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VLBI study of a sample of low-power compact symmetric objects

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Abstract. Compact symmetric objects (CSOs) are intrinsically compact extragalactic radio sources and are thought to represent the progenitors of classical radio galaxies. Several evolutionary models of the radio emission have been developed so far, but they mainly focus on the evolution of high-power jets. Low-power jets are more prone to instabilities than their high-power counterparts, and jet-medium interaction may decelerate or even disrupt the jet, preventing the formation of large scale structures. As a consequence, a large fraction of the energy of low-power jets is deposited in the host galaxy, and potentially impacts the distribution and kinematics of the ISM of the host galaxy for longer time than high-power jets.

In this paper, we present results on VLBI observations of a sample of low-power CSO candidates selected from the FIRST. These observations allow us to confirm their CSO nature by the study of their pc-scale morphology and spectral index distribution. Increasing the number of confirmed low-power CSOs is crucial for improving our knowledge of the evolutionary path of the radio emission and the influence the ambient medium may have on low-power jets at the beginning of their evolution.

1. Introduction

Compact symmetric objects (CSOs) are intrinsically compact extragalactic radio sources and represent the progenitors of classical radio galaxies. Several evolutionary models have been proposed to describe how the physical parameters (e.g. luminosity, expansion velocity, magnetic field) of high-power radio sources evolve as the relativistic jet propagates within the Interstellar medium (ISM) of the host galaxy and beyond (see e.g., Snellen et al. 2000). Weak jets are more prone to instabilities and seem to have a more individualised evolution scheme (Fig. 1; An & Baan 2012). The interaction of relativistic plasma with clouds of gas, or the mass loading by stellar winds may be able to decelerate and/or disrupt the jet even in presence of continuous supply of relativistic particles (e.g., Perucho et al. 2014). As a consequence, a large fraction of the energy of low-power jets is deposited in the host galaxy, and potentially impact the distribution and kinematics of the ISM of the host galaxy for longer time than high power jets. Increasing the number of confirmed low-power CSOs is crucial for improving our knowledge of the evolutionary path of radio emission and the influence of the jet on the host galaxy. To date, samples of low-power CSOs are contaminated by core-jet objects, whose size is not intrinsically compact, but it is foreshortened by geometrical effects. To circumvent this issue, we constructed a statistically complete sample of low-power CSOs from FIRST by making use of archival mas-resolution Very Long Baseline Interferometry (VLBI) observations at 1.4 GHz.

2. The sample

We constructed a sample of candidate CSOs selecting sources with a pc-scale two-sided structure in VLBI images at 1.4 GHz from the mJIVE-20 project (Deller & Middelberg 2014). The mJIVE-20 is a large project on the VLBA which uses filler time to systematically inspect a large sample of faint radio sources to identify any compact emission that may be present. The selection criteria applied for constructing the sample are: 1) sources with a well-resolved double structure in VLBI images, but unresolved in the FIRST survey; 2) the VLBI total flux density is consistent with the flux density from the FIRST, indicating no emission on scales between those sampled by VLBI and the resolution of the FIRST; 3) no flux density variability observed from the various epochs of the VLA Sky Survey (VLASS) within the uncertainties.

The final sample consists of 60 sources. Figure 1 shows the radio power vs linear size plot for extragalactic radio sources. The selected sources fall in the yellow region. Although optical photometry is available for many sources, information on the redshift (either spectroscopic or photometric) is known only for a bunch of them. For the sources without redshift information we computed the physical parameters assuming $z = 0.5$ and $z = 2.0$ (Fig. 2).

3. Radio observations

We performed deep VLBA observations at 5 GHz of 20 of the brightest sources (peak flux density at 1.4 GHz > 10 mJy/beam) in the sample to: i) determine the spectral index distribution and discriminate between steep-spectrum CSOs and core-jet blazars; ii) Pick up faint components

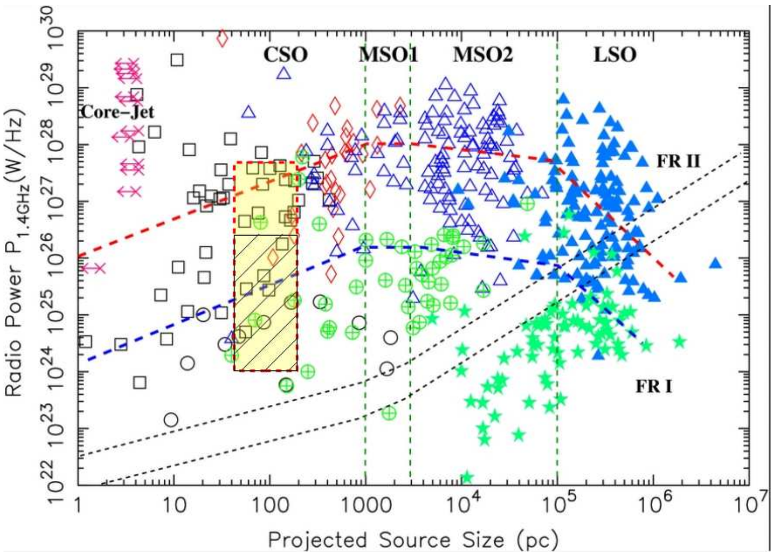

Fig. 1. Radio power vs linear size for extragalactic radio sources (adapted from An & Baan 2012). The yellow area shows the locus of the selected sources.

like extended lobes, undetected due to sensitivity limitation in earlier data, or core regions that are self-absorbed at 1.4 GHz. VLBA observations in C band were carried out between 2021 August and December in dual polarization and an aggregate bit rate of 2Gbps. Depending on the right ascension and declination of the target, observations are divided into 8 short scheduling blocks (from 4 to 5.5 hr each) in order to reduce slewing time and overheads.

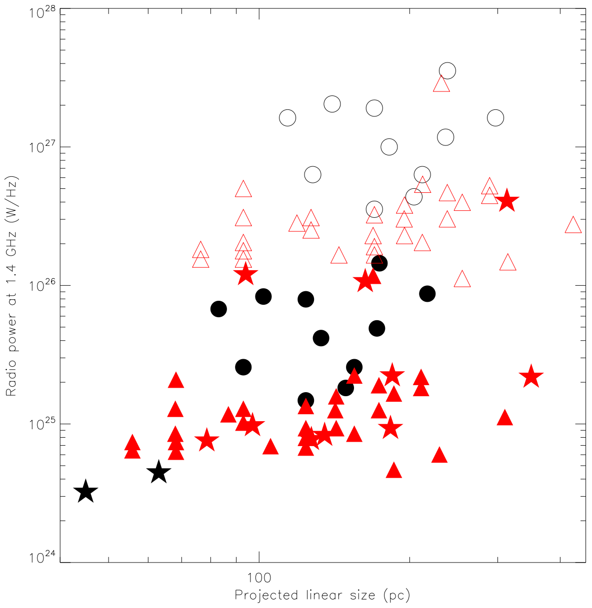

Fig. 2. The power-size plot for the candidate CSOs from our sample. Black circles/stars are the sources already observed at 5 GHz with VLBA (core-jet blazars have been removed), while the red triangles/stars are the remaining objects. Filled and empty symbols refer to values computed assuming redshift $z = 0.5$ and $z = 2$, respectively. Stars indicate objects with known redshift.

Calibration and data reduction were performed following the standard procedure described in the AIPS cook book [1] (see e.g. Orienti et al. 2020). Images were produced with the task IMAGR in AIPS. For the brightest sources (peak flux density $S_p > 5$ mJy beam^{-1}) the final images were produced after a few iterations of phase-only self-calibration.

For each target we retrieved the already calibrated datasets from the mJIVE-20 database [2]. Data have been imported into AIPS, bad data checked and flagged. After a few phase-only self-calibration iterations final images have been produced. For the brightest sources a final step of amplitude self-calibration with a solution interval of the scan length have been tried.

4. Preliminary results

The morphology and the spectral index distribution allow us to classify 12 sources as CSOs with two-sided steep-spectrum ($\alpha > 0.7$, $S \propto \nu^{-\alpha}$) structures, and 8 blazars with a steep-spectrum one-sided jet emerging from a flat-spectrum compact core (Fig. 3). In 3 CSOs we could detect the flat-spectrum core between the lobes, and 4 CSOs show significant flux-density asymmetry (flux ratio between the two lobes/hotsposts > 2). The radio power at 1.4 GHz and the linear size of the observed sources are in the range (3.2–87) $\times 10^{24}$ W/Hz (or up to 3.5×10^{27} W/Hz at $z = 2.0$), and 45–215 pc (or up to 300 pc at $z = 2.0$).

Our selection criteria should prevent the inclusion of blazars, but approximately 40 per cent of the 20 sources in the subsample considered here turned to have a core-jet structure. This fraction is compara-

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[1] `http://www.aips.nrao.edu/TEXT/PUBL/COOKBOOK.PDF`

[2] `https://safe.nrao.edu/vlba/mjivs/home.html`

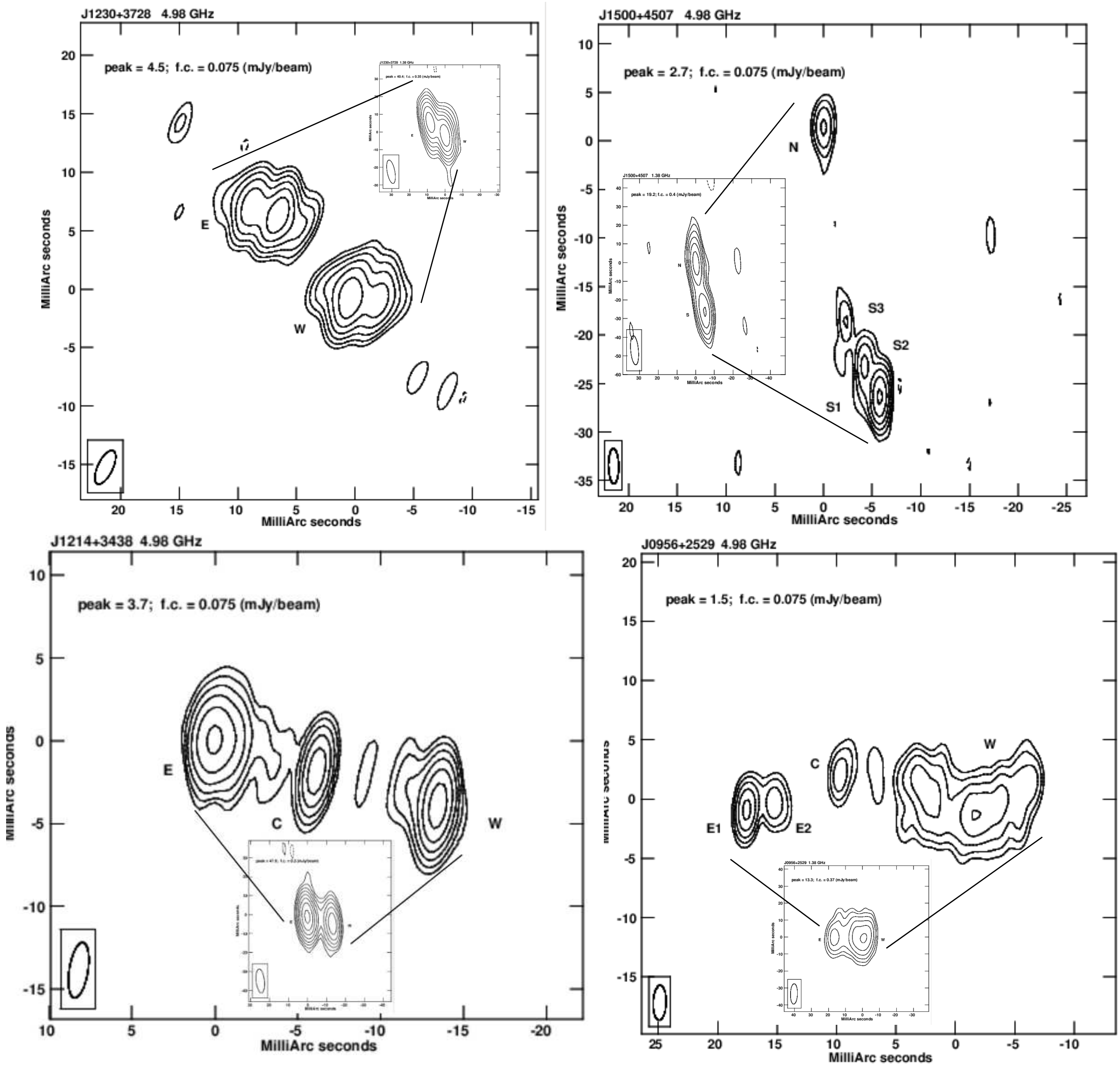

Fig. 3. Examples of VLBA images at 5 GHz of CSOs (left column) and core-jet blazars (right column). The inset shows the VLBA image at 1.4 GHz from the mJIVE-20 project. (Deller & Middelberg 2014)

ble to the percentage of blazars in the COINS sample (Peck et al. 2000), but it is significantly smaller than the percentage extrapolated on the basis of the GHz spectral shape (e.g., Tornianen et al. 2005; Orienti et al. 2007; Mingaliev et al. 2012).

5. Future plans

Our future plans include radio and optical observations. In particular, in the radio band we plan to perform VLBI observations at 5 GHz of the remaining sources of the sample in order to populate the region of the power-size plane which is still highly unknown. Observations of further 9 sources with peak > 6 mJy/beam have already been granted.

In the optical band, we will request photometric observations of the sources that turn out to be CSOs and for which no counterpart is detected in SDSS or Pan-STARRS images. Unveiling the host galaxy and redshift of all sources is pivotal for computing physical parameters, like luminosity, size, and estimate the magnetic field.

Finally, observational results will be compared with the outcome of dedicated MHD simulations of low-power decelerating jets (e.g., Rossi et al. 2020). This will allow us to study various evolutionary paths for low-power CSOs and investigate the importance of jet deceleration and jet-ISM interaction.

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