A&A 391, 47–54 (2002)
DOI: 10.1051/0004-6361:20020532

Astronomy & Astrophysics

FIRST-based survey of Compact Steep Spectrum sources

I. MERLIN images of arc-second scale objects

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Received 12 November 2001 / Accepted 5 April 2002

Abstract. Compact Steep Spectrum (CSS) sources are powerful extragalactic radio sources with angular dimensions of the order of a few arcseconds or less. Such a compactness is apparently linked to the youth of these objects. The majority of CSSs investigated so far have been known since the early 1980s. This paper is the first in a series where we report the results of an observational campaign targeted on a completely new sample of CSSs which are significantly weaker than those investigated before. The ultimate goal of that campaign is to find out how "weak" CSSs compare to "strong", classical ones, especially with regard to the morphologies. Here we present an analysis of morphological and physical properties of five relatively large sources based on MERLIN observations at 1.6 and 5 GHz.

Key words. radio continuum: galaxies – galaxies: active – galaxies: evolution

1. Introduction

Compact Steep Spectrum (CSS) sources (Kapahi 1981; Peacock & Wall 1982) form a well defined class of radio sources; they are powerful, compact (projected linear sizes ≤20 kpc and hence angular sizes of the order of a few arcseconds) and possess steep ($\alpha \geq 0.5$, $S \propto \nu^{-\alpha}$) spectra. CSSs are identified with quasars, radio galaxies and Seyferts. Wilkinson et al. (1984) found a morphological separation between CSS quasars and galaxies (see also Spencer et al. 1989; Fanti et al. 1990) which is similar to that observed for larger sources: radio galaxies generally have a simple double radio structure (sometimes with weak radio jets and weak radio cores) whilst quasars show either a triple structure (with a strong central component consisting of a bright jet) or complex structure.

An astrophysical interpretation of the CSS phenomenon has been given in Fanti et al. (1990). They show that in principle small apparent sizes of CSSs could result from the projection of "normal" Large Symmetric Objects (LSO), however only less than 25% of these objects are expected to be larger sources seen close to the line of sight. Most of them are supposed to be intrinsically small objects randomly oriented on the sky and their sub-galactic apparent linear dimensions can be explained by two main hypotheses. According to the first one CSS sources are confined by the interaction of the jet with an inhomogeneous, dense and possibly turbulent medium in the host galaxy which inhibits a normal development (van Breugel et al. 1984). In this scenario CSSs are so called *frustrated* objects. The second hypothesis (Phillips & Mutel 1982; Carvalho 1985; Mutel & Phillips 1988) – and this one has gained more observational support recently (see e.g. Fanti et al. 2000) – suggests that CSS sources may be the *young* stages of future LSOs and so the compactness of these objects is just an evolutionary effect: they are small because they have not had enough time to expand to supergalactic scales. If that hypothesis is correct, CSSs can be regarded as an intermediate class between even smaller Compact Symmetric Objects (CSOs) (Readhead et al. 1996) and LSOs and, together, these three groups of radio sources make up an evolutionary sequence. One of the main argument in favour of the evolution is that CSOs and some CSS sources, namely Medium-sized Symmetric Objects (MSOs) (Augusto et al. 1998) which are unbeamed CSSs, have similar morphologies to LSOs. On the other hand, the lobe speeds in CSO sources are high: ∼0.2c (Owsianik & Conway 1998; Owsianik et al. 1998), so CSOs quickly evolve into larger objects and MSOs seem to be perfect candidates to become post-CSOs. Most of the CSS sources known so far have sufficiently high radio luminosity that even assuming a strong decrease in luminosity as they evolve, they remain good candidates for future large scale Fanaroff–Riley class II (FRII) (Fanaroff & Riley 1974) sources with high radio luminosity. An additional support of this view comes from the morphological similarity of many CSSs to FRIIs as expected if the evolution is self-similar.

All studies of CSS sources made by 1995 i.e. until publication of papers by Dallacasa et al. (1995) and

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Sanghera et al. (1995), were based on the so called 3CRPW sample consisting of 54 sources (Spencer et al. 1989). The next step in such investigations can be made through extension of the available sample of CSSs toward weaker sources. For example, Saikia et al. (2001) selected a sample of 42 candidates from the S4 survey (Pauliny-Toth et al. 1978) which is complete to 0.5 Jy at 5 GHz and Fanti et al. (2001) – hereafter F2001 – derived a new sample of 87 CSSs with flux densities ≥0.8 Jy at 408 MHz from B3-VLA survey (Vigotti et al. 1989). Here we present a genuine method of finding weak CSSs which makes use of *Faint Images of Radio Sky at Twenty* (FIRST) (White et al. 1997). Its fine resolution (5.″4) is the crucial feature for that purpose. A strong motivation to conduct the research in this direction came from the fact that a number of CSS sources weaker than those in the 3CRPW sample have already been mapped with the VLA at 8.4 GHz by Patnaik et al. (1992)[1]. It appears that those sources have angular sizes of the same range as all the CSSs known so far, yet they are significantly weaker. There are two plausible explanations: a) these sources are those CSSs we see almost exactly face-on, so their Doppler boosting is minimal, or b) these sources form a new class of "weak" CSSs.

In 1996 we proposed observations based on newly released early results of FIRST aimed to discriminate between cases a) and b). If case a) is true then those ones with counter-jets should dominate among these new CSS sources; sources of this kind were rare in the 3CRPW sample. If case b) is true then there is a chance to find an elegant analogy: strong CSSs are "miniature FRIIs" whereas weak CSSs are "miniature FRIs". Taking into account the evolutionary scenario and assuming that radio sources evolve in a self-similar manner we might also say that strong CSSs from the 3CRPW sample evolve towards FRIIs whereas weak CSSs evolve towards FRIs. Testing such a possibility is among the goals of a series of papers resulting from interferometric (MERLIN, EVN, VLBA) observations of our FIRST-based sample of CSS candidates.

2. Sample selection

To select weak CSS sources from the FIRST catalogue we made the following steps:

a) From the source list based on Green Bank (GB) surveys at 21 and 6 cm White & Becker (1992) we selected those sources lying within the then current limits of the FIRST survey when FIRST covered the area of declination 28°–42°, having steep spectra ($\alpha > 0.5$) and being stronger than 150 mJy at 6 cm. (This flux density limit was chosen in order to produce a sample of manageable size.) The above declination limits indicate that the overlap between our sample and the B3-VLA survey based sample of F2001 (their limits are 37°15′–47°37′) is not large.

b) We identified FIRST sources with those GB survey sources. We found, quite expectedly, that thanks to a dramatic difference in the resolution, the majority of sources appearing as single in the GB survey turn out to be double (or multiple) on FIRST maps and so they are represented either as compact pairs or clusters of pointlike sources in the FIRST catalogue.

c) We rejected all such cases i.e. we selected only those sources that are single entities in the FIRST catalogue i.e. more compact than the FIRST beam (5.″4) and surrounded by an empty field. We adopted 1 arcmin as a radius of that field. Such a procedure allows us to make sure that we deal with isolated objects and not parts of larger objects.

d) We, again, checked whether our targets fulfill the spectrum steepness criterion: instead of GB-survey flux densities at 21 cm we used more accurate values from FIRST. We rejected candidates with flat spectra ($\alpha \leq 0.5$).

e) We found that all already known CSS sources lying within our RA and declination limits have been correctly selected so far. Obviously we rejected them.

f) We rejected the Gigahertz Peaked Spectrum (GPS) sources because – in our opinion – they constitute a separate class. The main reason for this is that GPSs are an order of magnitude more compact than CSSs and their spectra have a different shape. Our research was focused on "true" CSSs and not GPSs[2] To this end we identified our preliminary candidates with objects listed in 365 MHz Texas catalogue (Douglas et al. 1996). We passed only those objects which have non-inverted spectra between 365 and 1400 MHz. In other words the turnover frequencies of our sources lie below 365 MHz.

Finally we selected 60 candidates for CSS sources. Radio selected samples normally suffer from redshift information scarcity and it was the case here. Therefore, for the majority of our candidates it was not possible to calculate their distances and to judge which of them fulfill the linear size criterion for CSSs which, obviously, is of primary importance for the physics and evolution issues. Instead we used the angular size criterion which is still helpful for making sure we reject objects with excessively large linear sizes. Since the resolution of FIRST is 5.″4, we realised from the beginning that a number of those candidates may *not* fulfill the angular size criterion and so a rejection of sources with angular sizes larger than certain limit yet pointlike according to FIRST was planned as the first step after completion of the initial survey of all those 60 targets. Assuming that the linear sizes of a CSS source should remain below 20 kpc for currently adopted cosmological parameters, in particular for $H_0 = 72\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Freedman et al. 2001), we adopted 3″ for such a criterion.

[1] In principle Patnaik et al. (1992) sought candidates for pointlike phase calibrators among flat-spectrum objects in Green Bank surveys but the procedure they used was different from that used by e.g. White & Becker (1992). When we supplemented their list with flux densities from White & Becker it turned out that some of their candidates actually had steep-spectra. Consequently the VLA observations revealed resolved structure and so these objects could not be used as calibrators. In this way Patnaik et al. made a serendipitous discovery of several weak CSSs.

[2] A review of both GPS and CSS classes has been given by O'Dea (1998).

Table 1. Optical magnitudes and radio flux densities of 5 CSS sources at two frequencies.

Source	4C	RA (J2000)	DEC (J2000)	m_R	m_v	z	$F_{1.4\text{GHz}}$	$F_{4.85\text{GHz}}$	$\alpha^{4.85\text{GHz}}_{1.4\text{GHz}}$
0801+303	+30.13	08 04 42.148	30 12 37.91	18.1	19.2	1.446	1189	404	0.87
0805+406	+40.19	08 09 03.158	40 32 56.72	>20.8	21.1	–	437	179	0.72
0850+331	+33.22	08 53 21.100	32 55 00.60	–	–	–	465	208	0.65
1201+394		12 04 06.859	39 12 18.17	19.6	21.4	0.445	468	162	0.85
1233+418		12 35 35.706	41 37 07.40	17.9	20.8	0.25	651	276	0.69

Optical magnitudes derived from POSS plates using APM have been taken McMahon et al. (2002).
0805+406 has not been detected at R band – the m_R value quoted is an upper limit.
The redshift of 1233+418 is photometric.
Radio fluxes (in mJy) for 1400 MHz extracted from FIRST; radio fluxes (in mJy) for 4850 MHz extracted from GB6.

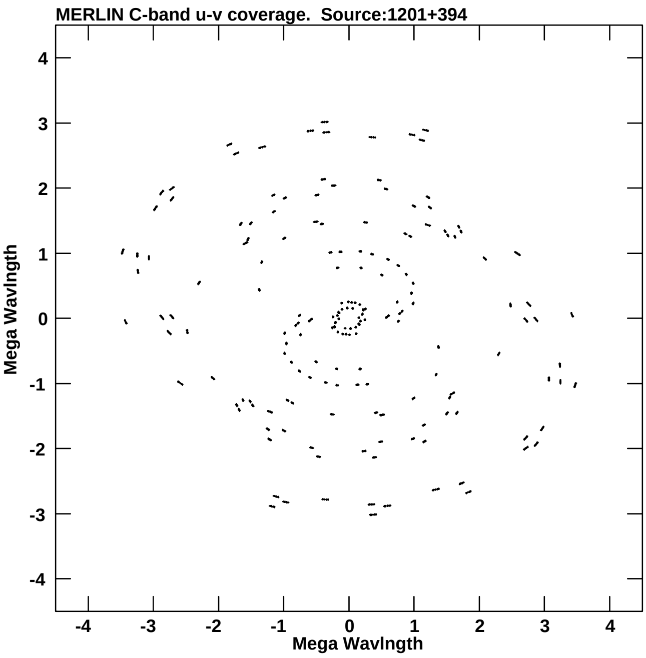

Fig. 1. Typical $u-v$ coverage during 5 GHz observations.

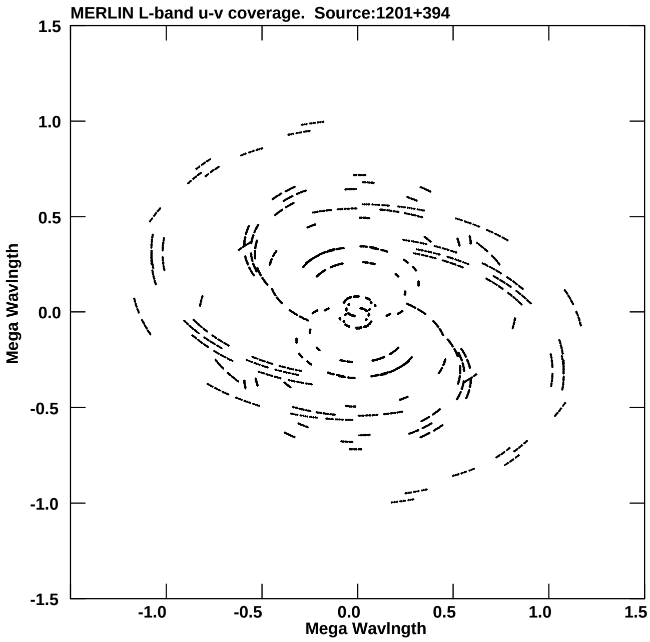

Fig. 2. Typical $u-v$ coverage during 1.6 GHz observations.

3. Observations and data reduction

The initial survey was performed with MERLIN at 5 GHz. At that frequency MERLIN attains a resolution of 0.″04 which is sufficient to make a final selection of actual CSSs from the list of our candidates. We made snapshot observations of the sample of CSS sources defined above in 1997. Our targets were observed 6 times in 10 min scans spread evenly over a 12-hour track. Six MERLIN telescopes were used. A typical $u-v$ coverage accomplished in those observations is shown in Fig. 1.

Phase calibrator sources chosen from the MERLIN Calibrator List (Patnaik et al. 1992) were observed twice per target scan for 1–2 min. Poor weather conditions allowed us to observe only a part of our sample in 1997, however we successfully observed and mapped about 3 dozen sources. At this point we rejected the sources which were too large to be regarded as CSS sources using a 3″ limit for the angular size. The remaining 21 objects were indeed new CSS sources. We divided them into 3 groups:

1) relatively large ones with sizes ranging from 1″ to 3″ (6 sources);
2) relatively compact ones with typical sizes of 0.″5 and double structure (9 sources);
3) relatively compact ones with typical sizes of 0.″5 and complex structure (6 sources).

Objects from groups 2 and 3 as well as the full list of objects in our sample will be described in subsequent papers. In this paper we focus on the first group i.e. on the objects possessing similar sizes to classical CSSs, yet less luminous[3]. Further observations have been made using MERLIN at 1.6 GHz in "snapshot" mode of six sources from the first group to make calculation of components' spectral indices possible. Again six MERLIN telescopes were used. A typical $u-v$ coverage accomplished in those observations is shown in Fig. 2.

[3] Three of them also belong to F2001 sample.

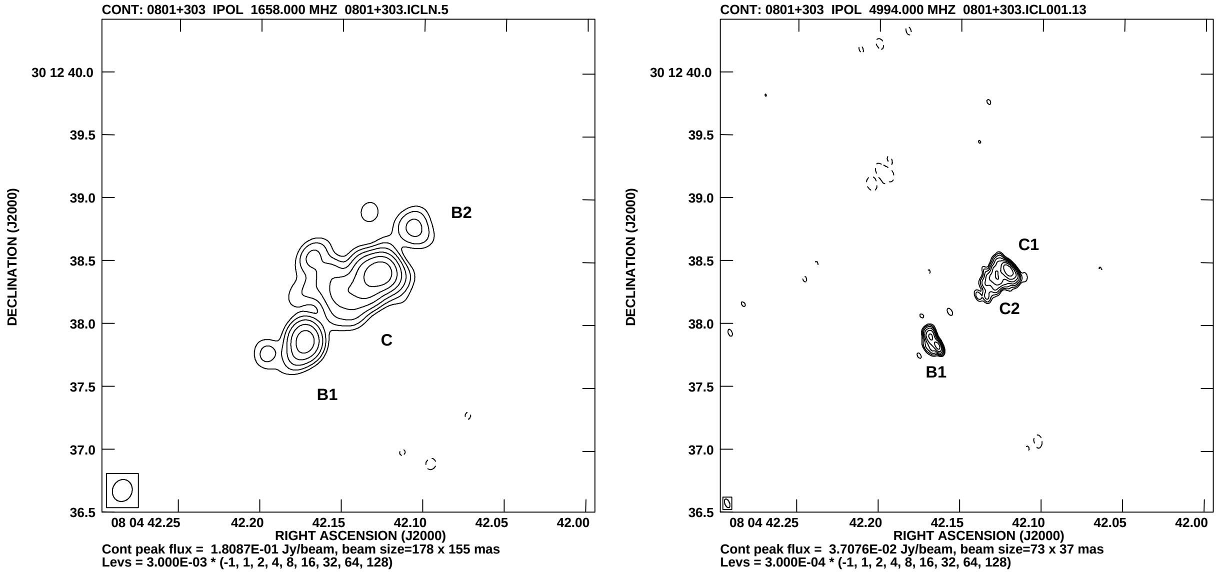

Fig. 3. MERLIN maps of 0801+303 at 1.6 GHz (left) and 5 GHz (right).

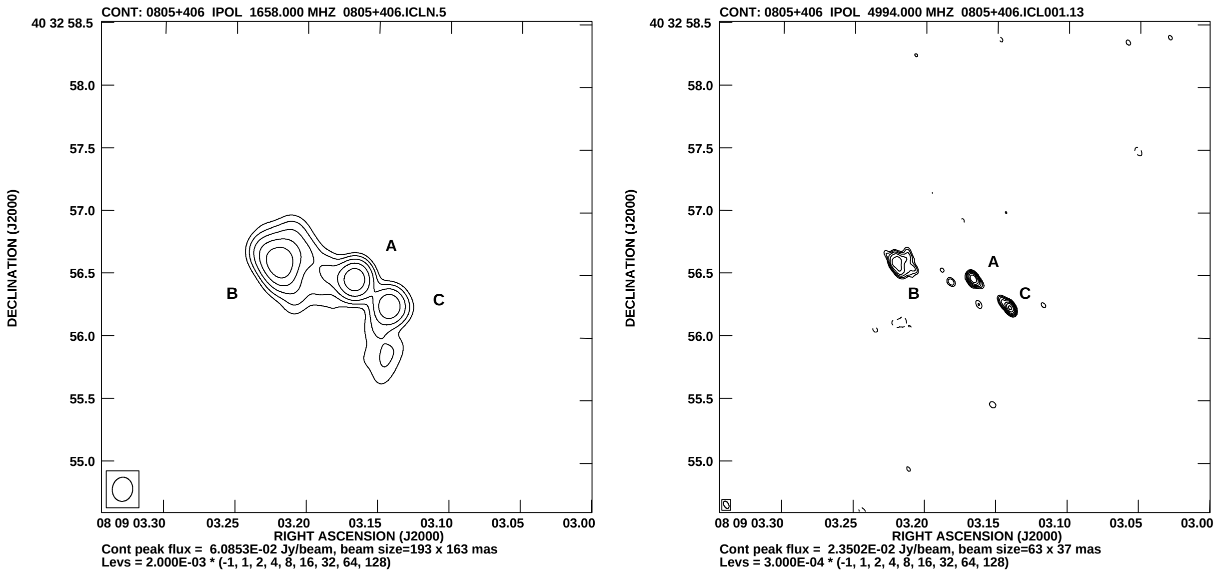

Fig. 4. MERLIN maps of 0805+406 at 1.6 GHz (left) and 5 GHz (right).

Here we present the observations of five sources (see Table 1) from the first group because the data for the sixth source (1236+327) were corrupt. Initial amplitude calibration was derived from daily observations of the unresolved source OQ208 giving a calibration error of <5% in flux density. The preliminary data reduction including phase-referencing was made using the AIPS-based PIPELINE procedure developed at JBO. The phase-calibrated images created with PIPELINE were refined in AIPS using several cycles of self-calibration and – in case of 1.6 MHz observations – amplitude self-calibration was applied at the end. The corrected data were mapped with IMAGR and the final maps are shown in Figs. 3 to 7. The lowest contour represents roughly a 3σ level.

We measured the flux densities of the components labelled on those maps and arrayed the results in Table 2. For the 3 targets also observed by F2001 (0805+406, 1201+394, 1233+418) we quoted their 4.86 GHz VLA measurements of respective components in the third column of that table. The differences in the 4.86 GHz flux densities measured with the VLA and MERLIN are attributed to the sparse $u-v$ coverage attained by MERLIN during the observations in snapshot mode. As a result, some flux pertinent to extended structures is missing on our 5 GHz maps. For calculation of the spectral indices (see Table 2) we used therefore VLA (A-conf.) 4.86 GHz fluxes taken from F2001 (when available) instead of those derived from our MERLIN maps.

1201+394 has clearly unbeamed lobes and its redshift is known; therefore we estimated the angular sizes θ_x, θ_y from the 1.6-GHz maps using the JMFIT program from the AIPS package and based on these values the physical parameters of the lobes were found using formulæ from Miley (1980). The results are shown in Table 3. The calculations of physical parameters were made for deceleration parameter $q_0 = 0.5$ which is used throughout this paper.

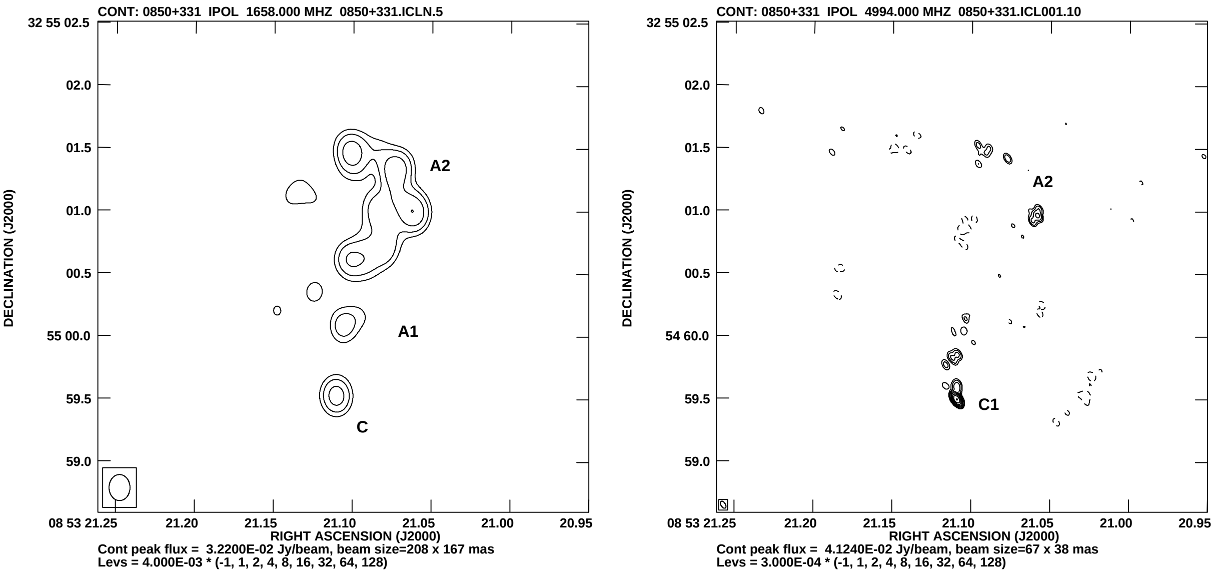

Fig. 5. MERLIN maps of 0850+331 at 1.6 GHz (left) and 5 GHz (right).

4. Notes on individual sources

0801+303. This radio source is identified with a QSO of redshift $z = 1.446$ (Hewitt & Burbidge 1989). The 1.6-GHz observation reveals a triple structure. The central, brightest component C is a core and the two structures B1 and B2 straddling it are lobes. The B1 lobe is much brighter than B2 (Fig. 3, left panel). The 5-GHz map shows a double structure of the source: the B1 lobe and more complex structure of the central component. The element C seen on the 1.6-GHz map is split here into two components: C1, which is probably the actual core, and C2, which is a part of the jet (Fig. 3, right panel). The spectrum of the component C is the flattest in the part identified with C1 and becoming steeper towards C2. The spectrum of component B1 is steep and the component B2 has presumably even steeper spectrum; it does not appear on the 5-GHz map at all.

0805+406. This source is an unconfirmed quasar (a "blue object") of unmeasured redshift (Gregorini et al. 1998; Vigotti et al. 1999). The map resulting from the 1.6-GHz observation shows a triple structure of the source. The brightest component C is a core, the A component is a part of the jet structure directed towards us and the B component is a lobe (Fig. 4, left panel). A triple structure of the source appears also on the 5-GHz map. Components C and A are compact and have higher luminosity than more extended component B (Fig. 4, right panel). The spectrum of component C is flat and its spectral index amounts to $\alpha = 0.26$. Also the component A has a rather flat spectrum ($\alpha = 0.46$) and only the component B is featured by a truly steep spectrum ($\alpha = 0.71$). That means the source is clearly a core-jet-lobe structure. Another confirmation of this comes from F2001; their maps additionally show a diffuse western component which may be related to the (hidden) counter-jet.

Table 2. Flux densities of sources' principal components.

Source/ component		Flux density [mJy]			Sp. index
		1.6 GHz	5.0 GHz	4.9 GHz	
		MERLIN		VLA	
0801+303	C	455.5	145.0		
	B1	118.3	40.9		
	B2	24.1			
0805+406	C	46.4	28.9	34.9	0.26
	A	77.6	26.6	47.3	0.46
	B	136.1	39.4	63.5	0.71
0850+331	C	23.0	47.2		
	A1	19.3	5.1		
	A2	194.3	14.3		
1201+394	B1	224.7	48.4	104.6	0.71
	B2	120.4	9.6	59.4	0.66
1233+418	C	281.5	98.5	141.5	0.64
	A	254.7	28.7	97.5	0.89

0850+331. There is no optical identification of this source (McMahon et al. 2002) so we do not know either its magnitude or redshift. The 1.6-GHz map shows the very complex structure of the source. The brightest component C is a core and structures A1 and A2 are fragments of a jet but the A1 component has lower radio emission than component A2. The brighter elements of A2 structure presumably represent the part of the jet seen at a smaller angle to the line of sight and so more Doppler-boosted (Fig. 5, left panel). The 5-GHz map also shows a complex structure of the source. The component C seen on the 1.6-GHz map, here falls apart into small elements which, again, seem to be fragments of the wiggling jet, except component C1 which is probably the actual core. We can hardly see the component A1 and the structure A2 also consists of a few small elements (Fig. 5, right panel).

1201+394. This source is identified with a radio galaxy of redshift $z = 0.445$ (Wan & Daly 1996). The 1.6-GHz map shows a symmetric, double structure of the source. The two extended components B1 and B2 are lobes but the lobe B1 has stronger radio emission (Fig. 6, left panel). The 5-GHz map shows the same symmetric, double structure with two lobes B1 (also brighter) and B2 (Fig. 6, right panel). The spectra of the lobes are steep and their spectral indices amount to $\alpha = 0.71$ for

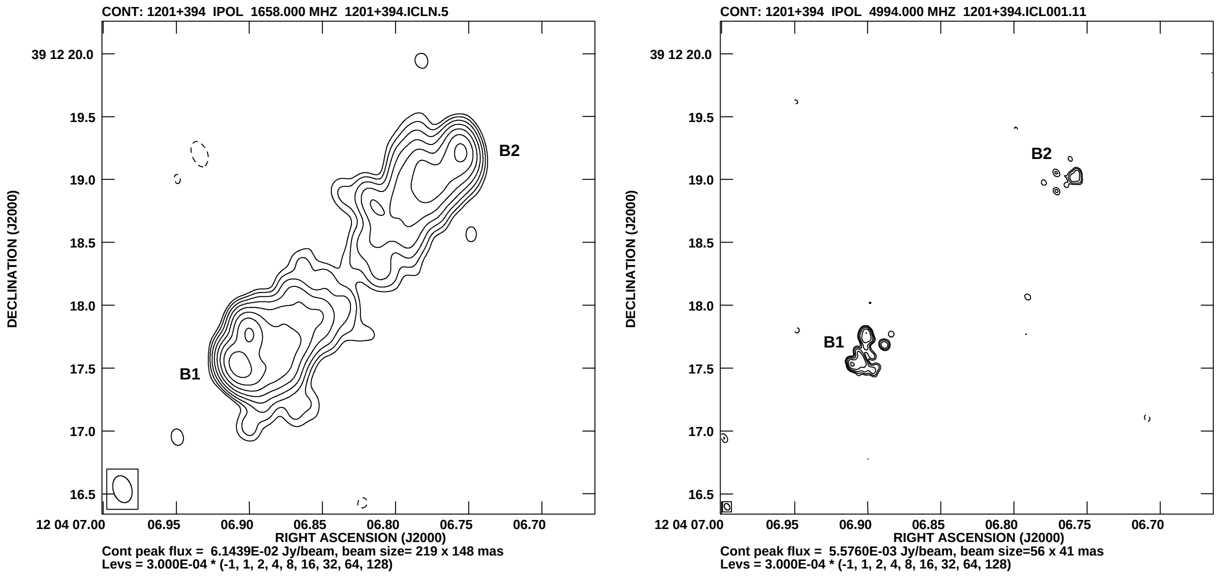

Fig. 6. MERLIN maps of 1201+394 at 1.6 GHz (left) and 5 GHz (right).

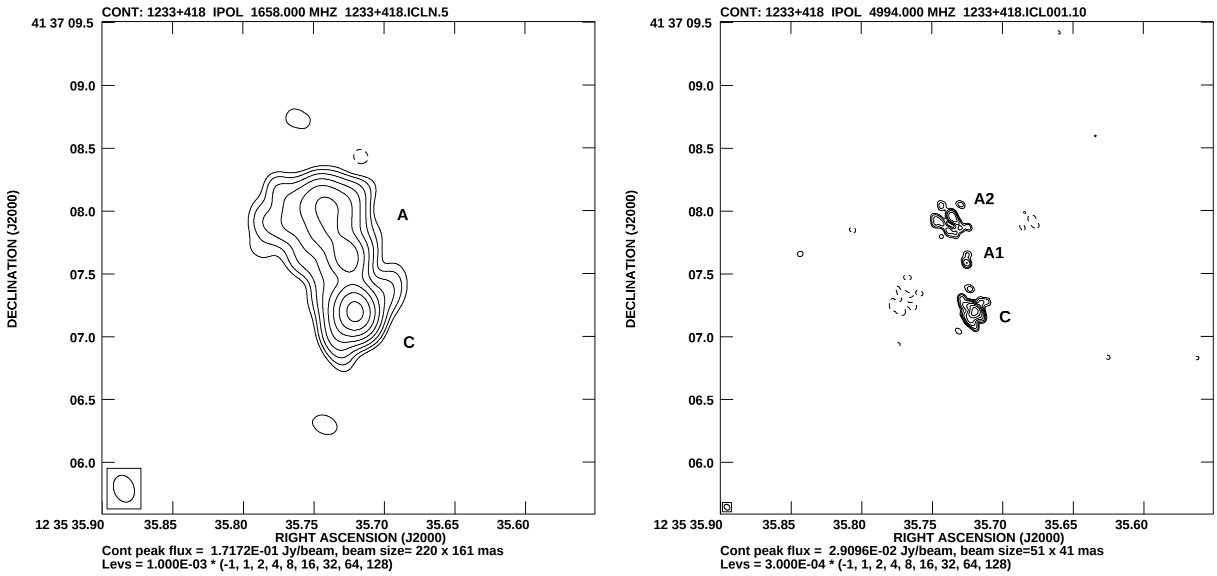

Fig. 7. MERLIN maps of 1233+418 at 1.6 GHz (left) and 5 GHz (right).

B1 and $\alpha = 0.66$ for B2. Physical parameters for both lobes are shown in Table 3. 1.6 GHz luminosities were calculated based on fluxes derived from our MERLIN maps; 5 GHz luminosities were calculated based on fluxes taken from F2001.

1233+418. This source is identified with a radio galaxy redshifted to $z = 0.25$ (Murgia et al. 1999). The 1.6-GHz map shows a core-jet structure; the source consists of two components: the core (component C) and an elongated jet structure (component A). Emission from the jet fragment lying closer to the core is high and it fades along the jet structure (Fig. 7, left panel). The 5-GHz observation shows a triple structure of the source. The brightest component C is probably a core. The jet component A is split here into two elements A1 and A2 (Fig. 7, right panel). All the components have steep or very steep spectra: the spectral index of the component C is $\alpha = 0.64$ and the spectral index of the component A amounts to $\alpha = 0.89$.

5. Discussion

New MERLIN 1.6 and 5-GHz maps show many details of the structures of weak CSS sources. None of these have both jets visible – most of them consist of a core, one-sided jet and sometimes a lobe. Jets of 0850+331 and 1233+418 have quite complex structures. There are no hotspots in the lobes of these sources although the lobes in 1201+394 are edge-brightened as in FRIIs. For all principal components of the 3 sources belonging both to our and F2001 samples we calculated the spectral indices. Cores have been found for four sources: 0801+303, 0805+406, 0850+331 and 1233+418. Three objects – two quasars and one radio galaxy – follow a division in radio morphology similar to that for LSOs and CSSs from the 3CRPW sample: galaxies are simple doubles whilst quasars show triple or complex structures. The fourth object, a radio galaxy 1233+418, is an exception – it shows an

Table 3. Physical parameters of the lobes of 1233+418.

Lobe	θ_x	θ_y	$L_{1.6\ \mathrm{GHz}}$	$L_{5\ \mathrm{GHz}}$	B_{me}	u_{me}	u_{tot}
	[mas]		[$10^{25}\,h^{-2}$ W Hz^{-1}]		[10^{-3} G]	[10^{-9} erg cm^{-3}]	[10^{58} erg]
B1	449	318	5.70	2.66	0.143	1.89	0.216
B2	705	249	3.06	1.51	0.103	0.977	0.171

asymmetric structure with a core and one-sided jet. (The remaining 5th object has no optical identification.) With an exception of 1201+394 all sources are moderately beamed.

The symmetric, double structure of 1201+394 and absence of a visible core indicate that this source lies almost in the sky plane so the calculated projected linear size – $l = 10.1h^{-1}$ kpc – is probably close to the physical size. 1201+394 is therefore MSO-type.

Because of the apparent lack of beaming in this source plus the fact we know its redshift and consequently the luminosity, we checked how this object would fit into the Fanaroff–Riley classification scheme (Fanaroff & Riley 1974). To this end we calculated the spectral index between 365 and 1400 MHz using the 365-MHz flux density from the Texas catalogue (1343 mJy). We found that $\alpha^{1.4\ \mathrm{GHz}}_{0.365\ \mathrm{GHz}} = 0.78$ is quite consistent with $\alpha^{4.85\ \mathrm{GHz}}_{1.4\ \mathrm{GHz}} = 0.85$ so using both of them and assuming that the indices remain valid down to 178 MHz we estimated the 178-MHz flux to be 2359 mJy or 2723 mJy respectively. The mean value derived from the above figures yields $L_{178\mathrm{MHz}} = 6.45 \times 10^{26}\,h^{-2}$ W Hz^{-1}. According to Fanaroff & Riley, the boundary value of $L_{178\mathrm{MHz}} \approx 3 \times 10^{25}\,h^{-2}$ W Hz^{-1} indicates the division of large-scale objects into two types: the FRII sources, which are beyond the luminosity boundary, and FRI sources which lie below. Our estimate is more than an order of magnitude higher than that dividing luminosity and indicates that indeed 1201+394 belongs to the FRII class.

Ledlow & Owen (1996) found that the radio luminosity of the FRI/FRII divide varied with optical luminosity. For a mixed sample of sources the dividing luminosity at 1.4 GHz is around $1.4 \times 10^{24}\,h^{-2}$ W Hz^{-1} for $M_R = -21.2$ which is the case of the galaxy identified with 1201+394. The rest frame radio luminosity of 1201+394 at 1.4 GHz is $1.2 \times 10^{26}\,h^{-2}$ W Hz^{-1} and so the source is again expected to be an FRII.

Fanti et al. (1995) and Readhead et al. (1996) using self-similar models predict that the luminosity is expected to decrease rapidly with size as the source evolves. O'Dea & Baum (1997) also show that a strong decrease in luminosity with size is expected as CSS sources evolve into LSOs and so 1201+394 might become an FRI-type object in the future. On the other hand this conjecture seems to be unlikely taking into account the clear FRII-like morphology of 1201+394 (an edge brightened double lobed structure). Self-similar evolution would result in the source maintaining the same morphology as it evolved. It is only for a flat external density profile that a source might be expected to maintain or increase in luminosity as predicted for GPS sources (Snellen et al. 2000) and so rather special conditions are required for the source to stay as an FRII. To add to the confusion, Zirbel (1997) found that FRI sources tend to be in richer groups than FRIIs and so may be in a flatter external density profile. Clearly the evolution of these sources is uncertain and further work on the lower luminosity CSSs is required.

6. Conclusions

MERLIN has been used to survey a sample of 60 weak Compact Steep Spectrum sources. This paper deals with five relatively large (arcsecond scale) sources. According to the evolutionary scheme compact doubles or, broadly speaking, CSOs are the progenitors of the extended doubles (Phillips & Mutel 1982; Carvalho 1985) and the CSS sources form an evolutionary link between those most compact/youngest objects and the classical double FRIIs. All CSS sources known so far have high radio luminosities and the radio structures of those which are unbeamed have FRII structures. It seemed reasonable to suspect that the lower radio luminosity CSSs could be the progenitors of less luminous FRI objects. Our investigations of a new sample of weak CSS sources were motivated by the above-mentioned view. The triple or double structures of the five CSS sources and the presence of one-sided core–jet structures indicate they are more similar to FRII objects than FRIs. The radio structure of 1201+394 is also similar to the structure of FRII object because of edge-brightening of the lobes. The remaining four sources seem to be moderately beamed. Their structures consist of a core and one-sided jet. None of these sources have counter-jets. This means that the low luminosities of these sources are not a consequence of a lack of significant Doppler boosting. We claim, therefore, they constitute a new class of "weak" CSS sources.

Acknowledgements. MERLIN is a UK National Facility operated by the University of Manchester on behalf of PPARC.

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Part of this research was made when MK stayed at JBO and received a scholarship provided by the EU under the Marie Curie Training Site scheme.

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