The kpc-scale radio source population

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Abstract

We are conducting a multi-wavelength (radio, optical, and X-ray) observational campaign to classify, morphologically and physically, a sample of 55 flat-spectrum radio sources dominated by structure on kpc-scales. This sample contains 22 compact-medium-sized symmetric object candidates, a class of objects thought to be the early stages of the evolution of radio galaxies. The vast majority of the remaining objects have core-plus-one-sided-jet structures, half of which present sharply bent jets, probably due to strong interactions with the interstellar medium of the host galaxies. Once the observational campaign is completed, we will constrain evolutionary theories of radio galaxies at their intermediate stages and possibly understand the physics of the hypothesized narrow line region in active galactic nuclei, given our advantageous statistical position.

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1 Introduction

Augusto et al. (1998) conducted the first systematic search for flat-spectrum radio sources with dominant structure on 90–300 mas angular scales (0.2–2 kpc linear scales at $z > 0.2$): gravitational lenses and compact-/medium-sized symmetric objects (CSO/MSOs), in particular. The selected sample of 55 such radio sources is described in Section 2. In Section 3 we discuss results, from this sample, pertaining to CSO/MSOs. These are symmetric double or triple sources, with sizes smaller than 15 kpc (e.g., Readhead et al. (1996a,b)). CSOs ($< 1$ kpc; aged $10^3–10^4$ years) and MSOs (1–15 kpc; aged $10^5–10^6$ years) present compact lobes ($< 20$ mas) having, overall, $\alpha < 0.75$ ($S_\nu \propto \nu^{-\alpha}$), and are probably the precursors of the large radio galaxies which they resemble. VLBI surveys have unveiled a significant population of eighteen 0.01–0.1 kpc CSOs, which constitute $\sim 6\%$ of a complete flux-limited sample of 293 flat-spectrum radio sources (CJF; Taylor et al. (1996a,b)). In the last section, we mention the potential of our sample in terms of understanding the hypothesized kpc-sized narrow-line region (NLR) in active galactic nuclei (AGN; e.g., Robson (1996)).

2 The Sample

Starting from the total of $\sim 4800$ sources in the Jodrell-VLA Astrometric Survey (e.g., Patnaik et al. (1992)) and the first part of the Cosmic Lens All Sky Survey (e.g., Browne et al. (1998)), Augusto et al. (1998) have first established a parent sample containing 1665 strong ($S_{8.4\text{ GHz}} > 100$ mJy), flat-spectrum ($\alpha_{1.4}^{4.85} < 0.5$) radio sources. From this sample, 55 sources were selected in accordance with an extra resolution criterion as described in Augusto et al. (1998). The completeness of this latter sample depends on both the separation and the flux density ratio of the components of each radio source in the parent sample. Unresolved single-component sources would be rejected.

With regard to the spectral properties of the 55-source sample (Augusto et al., 1998), 45 sources have power-law radio spectra down to the lowest measured frequency (which is 365 MHz for 31 of the objects and 151 MHz for 14 of them), 3 sources present complex spectra, and 7 have spectra peaked at $\sim 300$ MHz. It is relevant that only two of the fourteen 0.2–1 kpc CSO candidates in Table 1 can be classified as GHz-Peaked Spectrum Sources (GPSs), peaking at $\sim 0.5–10$ GHz. From the same table, only three CSO candidates have a peak at $\sim 300$ MHz. Hence, the statement “every CSO is a GPS source” (Bicknell et al., 1997) seems incorrect.

There are two main populations of radio sources uncovered on kpc scales by
Augusto et al. (1998). These consist of 22 CSO/MSOs and 30 core-plus-one-sided-jet (CJ) sources.

It is unfortunate that, for the vast majority of the 55 sources, information on any optical counterparts comes only from the Palomar Observatory Sky Survey (POSS) plates. Using POSS identifications, we have compared the abundance of blue stellar objects, red stellar objects, galaxies, and empty fields for the 55-source and the parent 1665-source samples. We have found that the fraction of blue stellar objects in the 55-source sample is half of the fraction of such objects in the 1665-source sample. Furthermore, the fraction of galaxies is three times larger in the 55-source sample. For the other two identification types examined, the results are comparable in both samples (one-third are empty fields and one-eighth are red stellar objects).

Thus, it seems that selecting kpc structure in the radio leads to selecting structure in the optical. There seems to exist a global bias against radio/optical unresolved sources. As regards redshift information, we have \( <z> \sim 0.7 \) for the 19 out of the 55 sources that have spectroscopic data. The faintest sources (namely, the 18 sources that correspond to POSS empty fields) still need redshift determinations, suggesting that the average redshift of the sample will increase. Unfortunately for the discussion on this paper, very few of the CSO/MSOs have measured redshifts (Table 1).

3 Compact/Medium Symmetric Objects

The sample of 22 CSO/MSO candidates found by Augusto et al. (1998) — Table 1 — contains 9 certain CSOs and two certain MSOs. Most likely, six of the remaining sources are MSOs, leaving five sources that could be either. The fact that for sources at \( z > 0.2 \) we have selected the ones dominated by structures on 0.2–2 kpc scales suggests a bias against the population of MSOs within our sample. Since most flat spectral-index sources will consist of a pair of compact lobes (plus, possibly, a core), they will be included in our sample only if their sizes are \( \leq 0\farcs3 \). Much larger sources (like B0824+355 in Table 1), consisting of very weak jets and low surface brightness extended lobes, are probably the exception. We believe that most MSOs in our sample will have sizes of \( \sim 1–2 \) kpc, much like the confirmed MSO B0205+722 (Table 1). Note that even if we allow for sources with \( z < 0.2 \), this will only favour the increase in number of small MSOs, since for the same angular dimensions seen, a lower redshift will translate into a smaller linear size.

Augusto et al. (1998) have shown that the 55-source sample includes every CSO from the 1665-source parent sample having a 160–300 mas separation (0.4–1 kpc for sources at \( z > 0.2 \)) between compact components with a flux-
density ratio of 7:1 or smaller. CSOs containing compact lobes with similar flux-density ratios are included in the sample down to a separation of 90 mas (0.2–0.6 kpc at z > 0.2). The key issue now is to review evidence for why virtually all CSOs present in the 1665-source parent sample are at most the 14 found by Augusto et al. (1998) among their 55-source sample. Typically, CSOs have weak cores (weaker than any of the lobes) and, hence, it is the lobes that are the ‘components’ that will go through the selection criterion of Augusto et al. (1998). It is very rare to find a CSO with lobes presenting flux density ratios greater than 7. In fact, there are not any of these cases among the 0.2–1 kpc CSOs in Table 1 or the eighteen 0.01–0.1 kpc CJF CSOs discussed here. Therefore, we believe that Augusto et al. (1998) have selected virtually all of the CSOs present in the 1665-source parent sample; these are shown in Table 1. In any case, for the discussion of this paper, we performed simulations (see below), which estimate the effects of the ‘resolution’ criterion on the CJF sample, before making any comparison between our CSO-fraction and that of the CJF. The simulations give results that are consistent with the ‘typical’ morphology of CSOs just presented.

Conservatively, taking a maximal number of 0.2–1 kpc CSOs as 14 (Table 1, including the sources classified as ‘question marks’) out of a parent sample containing 1665 sources, only ~ 0.8% of flux-limited samples seem to be such CSOs. It seems, then, that these are six times less common than 0.01–0.1 kpc CSOs (which constitute ~ 6% of CJF). Both the 0.2–1 kpc and the 0.01–0.1 kpc CSOs are dominated by components < 20 mas in size. Is the number difference due to luminosity evolution alone? Strong luminosity evolution takes place during the time that the 0.01-kpc scale CSOs grow to be 100-kpc scale radio sources (e.g., Readhead et al. (1996a [1])). Kaiser & Alexander (1997) have proposed a model in which the luminosity of double sources decreases proportionally to the square root of their size. If this relation applies continuously as the source evolves from the 0.01-kpc to the 100-kpc scale, then in the evolution from a 0.01–0.1 kpc to a 0.2–1 kpc CSO, size increases by a factor of ~ 10 and hence the luminosity decreases by ~ 3. Given that all CJF sources have S_{5\text{GHz}} > 350 \text{mJy} and, like the 55-source sample, have \alpha_{1.4}^{4.85} < 0.5, our flux-density criterion S_{8.4\text{GHz}} > 100 \text{mJy} allows a sampling ~ 3 times fainter, cancelling out the predicted luminosity evolution. Before rushing to other evolutionary explanations, we note that our selection process included a resolution criterion not present in CJF. Hence, we need to find out how many of the 18 CJF CSOs would remain in the CJF if it had an equivalent resolution criterion. The simplest way to do this is to use models fitted to the 18 CJF CSOs, expand the separation of the components by a factor of 10, and check whether they meet the criteria for inclusion in our sample. This will only give indicative results, of course. The models and maps are found in the literature from the VLBI surveys, except for three models that we crudely produced from the available maps.
Using the program FAKE in the Caltech VLBI package (Pearson, 1991), we have performed a test for the reliability of selection (details in Augusto et al. (1998)). Eleven out of the ‘order-of-magnitude-expanded’ 18 CJF 0.01–0.1 kpc CSOs would be in our sample. To contemplate the possibility that some of our 0.2–1 kpc CSOs might have been selected by a lucky combination of observational conditions, we also ran FAKE on the 14 such CSOs in Table 1. All of them are reliably in our sample.

The revised frequencies of CSOs are then \(\sim 0.8\%\) (14/1665) in our sample and \(\sim 4\%\) (11/293) in CJF. Since five of the fourteen 0.2–1 kpc CSO candidates in Table 1 could be >1 kpc MSOs, a conservative factor of \(\sim 5\) still remains between the abundance of CSOs in both samples. To explain this difference, we suggest evolution of the lobes in CSOs as they grow — self-similar growth of radio galaxies: the lobes start off as compact hot spots when 0.01–0.1 kpc apart and expand until they grow \(\sim 100\) kpc apart, as in normal radio galaxies. The number of 0.2–1 kpc young radio galaxies seems to be less than the number with sizes 0.01–0.1 kpc due to the resolution criterion used to select the 55-source sample in Augusto et al. (1998): only double (or triple) sources with compact (< 20 mas) components are in the sample. The extended lobes of Compact Steep Spectrum (\(\alpha > 0.5\)) radio sources, the dominant radio sources on 0.2–1 kpc scales, cannot be selected by the resolution criterion of Augusto et al. (1998).

4 Future

Once redshifts are determined for the remaining 36 of the 55 sources, we will not only classify CSO/MSOs correctly, according to their sizes, but also determine the linear (projected) sizes of the CJs. Most of these CJs might also show evidence for strong shocks in the NLR. Half of the CJs in the 55-source sample contain sharply bent jets that bend by more than 90\(^\circ\), in some cases more than once. This hints at strong interactions with the interstellar medium of the host galaxies. Altogether, the CSOs, MSOs, and CJs in our sample will give us clues about the composition and density of the NLR in galaxies because of their interactions with the NLRs of their hosts. Due to our good statistics, this might be a useful step forward towards understanding the standard model of AGN as a whole, and the NLR in particular.
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Table 1

The 22 compact/medium symmetric object (CSO/MSO) candidates found in the 55-source sample of Augusto et al. (1998). The linear size is calculated using $H_0=75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. For the vast majority of sources, without redshift information, formal classification is not possible. Nevertheless, independent of redshift, any object smaller than 175 mas is a CSO. Furthermore, assuming $z > 0.2$ for the remaining objects, angular sizes larger than 350 mas identify MSOs. Palomar Observatory Sky Survey (POSS) identifications are with galaxies (G), empty fields (EF), and blue or red stellar objects (BSO,RSO).

| Source B1950.0 | Angular size (mas) | Linear size (kpc) | Classification | POSS id. | z |
|---------------|-------------------|------------------|---------------|----------|---|
| 0046+316      | 300               | 0.09             | CSO           | G; 15$m$ | 0.015 |
| 0112+518      | 650               | (MSO)            |               |          |    |
| 0116+319      | 75                | 0.08             | CSO           | G; 16$m$ | 0.0592 |
| 0205+722      | 600               | 3                | MSO           | G; 18$m$ | 0.895 |
| 0225+187      | 225               | ?                |               |          |    |
| 0233+434      | 120               | CSO              | EF            |          |    |
| 0352+825      | 44                | CSO              | G; 15.5$m$    |          |    |
| 0638+357      | 400               | (MSO)            | EF            |          |    |
| 0732+237      | 175               | CSO              | EF            |          |    |
| 0817+710      | 225               | ?                | EF            |          |    |
| 0819+082      | 275               | ?                | RSO; 19.3$m$  |          |    |
| 0824+355      | 2000              | 11               | MSO           | RSO; 19.6$m$ | 2.249 |
| 1010+287      | 75                | CSO              | EF            |          |    |
| 1058+245      | 900               | (MSO)            | EF            |          |    |
| 1212+177      | 100               | CSO              | RSO; 20$m$    |          |    |
| 1233+539      | 240               | ?                | BSO; 19$m$    |          |    |
| 1504+105      | 110               | CSO              | ?; 16$m$      |          |    |
| 1628+216      | 800               | (MSO)            | ?             |          |    |
| 1801+036      | 1200              | (MSO)            | G; 17$m$      |          |    |
| 1928+681      | 120               | CSO              | BSO; 20.5$m$  |          |    |
| 1947+677      | 500               | (MSO)            | EF            |          |    |
| 2345+113      | 275               | ?                | G; 19$m$      |          |    |