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Sub-kiloparsec scale structures of Low Power Compact radio sources

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Abstract. We consider sources in the Bologna Complete Sample that are smaller than 10 kpc. We discuss the different reasons for such apparent compactness and present new phase-referenced VLBI images, as well as 8.4 and 22 GHz high-resolution VLA images, for two of them. These data allow us to discuss their peculiar sub-kiloparsec scale structure and to obtain new information on the evolution of radio loud AGNs. We show which developments are necessary and achievable in the coming years; in particular, we stress that the inclusion of large (64-m class), mm-wavelength radio telescopes, such as the Sardinia Radio Telescope, in a VLBI array is highly desirable.

1. Introduction

A very basic fact about the role of *Very Long Baseline Interferometry* (VLBI) in the study of AGNs at parsec-scale resolution is that high *resolution* and *sensitivity* are essential requirements. In order to improve the former, long baselines and short wavelength (e.g. 3 mm) are required; big telescopes and large observing- and recording bandwidths are necessary to increase the latter. Steps forward in both directions are highly desirable, as they would allow one to greatly improve the capability of VLBI in several astronomical fields. For example, a better resolution would allow us to study the sub-parsec scale properties of AGNs, the mechanisms of jet formation, the geometry of regions in the vicinity of super massive black holes. Moreover, since most objects in the Universe are distant and/or intrinsically weak, a good sensitivity is also badly needed. Additional requirements for a most useful VLBI array are wide spectrum, rapid response, easy accessibility. The construction of the Sardinia Radio Telescope (SRT) and its inclusion in the European VLBI Network are key steps in this direction.

Although VLBI is essential in several fields, in this contribution we will focus on its relevance to the study of radio loud AGNs. In particular, little is known about the bulk of the radio galaxy population at low powers. The Bologna Complete Sample (BCS, Giovannini et al. 2005), consists of 95 sources at $z < 0.1$, selected at low frequency with no nuclear flux density limit, and it is therefore free from any significant bias against low power cores. While most objects (82/95) in the sample are extended FRI or FRII radio galaxies, there are also 13 sources with a projected linear size smaller than 10 kpc.

While extended (kiloparsec-scale) radio galaxies are divided between FRI and FRII radio galaxies, according to their morphology and radio power, compact (sub-kiloparsec) radio sources are better divided on the basis of their parsec-scale properties. Some of them appear as compact radio sources because of projection effects; this includes BL Lacs and flat spectrum radio quasars (FSRQs), characterized by one-sidedness, superluminal motions, and high brightness temperatures. Other high power radio sources appear to be intrinsically small and are not affected by relativistic effects: Compact Symmetric Objects (CSOs) are small-sized (< 1 kpc), with emission on both sides of the central engine. On the basis of kinematics as well as spectral arguments, these objects are interpreted as young radio galaxies with ages $\lesssim 10^4$ years. Finally, Low Luminosity AGNs (LLAGNs) are commonly found in many nearby galaxies: they have intermediate radio spectra and show weak or no nuclear activity at other wavelengths. As crossed symbols in Fig. 1 show, a few of the compact objects in the BCS belong to the aforementioned classes, e.g. the BL Lac Mkn 421, the CSO 4C 31.04, the LLAGN NGC 4278.

However, excluding these few well-known objects, we do not have much information about the nature of the low power compact (LPC) radio sources that populate the lowest part of the linear size vs radio power diagram. Do they possess compact cores and/or extended sub-structures? What are their *intrinsic* properties, such as power and dimension? Are they compact because they are young, projected, frustrated, or something else?

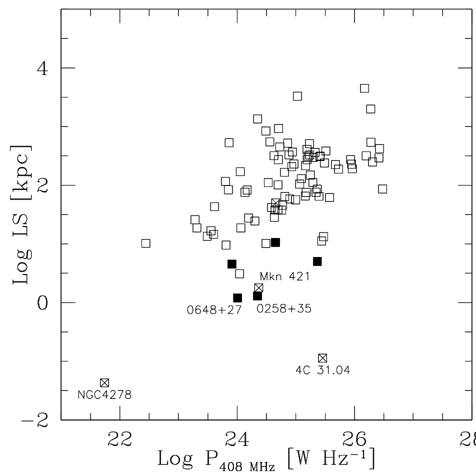

Fig. 1. Linear size vs radio power diagram for sources in the BCS (Giovannini et al. 2005), computed with $H_0 = 70$ km s^{-1}Mpc^{-1}. Filled squares indicate the LPCs studied in Giroletti et al. (2005a), with labels for the two sources discussed here; the crossed symbols with labels are for the archetypes of three different classes: BL Lacs (Mkn 421), CSOs (4C 31.04), and LLAGNs (NGC 4278).

2. Low Power Compact sources in the BCS

For low power sub-kiloparsec scale sources, it is clearly of great importance to obtain high resolution and sensitivity images. In a sample such as the BCS, it is currently possible to achieve these goals by considering: (i) high frequency (8.4 and 22 GHz) VLA A-array data and (ii) phase referenced 1.6 GHz VLBI data. It is nevertheless important to point out that for more distant or weaker sources the current instruments are still unsuitable for such a purpose. Moreover, the technique of phase referencing demands nearby calibrators, so an increase in sensitivity and monitoring is demanded in order to increase the number and improve the quality of the calibrators available for this. The advent of the SRT will therefore be beneficial to extending this line of research.

With these caveats in mind, we want to show here some new interesting results that we have derived from the study of five LPC in the BCS. We have obtained data for 0222+36, 0258+35, 0648+27, 1037+39, and 1855+27, which are marked with filled squares in Fig. 1. They are characterized by low frequency radio power in the range $23.9 < \mathrm{Log}P_{\mathrm{tot}} < 25.5$ (in W Hz^{-1} at 408 MHz) and projected angular sizes 1.5″< LAS < 10″. They look compact or double/triple in the few radio images available (taken from surveys such as the FIRST or from Fanti et al. 1987). They are typically associated with elliptical galaxies, with narrow lines. HST data of their nuclear regions are not available or affected by the presence of dust (e.g. 0648+27). In X-rays they are also hardly detected, with luminosities or upper limits $< 10^{42}$ erg s^{-1}.

With our new observations we have resolved the sub-kpc scale structure of the

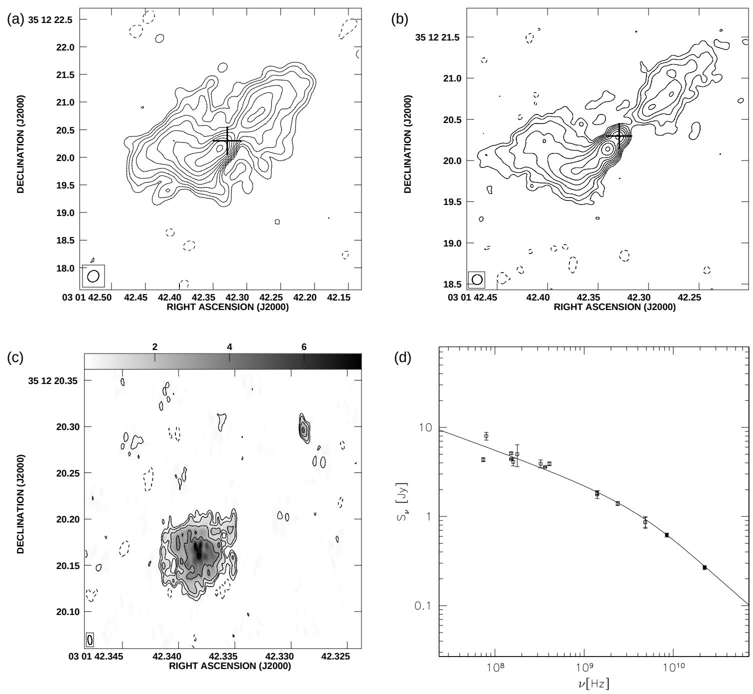

Fig. 2. Images and spectrum for 0258+35. (a) VLA at 8.4 GHz, (b) VLA at 22.5 GHz, (c) VLBA at 1.6 GHz, (d) spectrum. Contours are traced at (−1, 1, 2, 4, ...) times the 3σ noise level. The cross in the VLA images indicates the position of the VLBA core.

sources, identifying their cores and studying their spectral index. We have obtained new accurate measurements for parsec-scale properties, such as position and flux density, gaining new insights on intrinsic power, age, and possible evolutionary properties. A detailed analysis of our observations and results is presented in Giroletti et al. (2005a), while we focus here only on two representative sources.

2.1. 0258+35

The source 0258+35 has a low frequency flux density of $S_{408\,\mathrm{MHz}} = 3.9$ Jy, corresponding to $P_{408\,\mathrm{MHz}} = 10^{24.4}$ W Hz^{-1} at $z = 0.016$. Its largest angular size (LAS) is $\sim 4''$ and it looks like a double-lobed radio source (Fanti et al. 1987). On pc-scale it is only detected as a compact core-jet, although there is a clear excess of flux density on the shortest baselines that previous observations failed to image (Giovannini et al. 2001).

Our new data are shown in Fig. 2. The 22 GHz VLA image (Fig. 2b), thanks to its sub-arcsecond angular resolution, resolves the source into a small FRI-like, with a core, twin jets and diffuse, edge-dimmed lobes. The source's central peak is resolved into two components. Our phase-referenced VLBI data (Fig. 2c) show a faint compact component identified with the nuclear source and an extended "blob" at $\sim 0\farcs1$. As shown by the cross overlaid on the VLA images, the compact parsec-scale core is located in the central component at the base of the south-east jet-like feature. This component is easily identifiable in the 22 GHz image. Besides the faint compact core ($S_{\mathrm{c}} = 7.6$ mJy), the largest fraction of the flux density (240 mJy) in the VLBI image at 1.6 GHz is contained in a bright diffuse region coincident with the peak of the VLA images. It is noteworthy that crude self-calibration without phase-referencing would have failed to image this extended low brightness region, which contains some important information needed to understand the nature of this source.

We have estimated the average equipartition magnetic fields in the source, assuming a

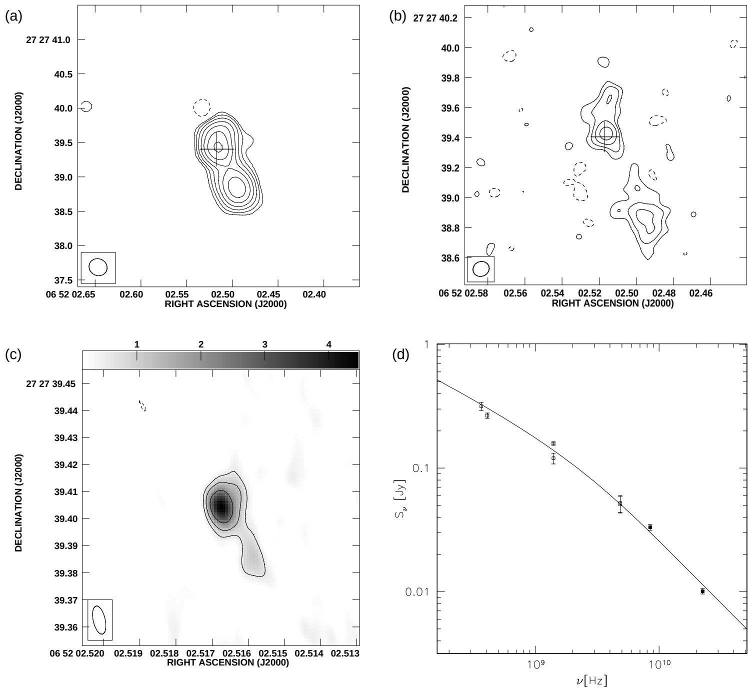

Fig. 3. Images and spectrum for 0648+27. Panels as in Fig. 2

uniform brightness in the source volume. This can be considered a good approximation, since the compact structures (core and knot) are only ∼ 20% of the total flux density at 5 GHz. We estimated $B_{eq} \sim 90\,\mu$Gauss. With this estimate and using the break frequency found in the total spectral index distribution (4.6 GHz, out of a good coverage between 74 MHz and 22 GHz, see Fig. 2d), we estimate an age of 7×10^5 yrs for this source. Of course, this is an average age and we expect that external diffuse regions are older with respect to the innermost region. This clearly shows the need for a wide frequency coverage combined with high angular resolution, in order to fit the spectra to single regions and not only to the source as a whole.

In light of these results, we speculate that this source might not grow to become a kiloparsec scale radio galaxy. No final hot spots demarcating the ends of the jets are visible and the source structure appears to strongly interact with the ISM as shown by the large bending of the arcsecond structure of the SE lobe (see Fig. 2a and b). Moreover, the estimated radiative age seems to imply an exceedingly low lobe advance velocity ($v_{\rm adv,syn}$ = 1500 m s^{-1}), so it is tempting to speculate that it was faster in the past and it has now ceased its advance.

2.2. 0648+27

This object (z = 0.0414, corresponding to 0.82 kpc/″, $P_{408\,\rm MHz} = 10^{24.02}$ W Hz^{-1}) was resolved into a double source with an extent of about 1.″5 in VLA observations at 8.4 GHz by Morganti et al. (2003), who also revealed a large amount of HI; however, the location of the core remained unknown and the radio structure was tentatively interpreted in terms of a pair of symmetric lobes.

Our 8.4 GHz VLA data (Fig. 3a) confirm the structure as a double; however, both components are resolved at 22 GHz, and a compact feature emerges in the North with a flux density of 2.5 mJy (see Fig. 3b). Its small size (<0.″07) and flatter spectral index suggest that this component is actually the core, with emission on either side. By providing an absolute position relative to the phase calibrator, our phase-referenced VLBI data lend strong support to this scenario. In fact, the emission in the VLBA image is located in the vicinity of the VLA peak in the northern lobe. The total flux density is only 12.8 mJy, with a peak of 4.4 mJy/beam. A faint jet-like structure is visible to the South-West, although the signal-to-noise is very poor and it could be spurious (see Fig. 3c).

The source flux density is dominated by the extended emission. The total spectrum of the source between 325 MHz and 22 GHz (Fig. 3d) has an index $\alpha \sim 0.8$, with a hint of steepening at high frequency ($\alpha_{8.4}^{22} = 1.22 \pm 0.02$). We estimate the average equipartition magnetic field in this source to be $B_{eq} \sim 95\,\mu$Gauss. Using the break frequency (2.9 GHz) estimated from total flux density measurements, we derive a minimum age for this source of about 1 Myr. We expect that the external lobe regions are older, confirming that this source is confined, and is expected to remain compact similarly to NGC 4278 (Giroletti et al. 2005b), despite its relatively higher total radio power and larger size.

3. Conclusions and perspectives

From our study of five LPC sources in the BCS, we find several possible causes of compactness. While projection seems to play a minor role in these sources, one or more of the following reasons are definitely involved: youth, frustration, short lived and/or intermittent activity of the central engine. These scenarios call for different physical states, from powerful jets with Doppler beaming to low kinematic power jets; we may even be probing the sources that make up the transition to radio quiet and non-active nucleus regime.

Samples as the BCS are therefore important to understand these differences and deserve to be completed to the faintest sources. The characteristics of SRT make its advent extremely important to this goal. The 64-m diameter will grant the necessary sensitivity; its location with respect to other European telescopes will yield a better coverage of the (u, v)-plane, resulting in improved fidelity and resolution; the availability of a millimeter wavelength receiver will further provide even better resolution and the possibility to study the spectrum up to high frequency. This last fact is most noteworthy, since millimeter wavelength observations are extremely challenging as of today, but their use is expected to become more and more relevant in the coming years.

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