the estimated amount of flux density contained in the components, the complexity of the structure and, in some cases, position angles for extensions. On the basis of the models we have derived a compactness parameter C defined as:

$C = 100$ (flux density contained in the model/total flux density) (%).

Table 1 contains information about the sources, the results of the flux density and VLBI measurements and the models. In detail the single columns contain:

Columns 1 and 2	Source names
Column 3	Optical identification (G = galaxy, Q = quasar, B = BL Lac object, E = empty field source)
Column 4	Spectral index between 2.7 and 5 GHz
Columns 5 and 6	5 GHz flux density at both epochs (I = 1978, II = 1979)
Column 7	Epoch of VLBI (I = 1978, II = 1979)
Columns 8–10	Average correlated flux density (in Jansky) on the three baselines NRAO-OVRO (N–O), MPI-NRAO (M–N), MPI-OVRO (M–O)
Column 11	Model type (C = circular, E = elliptical, CH = core halo, D = double)
Column 12	Compactness parameter C in %
Column 13	Size of extended components as major axis x minor axis in milliarcsec (the unresolved components in the core-halo models are 0.5 milliarcsec in extent and not especially listed)
Column 14	Position angle of extensions in degrees
Column 15	Comments

The optical identifications are taken from Véron and Véron (1974), Hewitt and Burbidge (1980), and Kühr (1980, 1981). The spectral indices are taken from Kühr et al. (1981).

5. Discussion

The detection of all but one source clearly confirms the expected connection between the existence of compact structure and a flat radio spectrum. Since the sources were selected on the basis of a 2-point spectral index criterion there are, however, several spectral shapes to distinguish, which are discussed in terms of the actual mechanism which produces the observed radiation. It is a common assumption that this radiation originates in partially optically thick synchrotron sources (e.g. Kellermann and Pauliny-Toth, 1981). In this scheme the flat and inverted ($\alpha \geqq 0$) spectra and the peaked spectra are dominated by compact, self-absorbed components, whereas the steep spectra ($\alpha \leqq -0.7$) represent the more extended, optically thin components. Although the sources with really steep spectra have been excluded from the sample by our selection criterion, the results indicate that, on average, sources with "steepish" spectra ($\alpha \leqq -0.2$) show a smaller degree of compactness (median $43 \pm 6\%$, $N = 20$) than those with spectral index $\alpha > -0.2$ (median $78 \pm 4\%$, $N = 36$). In this connection we note that 0945+66, the source not detected, is amongst the sources with the steepest overall spectral slopes (see complete spectrum in Kühr et al., 1981). Some sources contain both flat (at high frequencies) and steep (at low frequencies) components in their spectra and their compactness lies between the two extremes.

Because we have insufficient information about the larger scale structure and redshifts of the sources in our sample, we are unable to determine the source of the flux density not accounted for in our models. However, it is clear from three examples, that this "missing flux density" comes from regions covering a wide range of linear sizes: in the case of 3C454.3, it originates from a "jet" ~90 pc in extent (Pauliny-Toth et al., 1984), in 3C216 it comes from structure ~20 kpc in size (Schilizzi et al., 1982) while in 3C179, it comes from extended lobes ~130 kpc apart (Porcas, 1981).

We find a dependence of the compactness of the observed sources on the type of optical identification. Figure 1 shows the distribution of C for galaxies, quasars, BL Lac objects, and empty field sources. This indicates that galaxies are less compact (median $C = 48 \pm 16\%$, $N = 15$) than quasars ($75 \pm 7\%$, $N = 29$), BL Lac objects ($83 \pm 14\%$, $N = 7$) and empty fields ($78 \pm 13\%$, $N = 5$). Although there are only five empty field sources in the sample we

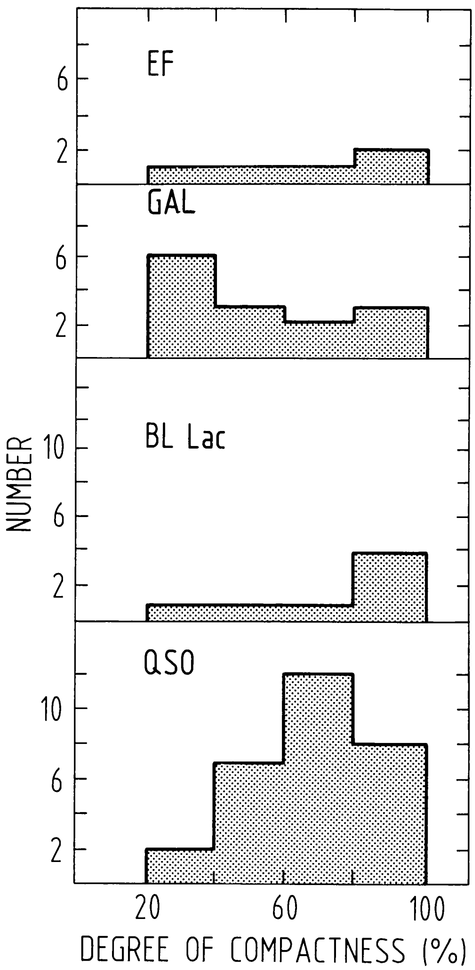

Fig. 1. Distributions of the compactness parameter C for the four types of optical identification galaxies (GAL; $N=15$, median $=48\pm16\%$), BL Lac objects (BL Lac; $N=7$, median $83\pm14\%$), quasars (QSO; $N=29$, median $=75\pm7\%$), and empty field sources (EF; $N=5$, median $=78\pm13\%$)

note that their compactness does not differ from that of quasars and BL Lac objects. There is only weak evidence from our data for the BL Lac objects being more compact than the quasars, an effect suggested by the results of Eckart et al. (1982) who studied sources taken from the MPIfR-S5 survey and fulfilling the same selection criteria as those in our sample but having declinations $\delta > 70°$. The compactness properties of the observed galaxies reflect the fact that they mainly show spectra with $\alpha \cong -0.5$ whereas BL Lac objects and quasars frequently have peaked or flat, variable spectra. In this sense there is some statistical evidence from our data that there exist morphological differences between the optical identification types.

For many of the sources observed our measurements give first information about the existence of milliarcsecond components and, additionally, a rough indication of their structure. Although we were forced by the limited data to favour the simplest models, we believe that most sources are well represented by them. This is supported by a comparison of our results with the detailed observations available for some sources observed in other experiments. There is good agreement in the basic properties like complexity, compactness and position angles of extensions, although our models cannot describe the fine structure in detail. Apart from providing basic statistical information on a homogeneous sample of sources selected at 5 GHz, the present data are a useful guide in planning more extensive VLBI observations of individual sources.

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