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A Population Study of Faint Compact Steep Spectrum Radio Sources: Self-Similar Growth

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Abstract: The main topic of this contribution is the investigation of the morphological self-similarity of the growth process during the gigahertz peaked spectrum (GPS) and compact steep spectrum (CSS) phase of evolving radio galaxies. By investigating a new sample of faint CSS radio sources we establish that self-similar evolution must hold for peaked spectrum sources over a wide range of luminosities as well as physical sizes. Thus, we argue that self-similarity should be regarded as an essential, intrinsic characteristic of the growth process of young radio sources, and be treated as such, and not merely as a supplementary constraint for evolution models.

Keywords: radio continuum: galaxies — galaxies: active — galaxies: evolution

1 Introduction: Self-Similar Growth of Young Radio Sources

The youthfulness of gigahertz peaked spectrum (GPS) radio galaxies has been clearly confirmed. The measurements of the outward motion of hot spots found for several GPS radio galaxies provide the best direct evidence for their very young age (e.g. Owsianik & Conway 1998; Tschager et al. 2000). Since it is not (yet) possible to measure the outward motion of compact steep spectrum (CSS) source hot spots, other means are necessary to establish an evolutionary link between GPS and CSS sources and construct models for this early phase of radio source evolution. Characteristics common to both classes of objects were investigated and correlations were found to exist between peak flux density, peak frequency, and the overall angular size (Snellen et al. 2000). These correlations reveal an underlying evolutionary link: assuming the spectral peak is due to synchrotron self-absorption these correlations demonstrate that the ratio between the overall angular size and the angular size of the dominant radio components producing the peaked spectrum is constant throughout the different samples of GPS and CSS sources, suggesting that peaked spectrum sources evolve in a *self-similar* way.

As part of our population study of faint CSS radio sources, we investigate how the members of our new faint sample relate to their bright relatives and to the bright and faint GPS radio galaxies from a purely radio evolutionary perspective. The sample is presented below in Section 2. Section 3 deals with the observational part. In Section 4 we extract the new results, and discuss their impact on existing understanding in Section 5.

2 The New, Faint Sample of CSS Radio Sources

Using the WENSS, NVSS, and FIRST radio surveys, we have constructed a sample of faint CSS sources to fill in the unexplored segment of the peak flux density–peak frequency plane. Unresolved radio sources with a flux density >250 mJy were selected from WENSS at 325 MHz, and correlated with the NVSS catalogue at 1.4 GHz to select sources with an optically thin radio spectrum of $\alpha < -0.5$ ($S \propto \nu^{\alpha}$). This selection on spectral index is the same as used by Fanti et al. (1990) for selecting bright CSS sources. We then correlated the sample of steep spectrum radio sources with the 1.4 GHz FIRST catalogue to select only those sources with a deconvolved size of $<2''$. Our working sample — restricted to $37° < \mathrm{dec} < 43°$ and $8^{\mathrm{h}} < \mathrm{RA} < 17^{\mathrm{h}}$ — comprises 88 sources. Our sample is a median factor of 10–30 fainter at 5 GHz than existing bright CSS samples.

3 The Observations

3.1 VLA-A 74 MHz Observations

The goal of these VLA observations was to obtain low frequency total flux density measurements and, thus, allow the detection of spectral turnovers occurring around 100 MHz. The peak frequency and peak flux density of a CSS spectrum are fundamental quantities: their knowledge is essential for modelling the evolution of radio sources at early stages in their life.

These non-standard observations required very careful planning in order to optimise the outcome. We needed to maximise the number of detectable targets, so we had

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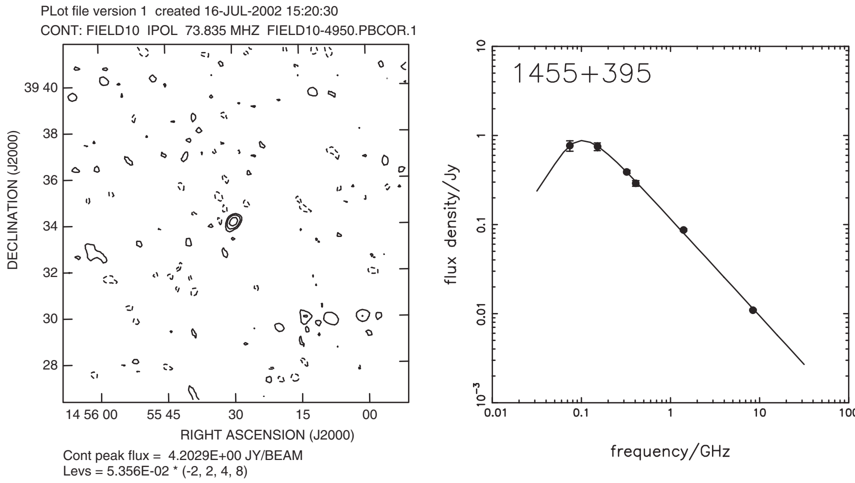

Figure 1 Example for 74 MHz data: image of faint CSS source J1455+3933 (left) and available spectral information with best fit (right).

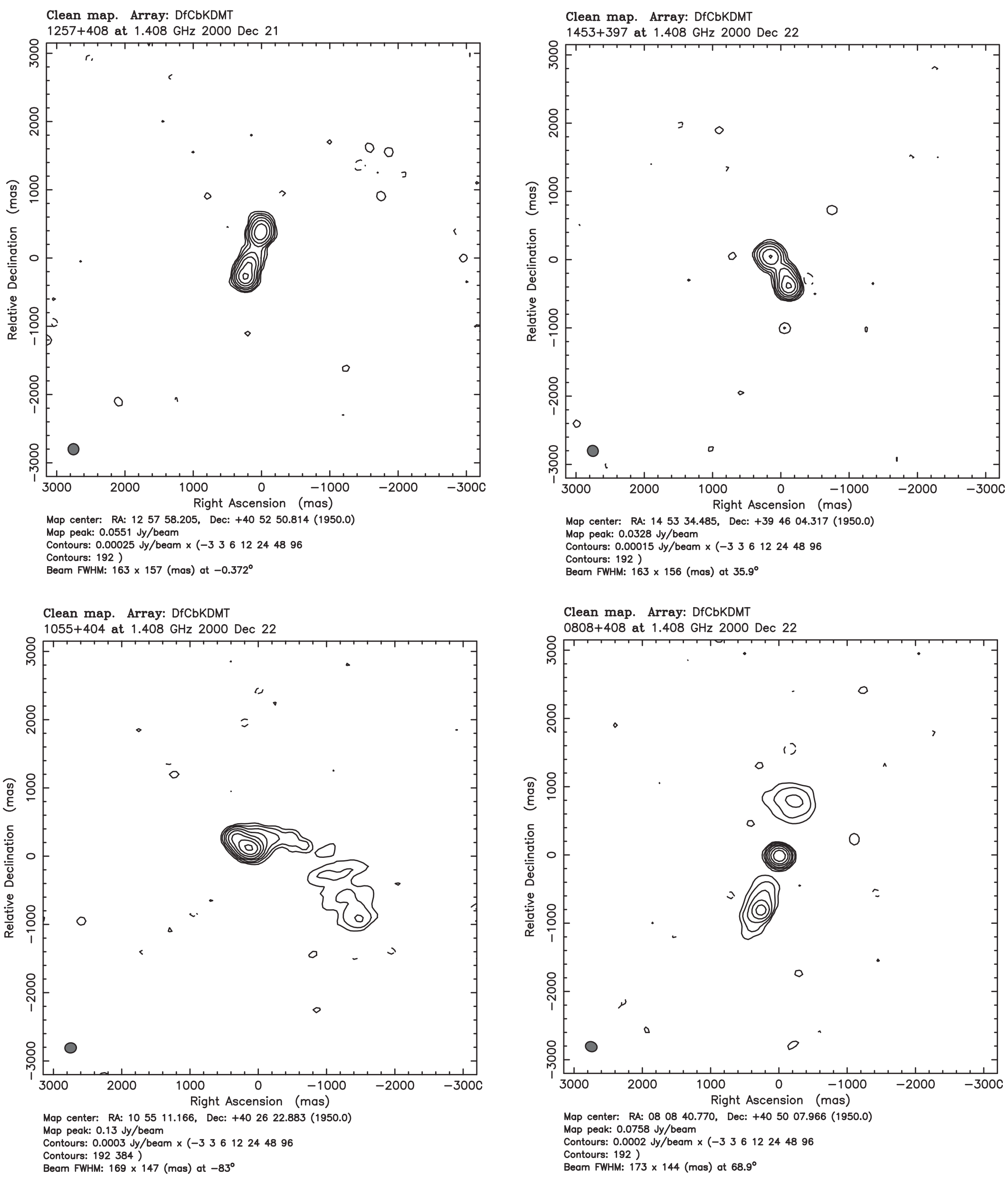

Figure 2 Four examples of MERLIN data: images used to determine morphological class and LAS. Objects shown are J1300+4036, J1455+3933, J0812+4041, and J1058+4010 (clockwise).

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to choose an observing mode working reliably at the highest possible correlator dump rate, excise RFI, handle bandpass smearing effects, keep sensitivity losses low, estimate ionospheric influence, and use imaging software under continuous development. More details about these data, their acquisition and reduction, quality assessment and subsequent handling for source extraction and spectral fitting will be provided and extensively discussed (W. Tschager et al., in preparation). However, it is worth noticing that the size of the primary beam FWHP of the 25 m VLA antennas is 700′ marking the area which needs to be imaged, whereas the synthesised beam of the VLA in A configuration at 74 MHz is approximately 24″. The choice of the fitting function depends mostly on the availabilty of spectral information: we adopted a function used by Moffet (1975). This function models peaked spectra using four parameters: S_{peak}, ν_{peak}, and the low and high frequency spectral indexes.

Using an area of reliable source extraction as large as the primary beam we were able to determine spectral turnovers for 49 objects of the working sample. For the remainder we could set limits on the peak position. Figure 1 shows an example of an extracted source and its radio spectral identikit.

3.2 MERLIN 1.6 GHz Observations

Using MERLIN in short-scan mode and phase referencing at 1.6 GHz, we observed a sample of 15 faint CSS sources in order to classify them morphologically, and to determine their overall angular extension, hereafter called largest angular size (LAS). The 15 objects were selected from the working sample on expected compact double morphology, resolution, correlated flux density, and redshift availability criteria. The observing time was chosen to obtain an image noise of about 0.20 mJy/beam. Figure 2 shows examples for MERLIN images. The two upper panels show objects clearly exposing their symmetric double nature. The morphology of the object in the bottom right panel shows symmetric structure with a bright central component. We did not allow objects with core–jet-like morphology (e.g. Figure 2, bottom left panel) affected by projection effects to enter and thus contaminate our faint CSS radio galaxy sample. Two objects out of 15 showed core–jet morphology and had to be excluded from further analysis.

4 Discussion

Important constraints on physical models of radio sources come from combined *spectral* and *morphological* studies of peaked spectrum sources.

The 1.6 GHz MERLIN observations provide us with images of the objects under investigation. We model-fitted the brightness distribution and determined the relative positions of the furthermost apart components and used this to estimate the LAS of each object (see Table 1).

The 74 MHz VLA observations allowed us to obtain, or at least to limit, peak flux density S_{peak} and peak frequency ν_{peak} for individual objects. Columns 3 and 4, and 7 and 8 of Table 1 list those two quantities for 13 objects observed with MERLIN.

Table 1. Peak quantities from the 74 MHz VLA observations and LAS measurements from MERLIN observations*

Name	LAS (mas)	S_{peak} (Jy)	ν_{peak} (GHz)
J0812+4041	770	>0.680	<0.151
J0931+4149	1780	>3.940	<0.074
J1028+3844	1790	3.674	0.064
J1235+4137	940	>3.660	<0.074
J1300+4036	760	>1.030	<0.151
J1320+3744	1060	>2.290	<0.151
J1455+3933	500	0.876	0.102
J1527+4147	1020	0.606	0.142
J1605+4135	1530	0.618	0.224
J1614+3944	1140	0.946	0.124
J1644+3739	700	0.469	0.135
J1645+4010	385	>1.190	<0.074
J1655+3916	1450	0.564	0.112

*For objects for which the spectral turnover could not be determined, limits could be set from the lowest frequency at which the flux density has been measured.

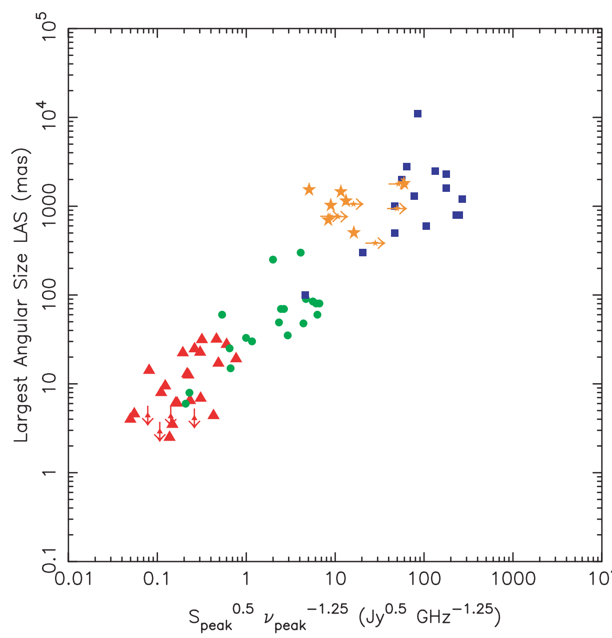

Figure 3 Correlation between source size and component size of GPS and CSS radio galaxies indicating self-similar evolution. The different symbols represent faint GPS (red triangles), bright GPS (green circles), faint CSS (orange stars) and bright CSS (blue squares) sources. Limits are represented with a combined symbol showing the symbol corresponding to one of the four groups and an arrow. The additional data used in this diagram come from Snellen et al. (2000).

Based on considerations of synchrotron self-absorption theory (Kellermann & Pauliny-Toth 1981) peak flux density and peak frequency combine in a way to form a quantity which is directly related to the angular component size: $\theta \propto S_{\text{peak}}^{0.5}\ \nu_{\text{peak}}^{-1.25}$. The diagram showing this quantity plotted against LAS is reproduced in Figure 3. Because

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both quantities — LAS, as well as $S_{\rm peak}^{0.5}\,\nu_{\rm peak}^{-1.25}$ — have approximately identical redshift dependence. Figure 3 shows an intrinsic correlation between the overall source size and the size of the individual components. Self-similarity holds over a wide range of luminosities and physical sizes, even without being able to clearly discriminate between objects belonging to different luminosity classes.

5 Conclusion

The conclusions we can draw from this investigation are twofold:

- Firstly, the faint CSS radio sources fill in a formerly empty area on the diagram shown in Figure 3, located between the bright GPS and bright CSS sources. This location of the newly obtained data points strongly supports self-similarity being an important characteristic of the growing process, which holds over an extended time interval during which the source grows from parsec scale to host galaxy size. However, it is not clear which mechanisms act together in order to create such a tight correlation, especially in view of the radical change in luminosity evolution GPS and/or CSS radio sources apparently must undergo (Snellen et al. 2000, 2003).
- Secondly, current modelling of radio source evolution uses self-similarity empirically in order to add a supplementary constraint between exponents of various power laws describing the time dependence of the growth processes of individual components and the whole source, and the density profile (e.g. Snellen et al. 2002; Perucho & Martí 2003). We are however convinced that more realistic evolution models for young radio sources should deliver self-similarity as a consequence of the necessary assumptions, and not simply use it as a boundary condition for the models.

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