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Parsec-scale view of CSS/GPS sources at 327 MHz

Daniele Dallacasa[1,2] | **Monica Orienti**[2]

[1]Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna,

[2]INAF-IRA, Bologna,

Correspondence
Daniele Dallacasa, INAF-IRA, Bologna, Via Gobetti 101, 40129 Bologna, Italy.
Email: ddallaca@ira.inaf.it

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Abstract

Global very long baseline interferometry (VLBI) observations at low frequencies are of great importance since they allow us to test the oldest part of the relativistic electron populations in young radio sources. At 327 MHz ($\lambda \sim 92$ cm), the most compact regions are self-absorbed, and the number of cores detected is very small. This could provide useful measurements of the magnetic field in the relativistic plasma, to be compared with the equipartition field derived from minimum energy arguments. Partial self-absorption takes place also in hot-spots. However, disentangling the hot-spot emission from that of the lobe turned out to be rather difficult. On the other hand, a clearer and more complete characterization of the volumes occupied by the magnetized relativistic plasma and its total energy content can be obtained at 327 MHz. In turn, an independent estimate of the source age can be inferred, on the basis of simple assumptions on the jet power. Here, we show that the ages derived in this way (between $2 \cdot 10^3$ and $5 \cdot 10^4$ year) are consistent with the radiative ages determined from the break frequency in the radio spectrum.

KEYWORDS

galaxies: active, radiation mechanisms: non-thermal, radio continuum: general

1 | INTRODUCTION

Young and then small radio sources need high angular resolution observations to properly determine their morphology. In general, the vast majority of the very long baseline interferometry (VLBI) experiments have been carried out mostly at 1.4 GHz or higher frequencies, where compact and flat-spectrum radio sources clearly shine, and the telescope availability and performance are at their best. Some VLBI studies at 327 MHz have been published (e.g., Cai et al. 2002; Lenc et al. 2008). However, the poor quality of the images did not allow us to carry out accurate studies of the physics in the radio sources which were detected. In this framework, steep-spectrum and extended (on angular scales of hundreds of milliarcsecond) emitting regions have been studied mainly by means of MERLIN observations at 1.67 and 5.0 GHz (e.g., Spencer et al., 1989; Ludke et al., 1998), with typical resolution of ~150 and 50 milliarcsecond, respectively.

The exploration of lower frequencies allows the study of lower energy and longer-lived relativistic electrons; they could reside in regions with little or no emission at cm wavelengths. At meter-wavelengths, steep spectrum regions are favored with respect to flat/inverted spectrum components. Therefore, mini hot-spots and mini lobes are expected to be the dominant regions of radio emission in objects with the main axis roughly perpendicular to the line of sight. Most of the compact steep spectrum/GHz-peaked spectrum (CSS/GPS) sources are in that condition, and, therefore, their emission is dominated by their hot-spots and lobes, with the former somehow affected by self-absorption.

VLBI studies of CSS/GPS sources at 327 MHz allow to determine the volume occupied by the relativistic plasma and then to define the work done by the jet pouring relativistic plasma to fill the lobes into the ambient medium, being an independent measure of the energy output of the active galactic nucleus.

2 | THE SAMPLE AND THE DATA

The 18 sources considered here are part of the 3CR-PW sample of CSS radio sources (Fanti et al. 1990, 1995). Given the high flux density limit in the catalogs they have been drawn from, they are among the most luminous young&small radio sources known to date.

Half of the targets are from the 3CR catalog listing sources brighter than 10 Jy at 178 MHz, while the remaining nine (including 3C93.1) are from the PW sample (Peacock & Wall 1981), whose flux density limit is 1.5 Jy at 2.7 GHz. These objects were added to the 3CR sample to tackle the bias against the smallest sources in which self-absorption introduces a flattening or even a turnover in the radio spectrum. The extrapolation of the optically thin radio spectrum would exceed 10 Jy at 178 MHz, allowing them to join the 3CR sample. As a consequence, the CSS sources from the PW catalog are generally smaller than those in the 3CR, and never exceed one arcsec in angular size.

The 18 targets were observed during two global VLBI experiments carried out at 327 MHz in 1992 for the 3CR CSS sources, and in 1995 for the objects from the PW sample. Details on the observations, data reduction, and results on individual sources are widely presented and discussed in Dallacasa et al. (2021). The final images have r.m.s noises ranging from ~1 to 6 mJy/beam. The resolution of about 20 milliarcsec was appropriate to carry out a study of the 18 target sources, whose typical largest angular sizes range from 0.5 to 2 arcsec. The quality of the final images is among the best one can find in the literature from VLBI observations at 327 MHz. To complete the proper morphological classification, we made use of VLBI images at 610 MHz (for the 3CR sources only, Nan et al. 1991), 1.67 and 5.0 MHz available in the literature (e.g., Dallacasa et al. 1995; Dallacasa et al. 2013; Fanti et al. 1985; Spencer et al. 1991).

First of all, in many targets (11/18) it has not been possible to account for the whole flux density measured with conventional interferometers, event taking into account a 10% flux density accuracy in both measurements. Unexpectedly, also sources whose flux density was fully accounted for in VLBI images at higher frequencies were affected.

Only in one source (B1829 + 29), we could detect a component (W in Dallacasa et al. 2021) which was unknown from earlier observations. However, our observations failed to detect two weak components seen on scales of a few arcsec in the MERLIN image at 1.67 GHz by Spencer et al. (1989). This means that the missing flux density should be attributed to low-surface brightness, steep-spectrum emitting regions with angular scales of about 1 arcsec, or larger (i.e., exceeding the largest angular scale sampled by our interferometric observation).

The radio structure generally confirmed the findings at high frequencies: four objects can be classified as complex, seven as double, and seven as triple. In the majority of cases, the radio emission is dominated by the mini-lobes, whose size appears larger than that measured in studies at higher frequencies, clear indication of the detection of steep-spectrum emission. As examples of the radio structures seen in our observations, we briefly discuss 3C298 (a quasar at $z = 1.437$) and 3C49 (a galaxy at $z = 0.621$).

The quasars 3C298 (Figure 1) and 3C138 were the only targets with the core detected in our observations (in 3C138 would be more appropriate to speak of "core region"). The comparison with the MERLIN + VLBI images of 3C298 available at 1.7 and 5 GHz (Fanti et al. 2002) clearly defines the true nature of the various components, being C the brightest region in their images, and then hosting the core of the source. At 327 MHz, self–absorption is relevant, leaving an emission which is fainter than the jet component (J). The hot-spots (E and W in Figure 1) are still the brightest regions, although they account for a relatively small fraction of the total volume. The lobes clearly account for the dominant part of the radio emission, and can be interpreted as back-flow tails in an FR-II model of the radio source. Their extension is oriented about 45° with respect to the source major axis, suggesting a possible relative motion of the jet ejection axis and the ambient medium. Their angular size is substantially larger than that visible at higher frequencies.

The majority of sources have morphologies similar to that of 3C49 (Figure 2), where the radio emission consists of two lobes, which are well resolved in this radio galaxy. Again, the hot spots (components E and W) are blended in the lobe emission and even in the full resolution image they are quite difficult to disentangle. The core is not visible, while it has been detected at high frequencies

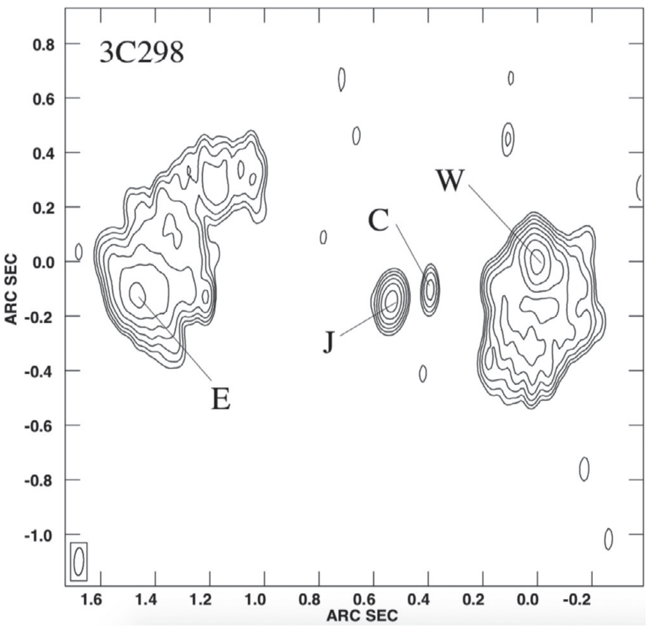

FIGURE 1 Global very long baseline interferometry (VLBI) image of the quasar 3C 298 at 327 MHz. The restoring beam is shown in the bottom left corner of the image. The peak is 1.58 Jy/beam. Contour levels are −3, 3, 6, 12, 25, 50, 100, 200, and 400 times the r.m.s. noise in the image, which is 0.003 Jy/beam (adapted from Dallacasa et al. 2021). C stands for core, J stands for jet, E stands for East, W stands for West

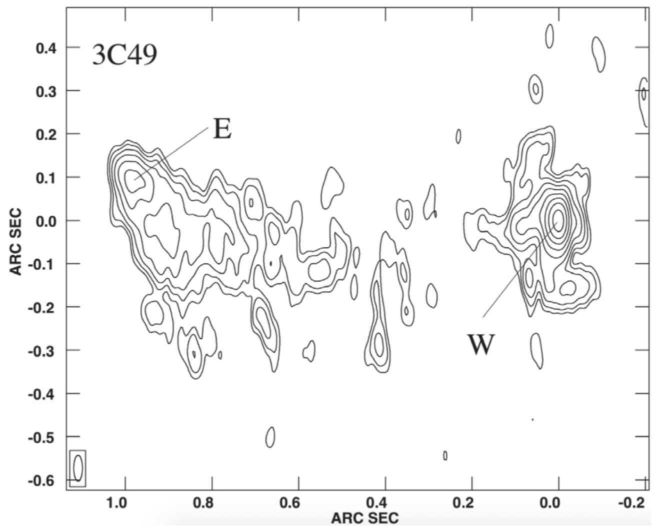

FIGURE 2 Global very long baseline interferometry (VLBI) image of the galaxy 3C 49 at 327 MHz. The restoring beam is shown in the bottom left corner of the image. The peak is 1.75 Jy/beam. Contour levels are −3, 3, 6, 12, 25, 50, 100, 200, 400, and 800 times the r.m.s. noise in the image, which is 0.0015 Jy/beam (adapted from Dallacasa et al. 2021)

as a very weak compact component close to the western lobe (Ludke et al. 1998). In many cases, the brightest lobe/hot-spot is the one closest to the core, suggesting that an inhomogeneous ambient medium is slowing down the source expansion, favoring the radio emission, with different effects on the two sides of the jets. The statistics on a dozen of sources support this possibility (Dallacasa et al. 2021).

3 | DYNAMICAL AGES

In principle, multifrequency VLBI observations could provide sensible spectral information on the radio emitting regions. A proper study should be made with images obtained by matched UV-coverages. This has not been possible for this study, given the relatively short snapshots taken at 610 MHz, and the much different sampling between our 327 MHz data and the higher frequencies (shorter wavelengths) mentioned earlier. Therefore, reliable values of the spectral index could be inferred for the whole component. Playing with data weights and UV-ranges, in some radio sources only, the flux density of hot-spots could be measured. This allowed us to determine the total flux density and, then, the minimum total energy content (E_{min}) of the lobes, and also their equipartition magnetic field (averaged over their volume). This point is particularly relevant since Dallacasa et al. (2021) found that more than 90% of the radio source energy is stored in the lobes. This can be considered as a measure of the total energy output of the central engine accumulated over the whole lifetime of the radio source.

The nearly instantaneous jet power (i.e., the power of the central engine) is determined by what we observe in the hot-spots.

By dividing the total energy stored into the lobes by the jet power, a rough estimate of the duration of the activity of the central engine can be derived. Here, we assume that the radio activity happened at a constant rate over the whole radio source lifetime.

If we assume a constant jet energy flux $F_e = c\Pi = P_{eq}A$ (Π = jet thrust, P_{eq} and A are the pressure and the cross-section of the hot-spot) we can derive an estimate of the time (τ) required to fill the lobe as it is observed now:

$$\tau \sim \frac{2 \cdot E_{min}}{F_e} \quad (1)$$

The assumption of a constant energy output carried out by the jet may be a limiting factor to this method. This has been tested with the sources target of these observations, where the radio spectrum is well defined with a large number of measurements, from ∼100 MHz to tens of GHz. The ages inferred in this way, ranging from $2{\cdot}10^3$ and $5 \cdot 10^4$ year (Dallacasa et al. 2021) are quite consistent with the radiative ages derived from the observation of the break frequency in the radio spectrum (Murgia et al. 1999) (see table 5 in Dallacasa et al. 2021). The equipartition field in the lobes we have obtained are systematically lower than those in (Murgia et al. 1999), since at 327 MHz the hot-spot emission is partially self-absorbed. Consequently, the contribution of the lobe (where the field is lower than in the hot-spot) becomes more relevant and this provides a value somehow smaller than in Murgia et al. (1999)). This, in turn, implies that our radiative ages are slightly larger.

More in general, this approach can be applied also to sources without radio spectra properly sampled.

4 | SUMMARY AND SOME ADDITIONAL CONSIDERATIONS

In most sources, a fraction of their single-dish total flux density at 327 MHz could not be accounted for. In some cases, there is indication of the presence of additional radio components on larger scales, like seen in MERLIN images.

More commonly, it is not clear how to deal with the missing flux density. It is possible that either low surface brightness emission is present on angular scales not sampled by our observations or the surface brightness of the missing component falls below our r.m.s. noise level. It is not, therefore, possible to have indication on its nature (remnants of earlier activity cycle, relativistic plasma escaping from the radio emitting region, etc.).

Jets and cores are rarely detected, and are generally faint representing a marginal contribution to the source total flux density. Hot spots and mini-lobes are dominant, accounting for the largest fraction of flux density in our observations. There is indication of synchrotron self-absorption acting on the hot-spots, being responsible for a spectral flattening or a turnover seen in the integrated radio spectrum of the smallest sources.

Asymmetries in the flux density of the two sides of the core (taking into account the position of the core detected at shorter wavelengths) are less prominent than at high frequencies, and there is a general decrease of the flux density ratio with the source linear size.

In the light of AGN physics, we must keep in mind that, in small&young radio sources the Lorentz factors of the relativistic electrons may be substantially smaller than in extended radio sources. In fact, the magnetic field in CSS/GPS radio sources are 2–3 orders of magnitudes larger that in FR–I and FR–II radio galaxies and quasars. Therefore, their time evolution/decay is much faster. In case the central engine switches off, the radio emission is destined to fade away quite quickly.

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ORCID

Daniele Dallacasa https://orcid.org/0000-0003-1246-6492

Monica Orienti https://orcid.org/0000-0003-4470-7094

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AUTHOR BIOGRAPHIES

Daniele Dallacasa is Associate Professor at the Department of Physics and Astronomy at the University of Bologna. His main research interests cover different area of extragalactic radio astronomy: young

& small radio sources, giant radio galaxies, and diffuse radio emission in clusters of galaxies.

Monica Orienti is a Scientific Staff member of the Institute of Radio Astronomy in Bologna of the National Institute of Astrophysics, Italy. Her research interests cover different topics mainly related to the study of radio emission from extragalactic objects and their role in the very high energy emission from AGNs.

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