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MERLIN observations of steep-spectrum radio sources at 6 cm

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SUMMARY

We present high-resolution observations of steep-spectrum radio sources made with MERLIN at 5 GHz. Thirty-one objects, comprising 11 quasars and 20 galaxies, most of them being 'Compact Steep-Spectrum' sources (CSSs), have been mapped with resolutions from 80 to 150 mas. This completes the current series of observations of CSS sources made with MERLIN at 5 GHz. We find that the majority of the quasars have complex structures, while galaxies tend to have double or triple structures, consistent with other recent studies of CSSs.

1 INTRODUCTION

In the last decade, high-resolution observations of Compact Steep-Spectrum (CSS) radio sources have yielded much information on their structures and statistics (van Breugel, Miley & Heckman, 1984; Pearson, Perley & Readhead 1985; Fanti *et al.* 1985; Spencer *et al.* 1989). A variety of structures (doubles, triples, core–jet and complex) have been revealed by systematic observations with the very large array (VLA), MERLIN (mostly at $\lambda 18$ cm) and European very long baseline interferometer (VLBI).

Wilkinson *et al.* (1984) find a clear-cut morphological separation between CSS quasars and galaxies (see also Spencer *et al.* 1989). While quasars tend to have complex and distorted structures, galaxies are usually doubles or triples (see Akujor, Spencer & Wilkinson 1990; Fanti *et al.* 1990). Some of the unresolved issues in CSS astrophysics are whether they are intrinsically young compact sources, confined to galactic dimensions by dense ambient media, or appear small due to projection effects. It is quite possible that the compactness of these sources cannot be explained by a single factor, and the CSS structure will be better elucidated through a steady accumulation of data on many objects – particularly by imaging the core–jet emission regions of these sources with subarcsecond resolution.

In this paper, we present 6-cm MERLIN observations of 31 radio sources (the majority of them being CSS sources) at resolutions of 80 to 150 mas, i.e. not including a Cambridge telescope. For many of these CSS sources, data on these scales fill the existing gap between lower-resolution VLA and MERLIN observations and the higher-resolution VLBI observations. It is also the first major presentation of a collection of maps of compact radio sources on this resolution scale at 5 GHz.

2 OBSERVATIONS

The CSS sources in our list were selected from the 3CR sample. They have steep radio spectra ($\alpha \geqslant 0.5$; $S \propto \nu^{-\alpha}$) and most have the majority of their flux density contained in regions $\leqslant 15$ kpc (see Fanti *et al.* 1990). For those sources which meet the selection criteria but whose maps are not presented here, nearly all have published MERLIN 5-GHz maps (e.g. 3C309.1, Wilkinson *et al.* 1984). We present maps of a few sources with previously published MERLIN 5-GHz maps (e.g. 3C49, 138; Fanti *et al.* 1989). In these cases we have reanalysed the data and used different restoring beams. Some sources do not strictly satisfy our criteria but have been included mainly because they have moderately compact sizes, or were earlier thought to be CSSs. Most of such objects (3C153, 196, 270.1, 380) belong to the Akujor, Browne & Wilkinson (1988) sample of moderately compact steep-spectrum sources. The present set of maps do not constitute a complete sample such as that of Fanti *et al.* (1985), but there is considerable overlap with their sample.

The observations were taken over the period 1982 to 1988, each observation lasting on average 14 hr (see Table 1). The details of the MERLIN telescope configuration have been described by Thomasson (1986). Only five of the MERLIN telescopes (MK2, Defford, Darnhall, Knockin and Tabley) were used for these observations. The radio source 0552 + 398 was used as a calibrator and flux densities were established using 3C286 and 3C287 on the scale of Baars *et al.* (1977).

After the initial calibration, the data reduction was performed using self-calibration (Cornwell & Wilkinson 1981) in the difference-mapping programme in the Jodrell bank OLAF package and National Radio Astronomy Observatory (NRAO) AIPS routines. The restoring beams vary from 80 to 150 mas depending on whether we needed to highlight detailed features or extended structures. The images (Fig. 1) and source parameters (Table 1) are presented in order of increasing right ascension. The typical dynamic range (defined as peak surface brightness to rms off source) is about 500:1.

In sources with significant extended structure, our measured flux densities are systematically lower than the total flux densities. This is because extended weak features are resolved out by MERLIN due to the absence of short spacings in the array.

3 COMMENTS ON INDIVIDUAL SOURCES

While brief comments are made on majority of the sources in our list, we refer the reader to Spencer *et al.* (1991) for

Table 1. Observational parameters.

IAU Name	3CR	Opt	Z	Obs Date	T_{obs}	θ_{HPBW}	AR	Str.	S_{peak}	σ_{rms}	S_{comp}	Refs
0127+233	3C43	Q	1.459	83-08-28	15.0	80	1.1	C	273	1.0	764	4,7,13
0134+329	3C48	Q	0.367	82-06-11	34.0	80	1.4	C	1073	1.3	896	3,4,7,12,21
											3151	
0138+136	3C49	G	0.621	82-04-22	8.5	80	5.5	D	537	0.8	584	4,5,6,7
											88	
0221+276	3C67	G	0.310	83-09-04	28.0	100	6.6	D/C	165	0.3	247	3,4,5,7
											423	
0345+337	3C93.1	G	0.244	83-08-24	15.0	80	1.0	C	241	1.1	537	7
0518+165	3C138	Q	0.759	82-04-21	7.0	80	3.4	C/CJ	1330	1	100	3,4,6,7
											885	
											827	
											1812	
0605+480	3C153	G	0.277	88-02-06	14.5	100	5.1	D	132	0.1	20	1,17
											124	
											307	
0658+380	3C173	G	0.292	83-08-27	26.0	100	6.1	D?	151	1.1	373	7
											41	
0809+486	3C196	Q	0.871	82-04-29	24.0	100	5.9	D	252	0.9	974	1,15,16,17,19
											1273	
0855+143	3C212	Q	1.043	82-04-27	12.0	100	34	T	137	0.6	13	2
											186	
											74	
0858+292	3C213.1	G	0.194	83-09-04	26.0	100	1.4	T	58	0.5	149	7
1019+222	3C241	G	1.617	83-09-02	14.0	80	5.5	T	149	0.8	184	4,5,7
											40	
											5	
											83	
1122+195	3C258	G	0.165	83-08-28	13.0	80	1.5	CJ	227	0.7	266	
											86	
1140+223	3C263.1	G	0.360	88-01-18	14.0	150	15	D	132	0.3	14	2
											165	
											179	
1203+645	3C268.3	G	0.371	83-04-23	24.0	100	4.5	D	294	0.8	648	3,4,5,7
											348	
1218+339	3C270.1	Q	1.519	82-06-05	18.0	150	24	T	172	0.3	201	2,16
											219	
1250+568	3C277.1	Q	0.320	82-04-24	16.0	80	4.1	T	226	1.4	162	3,4,7
											28	
											324	
1328+307	3C286	Q	0.849	83-08-26	13.0	100	1.2	CJ?	5767	3.8	6880	3,4,7,13,14
1350+316	3C293	G	0.045	82-05-11	14.5	100	4.9	D/C	118	0.8	83	2,4,9,18
											507	
1416+067	3C298	Q	1.439	83-08-29	10.0	80	6.6	T	430	1.3	259	4,7,11
											515	
											133	
											429	
1419+419	3C299	G	0.367	83-09-13	32.0	100	1.9	C	177	0.9	1097	3,4,7,13
1443+773	3C303.1	G	0.267	83-08-25	17.0	80	6.6	D	207	0.7	11	4,5,7
											637	
1447+771	3C305.1	G	1.132	83-08-31	21.0	80	8.2	D	99	0.3	20	4,7
											179	
1517+204	3C318	G	0.752	82-04-21	12.0	100	2.6	D/T	251	0.6	136	4,7,13
											407	
1634+628	3C343	Q	0.988	82-04-25	17.0	100	1.0	C	838	0.6	1190	4
1637+626	3C343.1	G	0.750	82-04-25	16.0	80	2	D	507	0.7	678	3,4,5,7
											329	

Table 1 – *continued*

IAU Name	3CR	Opt	Z	Obs Date	T_{obs}	θ_{HPBW}	AR	Str.	S_{peak}	σ_{rms}	S_{comp}	Refs
1641+173	3C346	G	0.161	82-04-26	8.0	100	8.6	D/C	272	0.4	286	1,13
											141	
1828+487	3C380	Q	0.691	88-01-20	24.0	150	3.6	C	2567	0.8	156	4,8,12
											309	
											3120	
2249+185	3C454	Q	1.757	83-09-26	18.5	100	6.3	T	357	0.6	31	4,13,20
											20	
											758	
2248+716	3C454.1	G	1.841	82-04-23	11.0	100	7.1	D	115	0.2	145	4,7
											41	
2252+129	3C455	G	0.543	83-08-27	12.0	100	8.1	D	34	0.6	173	2,7,16
											96	

Notes on table: Column 1: IAU; 2: 3CR name; 3: optical type; 4; redshift, z; 5: date of obs.; 6: length of obs. (hr); 7: restoring beam, θ in mas; 8: axial ratio, AR; 9: structure, D – double, T – triple; CJ – core-jet, C – complex; 10: peak brightness (mJy/beam); 11: rms noise in map (mJy/beam); 12: component flux density in mJy; 13: References to published maps: [1] Pooley & Henbest (1974); [2] Jenkins, Pooley & Riley (1977); [3] van Breugel, Miley & Heckman (1984); [4] Pearson, Perley & Readhead (1985); [5] Fanti *et al.* (1985); [6] Fanti *et al.* (1989); [7] Spencer *et al.* (1989); [8] Wilkinson *et al.* (1991 and refs); [9] Bridle, Fomalont & Cornwell (1981); [10] Kollgard, Wardle & Roberts (1989); [11] Graham & Matveyenko (1984); [12] Simon *et al.* (1990); [13] Spencer *et al.* (1990); [14] Simon *et al.* (1980); [15] Lonsdale & Morison (1980); [16] Schilizzi, Kapahi & Neff (1982); [17] Lonsdale & Morison (1983); [18] Leahy & Williams (1984); [19] Lonsdale & Barthel (1984); [20] Cawthorne *et al.* (1986); [21] Wilkinson *et al.* (1990).

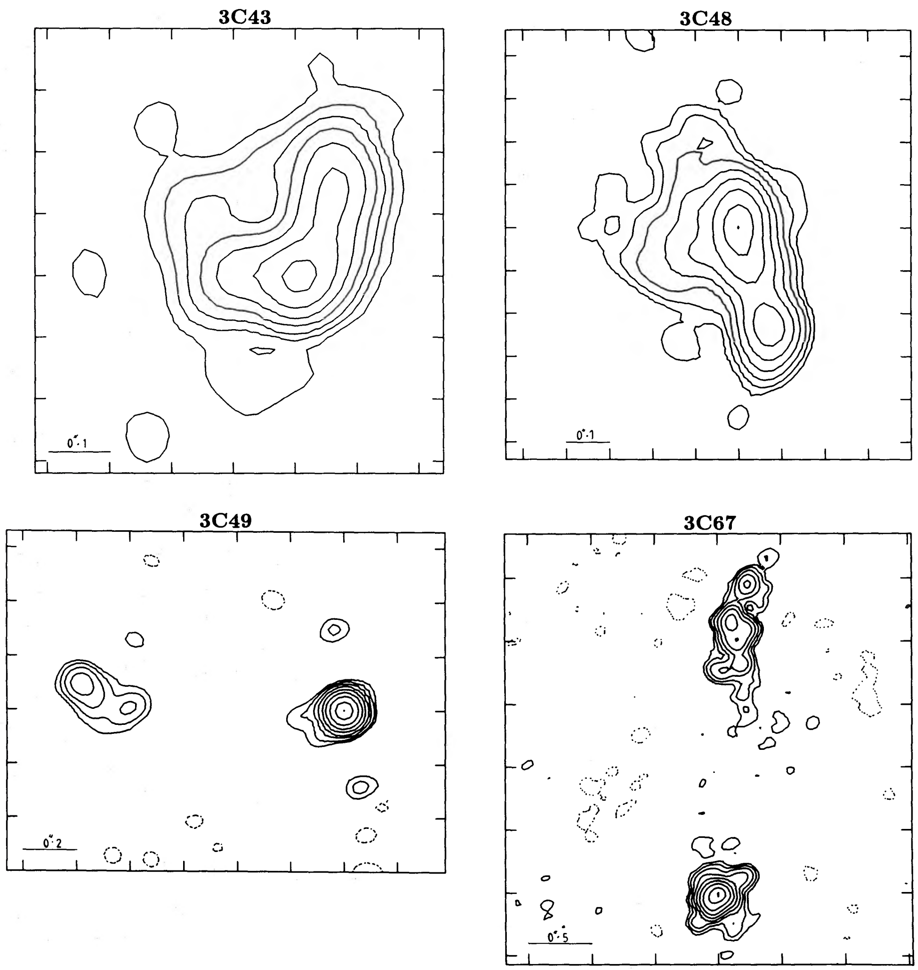

Figure 1. Maps of the sources at 5 GHz. The restoring beams are given in Table 1 in each case. The contours are logarithmic, as percentages of peak brightness; the peak contour being 99 per cent, others are 64, 32, 16, 8, 4, 2, 1, 0.5, ...

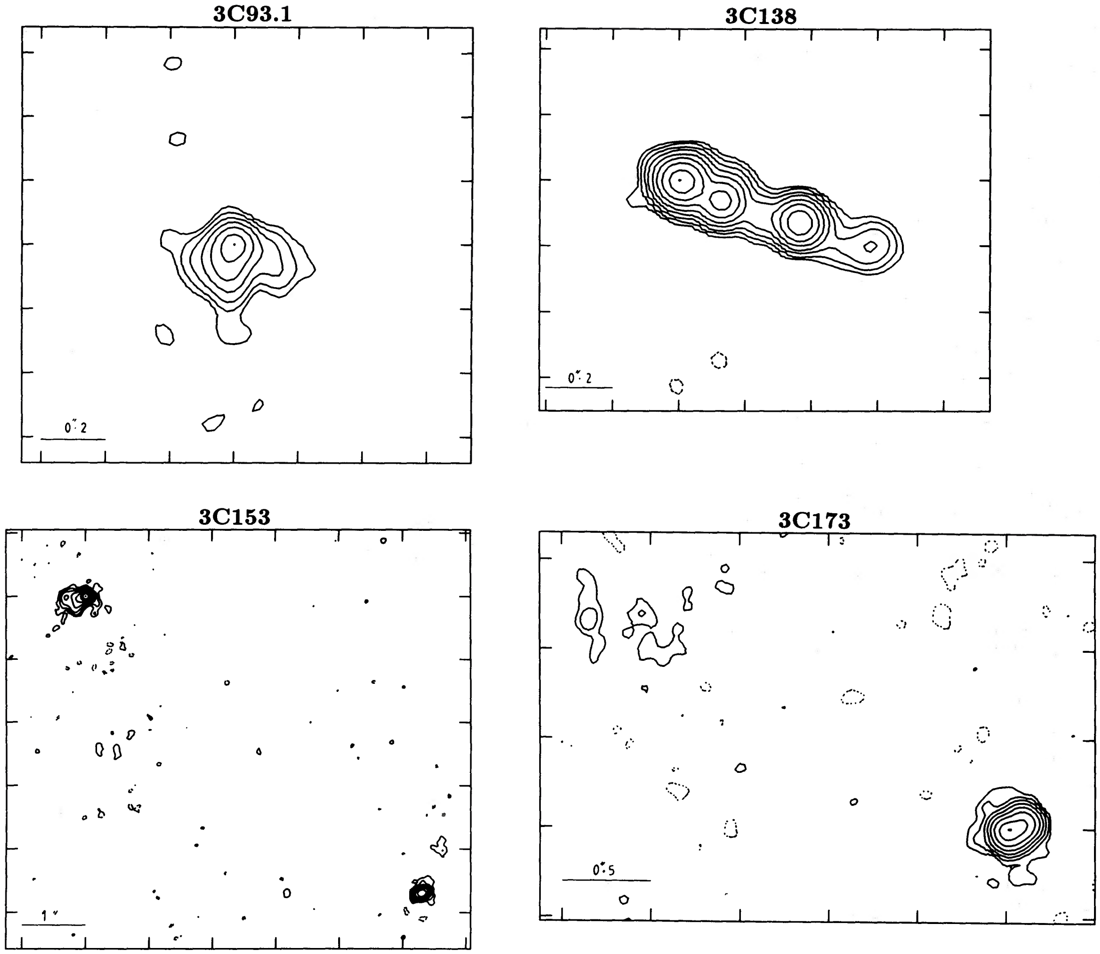

Figure 1 – *continued*

detailed discussion of the properties of some of these sources.

3C43, quasar. The lower-resolution maps (Pearson *et al.* 1985; Spencer *et al.* 1989) reveal an extended misaligned triple structure. Our map shows the central component of the triple.

3C48, quasar. Our map of this powerful source is in broad agreement with the low-frequency VLBI map by Simon *et al.* (1990) and the 1.6-GHz 'World Array' image by Wilkinson *et al.* (1990) but these reveal a more convoluted and complicated structure. The comparison also indicates that the core is very weak and is embedded in the lower end of the southern component in our map.

3C49, galaxy. This is an asymmetric double source. The radio component, possibly the core seen in Fanti *et al.* (1989) maps, is not visible in our map. This suggests that the component is extended since our 5-GHz map has a smaller restoring beam than theirs.

3C67, galaxy. Our map confirms the complex and triple-like structure of the northern lobe as suggested by Spencer *et al.* (1989) and found on VLBI scales (Fanti *et al.* 1985).

3C93.1, galaxy. This source has a complex structure with wing-like extensions which requires higher-resolution observations to understand it.

3C138, quasar. Our map made with 80 mas (circular) beam is consistent with the MERLIN map (90×60 mas^2) by Fanti *et al.* (1989) made from the same data set, but our new map reveals more clearly the knotty structure. If the third knot to the west is the core, as suggested by Fanti *et al.* (1989), our map suggests the existence of a counter-jet in this source.

3C173, galaxy. The double structure is consistent with the lower frequency map by Spencer *et al.* (1989). The NE component is weak and very diffuse, accounting for ~10 per cent of the total flux density.

3C212, quasar. A triple structure is revealed by our map and is consistent with an earlier Cambridge map (Jenkins, Pooley & Riley 1977). The weak NW lobe is barely detected, and the central component has an extension pointing towards the SE lobe.

3C213.1, galaxy. This is one of the few galaxies with complex structures. The bright central component produces

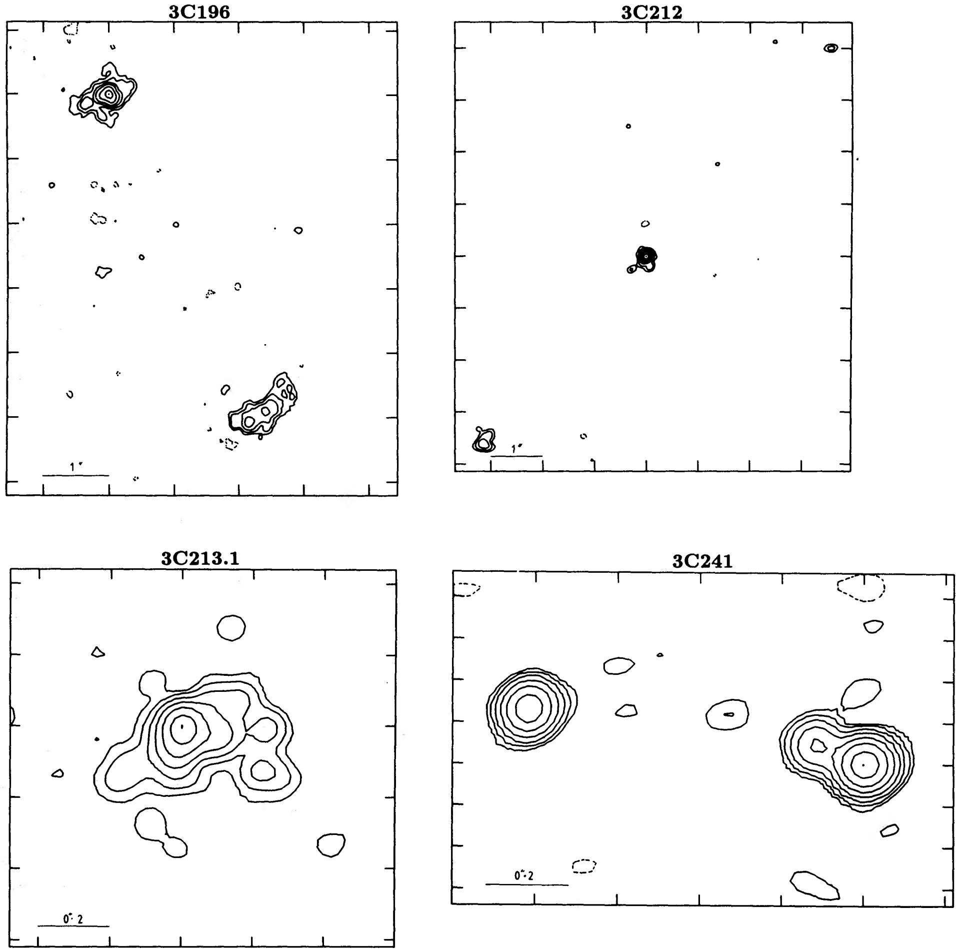

Figure 1 – *continued*

about 41 per cent of the total measured flux density. A lower-resolution map (Spencer *et al.* 1989) shows a weaker component ~ 6 arcsec away in the NW direction which we do not detect.

3C241, galaxy. The source has a weak central component ($S_{6\,\mathrm{cm}} \sim 5$ mJy) which van Breugel *et al.* (in preparation) have shown to be the radio core.

3C258, galaxy. This appears to have a double structure. No previous map has been published. The brighter component produces about 86 per cent of the total measured flux density.

3C270.1, quasar. This has a triple radio structure (see Jenkins *et al.* 1977; Schilizzi, Kapahi & Neff 1982). The northern component is weak and diffuse, and is barely detectable in our map.

3C293, galaxy. This is a very peculiar radio source identified with a 14.3-mag E6 galaxy VV 5-33-12 (Wyndham 1965). VLA observations (Bridle, Fomalont & Cornwell 1981) shows that it is ~ 3 arcmin in extent, but its central region contains a 'double' radio source. This is what appears in our map, the rest of the extended emission being resolved out by MERLIN at 5 GHz. Other extended sources whose central regions contain steep-spectrum kpc-scale double radio sources include Cen A, Vir A, 3C236 and 3C315 (see Leahy & Williams 1984; van Breugel 1984).

3C298, quasar. This is a multi-component radio source. The second component from the west has a flat spectrum (see Graham & Matveyenko 1984) and is likely to be the radio core.

3C299, galaxy. Lower-resolution maps (see Spencer *et al.* 1989) show a related component ~ 12.5 arcsec SW of the main source (see also Spencer *et al.* 1991; van Breugel *et al.*, in preparation). The unusual 'rectangular' shape of the source seen in our map is also present in the 1666-MHz map by Spencer *et al.* (1990).

3C303.1, galaxy. It has an asymmetric double structure consistent with lower resolution maps (Pearson *et al.* 1985; Spencer *et al.* 1989). The weak northern component contains only ~ 2 per cent of the total flux density.

3C318, galaxy. The quoted flux densities in Table 1 are for

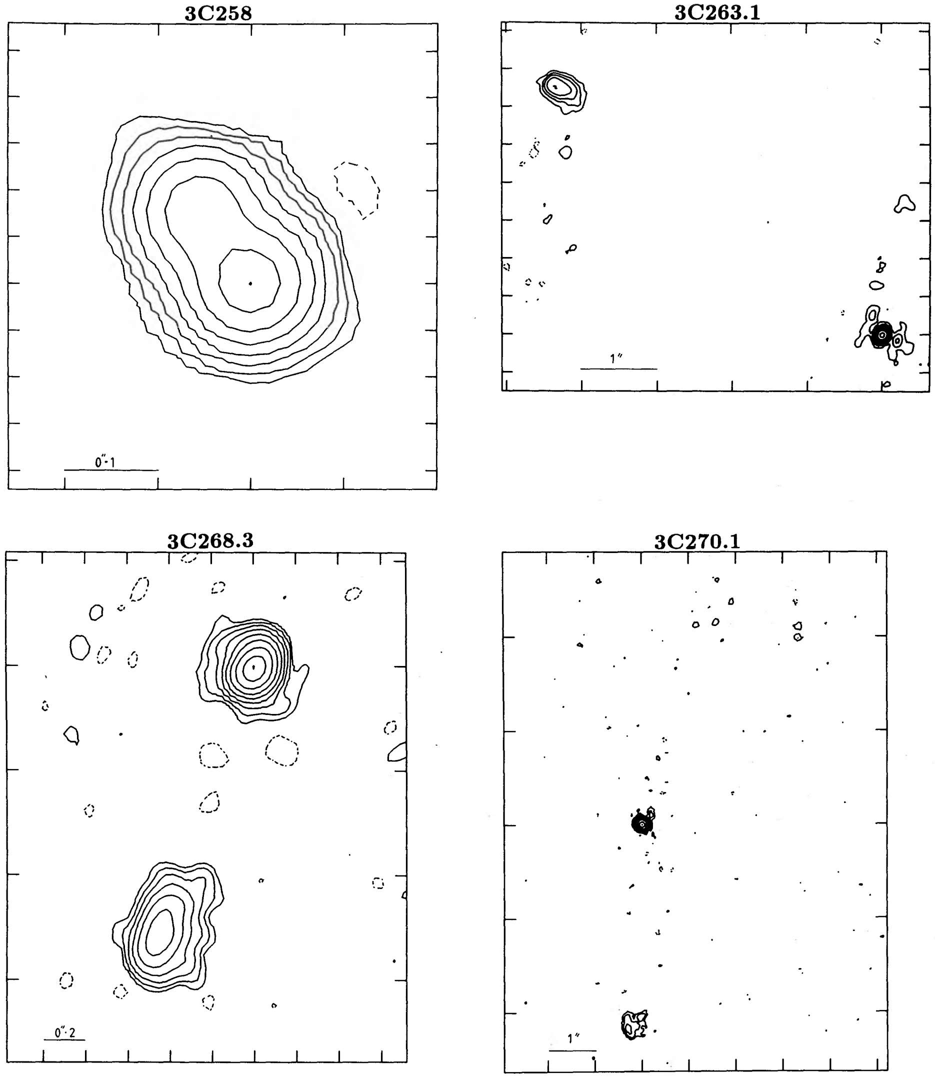

Figure 1 – *continued*

the two well-separated components. The northern component has a jet-like extension that accounts for about 28 per cent its flux density.

3C346, galaxy. Lower-resolution maps (Pooley & Henbest 1974; Spencer *et al.* 1991) show that this source is embedded in a large cocoon which we do not detect. The eastern component has a jet-like extension, and comparison with the low-resolution maps (Spencer *et al.* 1991; Stannard, in preparation) suggests that the western component has a flat spectrum and may be the radio core.

3C380, quasar. The map presented here is made from a combination of MERLIN and VLA data. Maps made from the individual arrays have been presented in Wilkinson *et al.* (1991). This map which fairly represents some of the extended and compact features also shows leading edge-brightening of the NW complex. Flux densities given in Table 1 refer only to the three bright features in the map.

3C454.1, galaxy. This source has a peculiar radio structure. There are two well-separated asymmetric components. Both components have jet-like extensions aligned in PA ~ −45°.

4 DISCUSSION

The maps reveal a variety of structures, and we can attempt to classify the sources on the basis of our maps. There are 11 quasars and 20 galaxies in our sample of 31 objects. Fanti *et al.* (1990) give working criteria for morphological classification of CSSs. Following their scheme, we find simple (double or triple) structures in 4 (36 per cent) quasars and 16 (80 per cent) galaxies; while 7 (67 per cent) quasars and 4 (20 per cent) galaxies have complex (including core-jet) structures. We can test that this difference in structure is statistically significant by assuming a null hypothesis that there is no difference in complexity between quasars and galaxies. Using a χ^2 contingency test we find that there is $\leqslant 5$ per cent chance that there is no difference.

It is also possible to differentiate between simple and com-

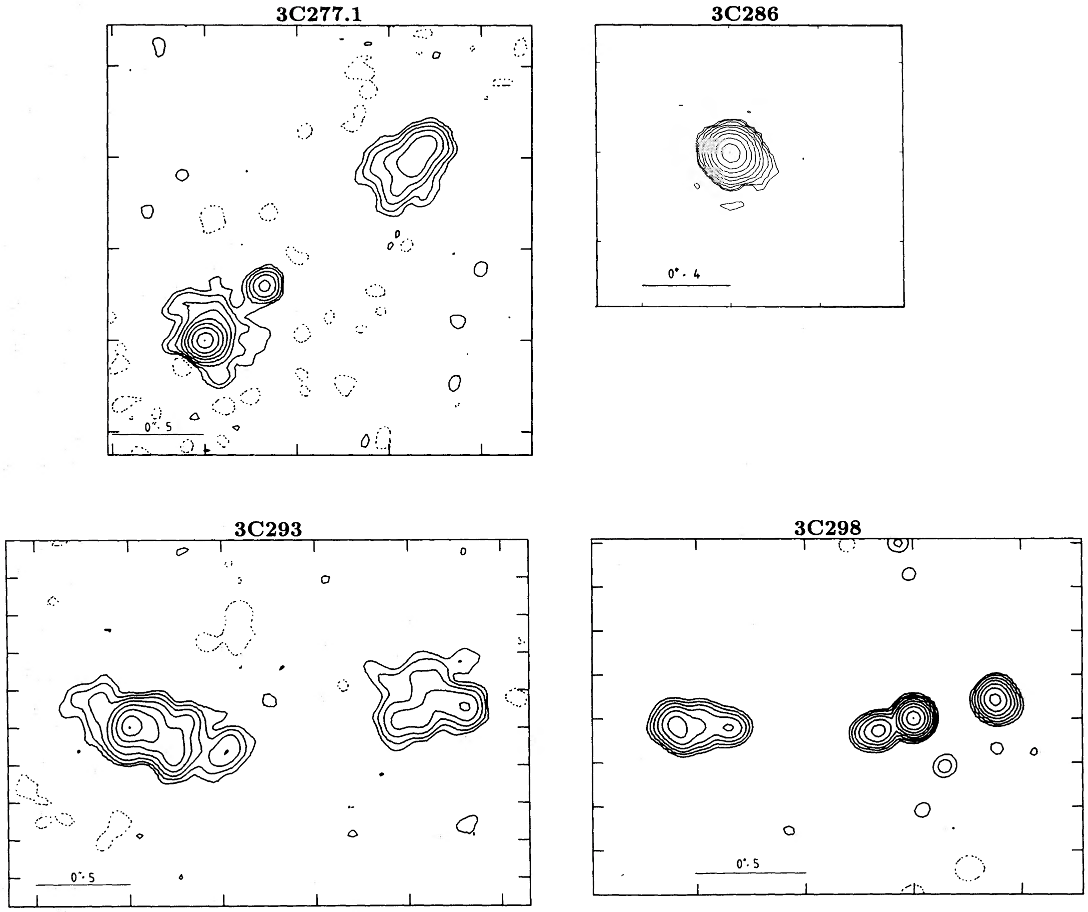

Figure 1 – *continued*

plex structures based on source axial ratios, ARs (Akujor *et al.* 1988), defined as the ratio of the largest size of the source to the maximum size in the perpendicular direction (see also Leahy & Williams 1984). This is fairly independent of the quality of the maps and the number of resolution elements across the source. For example, 3C43 is a triple on larger scales (see Spencer *et al.* 1989), but is highly distorted at higher resolutions (this paper). Following this scheme which takes sources with AR$\geqslant$4 as being simple, we find that 73 per cent of the quasars have complex structures, while simple structures are found in 70 per cent of the galaxies. Again quasars tend to have more complex structures than galaxies, consistent with earlier results for CSSs (Wilkinson *et al.* 1984; Spencer *et al.* 1989; Fanti *et al.* 1990) and their slightly more extended counterparts (Akujor *et al.* 1988).

When maps published at other resolutions are taken into account, one notices that, in CSSs with double or multiple hotspots in their lobes, the brighter hotspot is usually set back from the outer edge. Such features present in 3C67, 138 (see Fanti *et al.* 1985), 241, 293, 343.1 (Fanti *et al.* 1989) and 380 (Wilkinson *et al.* 1991), have also been found in large FRII doubles (Leahy & Perley, private communication). This suggests that a common mechanism may be responsible for hotspots in both CSSs and large FRII sources.

Our results, thus, confirm the earlier conclusion, based on lower resolution MERLIN 18-cm observations and the VLA maps, that CSS quasars have generally more complex structure than CSS galaxies (Spencer *et al.* 1989). Galaxies have weak cores usually with double components, but a few, e.g. 3C67, do show complex structure within their lobes, as does the classical-double source Cygnus A (Hargrave & Ryle 1974).

These maps complete the publication of MERLIN Phase I (i.e. not including the Cambridge telescope) observations of CSS sources. This class of sources proved to be the most fruitful for MERLIN observations since they are small in size and have high brightness. The new MERLIN (Phase II) including the new Cambridge 32-m telescope and more sensitive receiver systems is expected to yield maps of these sources with higher resolution and greater dynamic range. We await with interest the availability of these data.

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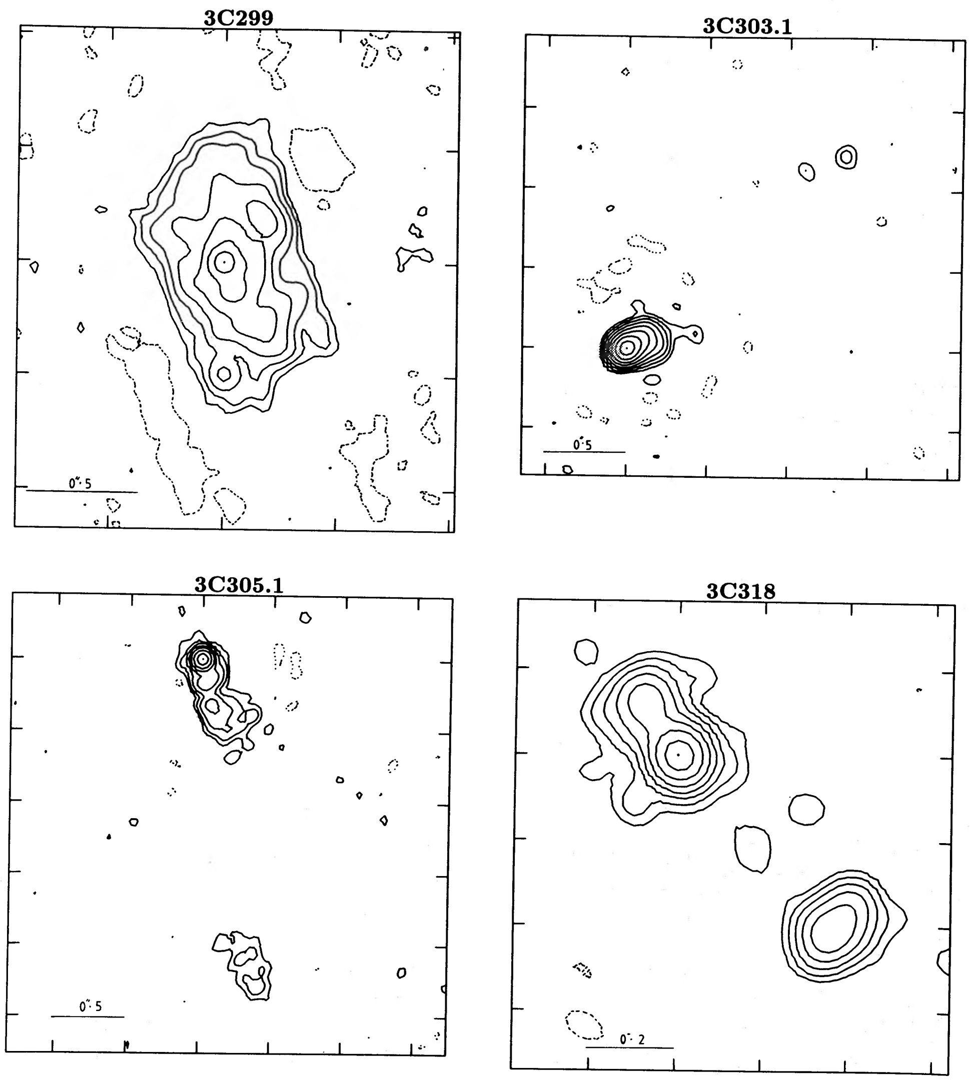

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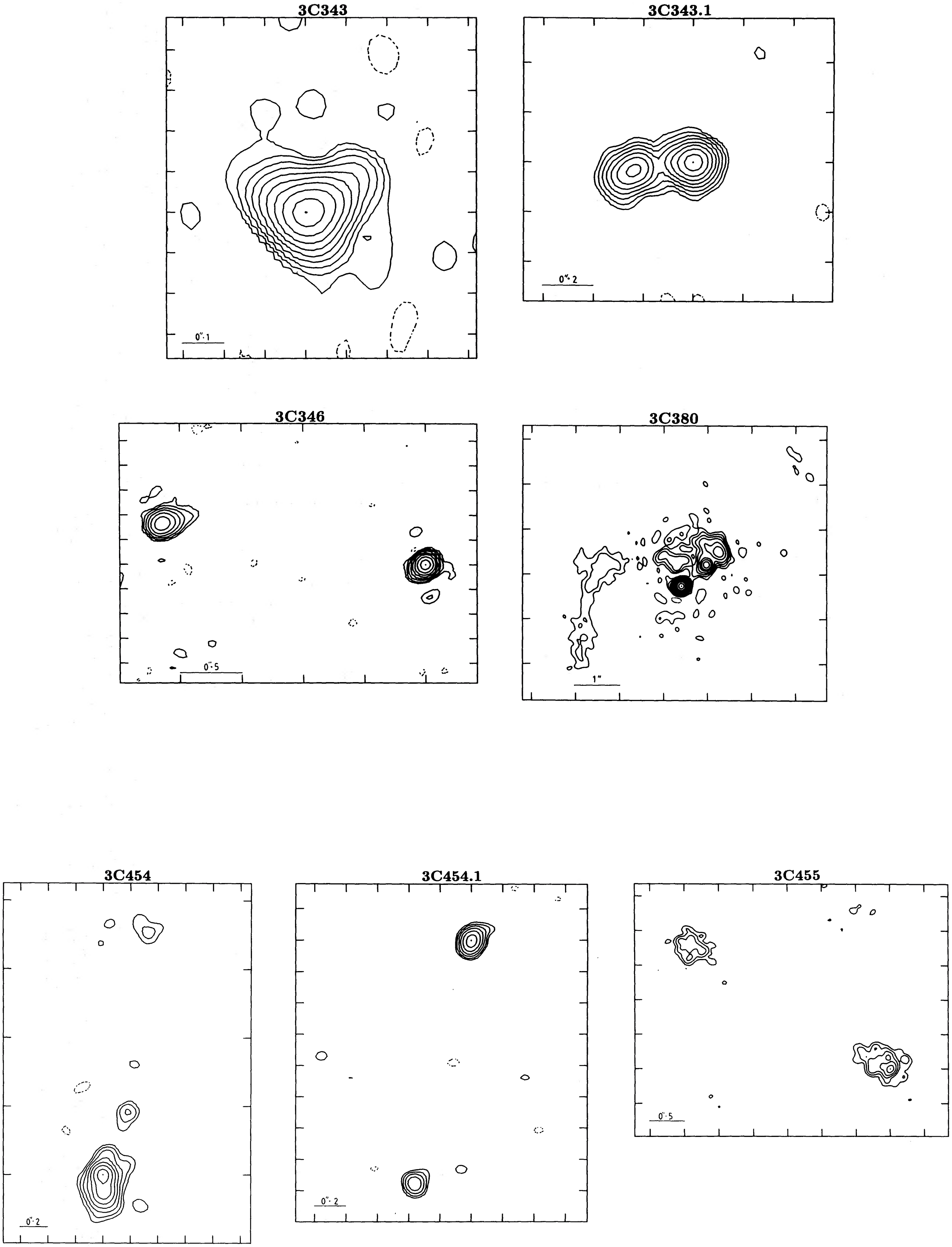

Figure 1 – *continued*

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