Physical properties of young radio sources: VLBA observations of high-frequency peaking radio sources

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ABSTRACT
Multifrequency Very Long Baseline Array (VLBA) observations were performed to study the radio morphology and synchrotron spectra of four high-frequency peaking radio sources. They are resolved into several compact components and the radio emission is dominated by hotspots/lobes. The core region is detected unambiguously in J1335+5844 and J1735+5049. The spectra of the main source components peak above 3 GHz. Assuming that the spectral peak is produced by synchrotron self-absorption, we estimate the magnetic field directly from observable quantities: in half of the components it agrees with the equipartition field, while in the others the difference exceeds an order of magnitude. By comparing the physical properties of the targets with those of larger objects, we found that the luminosity increases with linear size for sources smaller than a few kpc, while it decreases for larger objects. The asymmetric sources J1335+5844 and J1735+5049 suggest that the ambient medium is inhomogeneous and is able to influence the evolution of the radio emission even during its first stages. The core luminosity increases with linear size for sources up to a few kpc, while it seems constant for larger sources, suggesting an evolution independent of source total luminosity.

Key words: radiation mechanisms: non-thermal – galaxies: active – quasars: general – radio continuum: general.

1 INTRODUCTION
Understanding how radio emission originates and evolves in extragalactic radio sources is one of the greatest challenges faced by modern astrophysics.

In the evolutionary scenario, the size of a radio source is strictly related to its age. Given their intrinsically compact sizes, usually smaller than those of their host galaxies, the population of compact steep-spectrum (CSS) and GHz-peaked spectrum (GPS) radio sources were proposed as the progenitors of classical radio galaxies (Fanti et al. 1995; Readhead et al. 1996; Snellen et al. 2000a). Indeed, their radio structure is usually a scaled-down version of that of a Fanaroff–Riley type II (FR II) galaxy (Fanaroff & Riley 1974). It is mostly accepted that at least the two-sided (or symmetric) objects of this class represent a young stage in radio source evolution. Depending on their linear size, they are termed as compact symmetric objects (CSO) or medium symmetric objects (MSO) if they are smaller or larger than 1 kpc, respectively (Fanti et al. 1995), although for a strict application of the definition the core must be detected.

The genuine youth of these objects is strongly supported by the determination of kinematic and radiative ages in about 20 of the most compact CSS/GPS objects, which were found to be a few thousand years old or less (e.g. Owsianik, Conway & Polatidis 1998; Murgia 2003; Polatidis & Conway 2003; Giorello & Polatidis 2009).

The determination of the physical properties in objects at the beginning of their evolution is crucial for setting tight constraints on the initial conditions of the radio emission. To this aim, the selection of radio sources in the very first stages of radio emission is necessary. Following the empirical anticorrelation between spectral peak frequency and source size (i.e. the source age) found by O’Dea & Baum (1997), the youngest objects should be sought among high-frequency peaking (HFP) radio sources. A sample of young HFP candidates was selected by Dallacasa et al. (2000) on the basis of their inverted spectrum between 1.4 and 5 GHz. The contamination from variable, boosted objects was removed on the basis of their variability, morphology and polarization properties (Tinti et al. 2005; Orienti et al. 2006; Orienti, Dallacasa & Stanghellini 2007; Orienti & Dallacasa 2008a). The sample of genuine young HFP candidates is reported in Orienti & Dallacasa (2008a). A crucial requirement for classifying a source unambiguously as a genuinely young radio source is detection of the core component. Among the sources in the sample of young HFP candidates (Orienti & Dallacasa 2008a), the core has been detected in three objects: J0111+3906, J0650+6001 and J1511+0518. Studies of the proper motion in J0111+3906 (Owsianik et al. 1998), J0650+6001 (Orienti & Dallacasa 2010) and J1511+0518 (Orienti & Dallacasa 2008b; An...
et al. 2012) estimate a kinematic age of a few hundred years, indicating that HFPs are at an early stage of their radio evolution/growth.

In this article, we present multifrequency Very Long Baseline Array (VLBA) observations of an additional four HFP objects with the aim of detecting the core component and determining the physical properties, such as the peak frequency, magnetic field and luminosity, which are important for constraining the evolutionary models.

The article is organized as follows. Section 2 describes the observations and data reduction; Section 3 presents a description of the target sources and the results from spectral analysis; a discussion and summary are presented in Sections 4 and 5. An appendix with Very Large Array (VLA) flux densities of sources from the bright HFP sample is provided.

Throughout this article, we assume $H_0 = 71 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$ in a flat Universe. The spectral index is defined as $\alpha = \frac{\log \nu_2 - \log \nu_1}{\log \nu_2 - \log \nu_1}$.

2 OBSERVATIONS AND DATA REDUCTION

VLBA observations of the four HFP sources J0037+0808, J1335+5844, J1735+5049 and J2203+1007 from the bright HFP sample (Dallacasa et al. 2000) were performed in full polarization with a recording bandwidth of 32 MHz at 256 Mbps in the $L$ (1.4 and 1.6 GHz), $S$ (2.2 GHz), $C$ (4.6 and 5.0 GHz), $X$ (8.1 and 8.4 GHz) and $U$ (15 GHz) bands. The sources J1335+5844 and J1735+5049 were bright enough to allow detection at high frequencies and observations at 22 GHz ($K$ band) were performed for these two sources.

Observations were carried out between 2010 January and 2011 January in four different runs (one per source), for a total observing time of 36 h. In each observing run, the target source was observed interleaved with its calibrator, in order to optimize the $uv$ coverage, and cycling through the frequencies. This allows us to consider the observations at the various frequencies almost simultaneously. In L, C and X bands, the intermediate frequencies are separated by about 300 MHz in order to improve the frequency coverage of the source spectra.

The correlation was performed at the VLBA correlator in Socorro and data reduction was carried out with the NRAO’s Astronomical Image Processing System (AIPS) package. After the application of system temperature and antenna gain information, the amplitudes were checked by using data from the fringe finders DA 195 (J0555+3948), 4C 39.25 (J0927+3902), 3C 345 (J1642+3948) and 3C 454.3 (J2253+1608). All the gain corrections were found to be within 5 per cent in $L$, $C$ and $X$ bands, 7 per cent in $S$ and $U$ bands and 10 per cent in the $K$ band, which can be conservatively assumed as the absolute calibration error ($\sigma_c$). The sources were strong enough to allow fringe fitting. Final images were produced after a number of phase self-calibration iterations. At the end of the self-calibration iteration, we applied amplitude calibration to remove residual systematic errors.

The final root-mean-square (rms) noises ($\sigma$) are generally between 0.08 and 0.5 mJy beam$^{-1}$, being worst at the highest frequency.

3 RESULTS

Multifrequency observations with milliarcsecond (mas) resolution are the main tool used to study the morphology and the physical properties of very young, compact radio sources.

The total flux density of each source is reported in Table 1 and was measured using TVSTAT, which performs an aperture integration over a selected region on the image plane. We also derived the flux density and the deconvolved angular size of each source component by using the AIPS task JMFIT, which performs a Gaussian fit to the source components on the image plane. The formal uncertainty in the deconvolved angular size obtained from the fit is $<0.1$ mas. As expected, the sum of the flux density from each component agrees with the total flux density measured on the whole source structure. Source components are referred to as north (N), south (S), east (E), west (W) and flat-spectrum core (C) when detected.

Observational parameters of the source components are reported in Table 2.

The uncertainty in the flux density arises from both the calibration error $\sigma_c$ (see Section 2) and the measurement error $\sigma_m$. The latter represents the off-source rms noise level measured on the image plane and is related to the source size $\theta_{\text{obs}}$ normalized by the beam size $\theta_{\text{beam}}$ as $\sigma_m = \text{rms} \times (\theta_{\text{obs}}/\theta_{\text{beam}})^{1/2}$. The flux density error $\sigma_S$ reported in Tables 1 and 2 takes both uncertainties into account. It corresponds to $\sigma_S = \sqrt{\sigma_c^2 + \sigma_m^2}$ and is generally dominated by $\sigma_c$, which usually exceeds $\sigma_m$.

3.1 Notes on individual sources

J0037+0808: no optical counterpart is found in the Sloan Digital Sky Survey Data Release 9 (SDSS DR9) image (Ahn et al. 2012). Observations at the higher frequencies resolve the source structure into three main components (Fig. 1). The east component, E, dominates the radio emission, accounting for more than 80 per cent of the total flux density. At high frequencies, component E is resolved into two subcomponents E1 and E2, separated by about 1 mas. Component E2 has a flat spectrum, $\alpha_{E2} \sim 0.25$, and it may host the source core. If E2 is the source core, the source structure is symmetric, with components E1 and W at roughly the same distance from E2. However, their flux densities are very different and the flux-density ratio is $S_{E1}/S_W \sim 4.4$ at 8.4 and 15 GHz, respectively.

The source has a total angular size of about 3.4 mas.

J1335+5844: in the SDSS image this source is associated with a galaxy with an estimated photometric redshift of 0.58 (Ahn et al. 2012). At low frequencies the source shows a

Table 1. VLBA total flux density. Column 1: source name; column 2: redshift ($z$ = photometric redshift); columns 3, 4, 5, 6, 7, 8, 9, 10 and 11: VLBA flux density at 1.4, 1.6, 2.2, 4.6, 5.0, 8.1, 8.4, 15 and 22 GHz, respectively; column 12: reference for the redshift [1 = Sloan Digital Sky Survey Data Release 9 (SDSS DR9: Ahn et al. 2012); 2 = Britzen et al. (2008); 3 = Healey et al. (2006)].

| Source       | $z$   | $S_{1.4}$ mJy | $S_{1.6}$ mJy | $S_{2.2}$ mJy | $S_{4.6}$ mJy | $S_{15}$ mJy | $S_{22}$ mJy |
|--------------|-------|---------------|---------------|---------------|---------------|--------------|--------------|
| J0037+0808   | 0.58  | 94 ± 5        | 111 ± 6       | 177 ± 9       | 264 ± 13      | 270 ± 13     | 260 ± 13     |
| J1335+5844   | 0.58  | 280 ± 14      | 349 ± 17      | 578 ± 40      | 653 ± 33      | 659 ± 33     | 638 ± 33     |
| J1735+5049   | 0.835 | 457 ± 23      | 471 ± 23      | 573 ± 29      | 873 ± 44      | 890 ± 44     | 906 ± 45     |
| J2203+1007   | 1.005 | 115 ± 6       | 133 ± 7       | 213 ± 15      | 277 ± 14      | 282 ± 14     | 201 ± 10     |
|              |       |               |               |               |               |              |              |
| Ref.         |       |               |               |               |               |              |              |
double structure, with the south component, S, being the brightest one (Fig. 2). In contrast, above 8.1 GHz the radio emission is dominated by the northern component, N, which is resolved into three subcomponents: N1 is a very compact hotspot, while N2 and N3 are likely jet regions. The diffuse emission enshrouding the southern hotspot is almost resolved out in the images at high frequencies.

Component C has a flat spectrum ($\alpha_{15}^c \sim 0$) and is identified as the source core. Its flux density is 1.6 mJy at 22 GHz, representing about 0.5 per cent of the total flux density at such frequencies. The core is located at about 5.6 mas ($\sim 37$ pc) from N1 and 7.6 mas ($\sim 50$ pc) from S, indicating that the brighter component at the higher frequencies is also the closest to the core.

The core component was not detected in earlier VLBA observations presented in Orienti et al. (2006), likely due to the inadequate dynamic range, while it was detected in deeper 15-GHz VLBA observations by Dallacasa et al. (2005) and An et al. (2012), but the lack of simultaneous spectral index information precluded a secure identification as the nucleus.

The source has a total angular size of about 15.5 mas, which corresponds to a linear size of $\sim 100$ pc.

J1335+5844 was not part of the CSOs Observed In the Northern Sky (COINS) sample of CSO candidates selected by Peck & Taylor (2000), due to its flat overall spectrum between 1.4 and 5 GHz (Taylor et al. 1996). However, the flat spectrum does not come from a boosted core–jet source, but arises from the northern, compact hotspot, which is absorbed below 10 GHz (Fig. 2). The unambiguous detection of the core allows us to classify this source as a genuine CSO.

J1335+5049: the source is associated with a galaxy at redshift $z = 0.835$ (Britzen et al. 2008). At low frequencies, the radio source shows a double structure and the radio emission is dominated by the southern component S. In the 15-GHz image, a central component is detected almost halfway between components N and S, becoming clearly resolved at 22 GHz (Fig. 3). This component has an inverted spectrum ($\alpha_{15}^c \sim -0.4$) and is identified as the source core. Its flux density is 14 mJy at 22 GHz, representing 2 per cent of the total flux density at such frequencies.

The source has a total angular size of about 5.3 mas, which corresponds to a linear size of $\sim 40$ pc.

J1735+5049 was not part of the COINS sample of CSO candidates selected by Peck & Taylor (2000), due to its flat overall spectrum between 1.4 and 5 GHz (Taylor et al. 1996). As in the case of J1335+5844, the flat spectrum does not come from a boosted core–jet source but arises from the compact hotspots, which are absorbed below 6 GHz (Fig. 3). The unambiguous detection of the core allows us to classify this source as a genuine CSO.

J2203+1007: the source is associated with a narrow-line galaxy at redshift $z = 1.005$ (Healey et al. 2008). The radio emission has a double structure (Fig. 4) and is dominated by the east component, E, which accounts for more than 65 per cent of the total flux density. Observations at higher frequencies resolve components E and W into subcomponents, showing the complex morphology of the object. No flat-spectrum component is detected, leaving the core region unidentified at the mJy level, limiting its fractional contribution to the total flux density below 1 per cent at 15 GHz.

The source has a total angular size of about 12 mas, which corresponds to a linear size of $\sim 97$ pc.

3.2 Radio spectra

The availability of high-resolution observations at various frequencies performed almost simultaneously in both optically thick and
Figure 1. VLBA observations of J0037+0808 at (a) 1.6 GHz, (b) 2.2 GHz, (c) 5.0 GHz, (d) 8.1 GHz and (e) 15 GHz. On each image we provide the peak flux density in mJy beam$^{-1}$ and the first contour intensity (f.c.) in mJy beam$^{-1}$, which corresponds to three times the off-source noise level measured on the image plane. Contours increase by a factor of 2. The restoring beam is plotted in the bottom left corner of each panel.

optically thin regimes allows us to study the radio spectrum of the main components. Following Orienti et al. (2007) and Orienti, Dallacasa & Stanghellini (2010), we modelled each spectrum with a pure analytical function:

$$\log S = a + \log(\nu) \times [b + c \times \log(\nu)],$$

where $S$ is the flux density, $\nu$ is the frequency and $a$, $b$ and $c$ are numeric parameters without any direct physical meaning. The best fits to the spectra are shown in Fig. 5 and the derived peak frequency and peak flux density are reported in Table 3. Tabulated uncertainties are from the fit only.

The peak parameters derived from the integrated spectra are in good agreement with the values obtained in Orienti et al. (2007) on the basis of VLA observations, pointing out both the lack of significant spectral variability and the lack of extended low-surface-brightness emission undetectable by VLBA observations. The overall spectra peak at about 5 GHz or at higher frequencies, as a consequence of the selection criteria (see Dallacasa et al. 2000). Fig. 5 shows the overall spectrum, together with the spectra of the main components as derived by our VLBA observations. In all four sources, the overall spectra are easily explained as the result of the superposition of the spectra of the individual main components; in general two, both characterized by different peak frequencies. When the main radio-emitting regions have different turnover frequencies, their relative contribution to the overall spectrum may change significantly at different frequencies. As a consequence, the peak frequency of the overall spectrum is located between the spectral peaks of the dominant subcomponents. This is particularly noticeable in the case of J1335+5844, where the two main components have similar peak flux densities but very different peak frequencies: 3.3 and 10.9 GHz. As a result, the peak of the overall spectrum occurs at about 5.6 GHz.

In the other sources, the overall spectrum is mainly influenced by the component that generally dominates the radio emission at all observing frequencies.

4 DISCUSSION

4.1 Radio morphology

Our multifrequency, high angular resolution VLBA observations allow us to resolve the source structure in many compact components and to determine their nature by using the spectral index information. In general, the radio emission is dominated by one of the hotspots/lobes. The flux-density ratio between the components of the same radio source ranges between 2 and 10, showing an asymmetric luminosity distribution. The optically thin spectral index of the hotspot components is about 0.7, although it is difficult to disentangle the hotspot region from the surrounding mini-lobe. In J1335+5844 and J1735+5049, the main hotspot is very compact and hence its radio emission is self-absorbed below 10 GHz. For this reason the spectra are flat ($\alpha = 0.2–0.4$) due to the presence...
Figure 2. VLBA observations of J1335+5844 at (a) 1.6 GHz, (b) 2.2 GHz, (c) 5.0 GHz, (d) 8.4 GHz, (e) 15 GHz and (f) 22 GHz. On each image we provide the peak flux density in mJy beam$^{-1}$ and the first contour intensity (f.c.) in mJy beam$^{-1}$, which corresponds to three times the off-source noise level measured on the image plane. Contours increase by a factor of 2. The restoring beam is plotted in the bottom left corner of each panel.

of opacity effects up to high frequencies, which prevent us from determining the intrinsic spectral index of the fully optically thin emission.

The steep spectra found in other compact components ($\alpha > 1.0$) may reflect some missing flux density at the highest frequency, likely due to the lack of the shortest baselines.

Among the four HFPs studied in this article, the core is detected unambiguously in J1335+5844 and J1735+5049 and represents a small fraction ($\leq 2$ per cent) of the source total emission at the highest observing frequency, indicating the lack of boosting effects. In J0037+0808 we suggest the central component, E2, as the core candidate on the basis of its flat spectrum. In this source, the E2 component accounts for about 27 per cent of the total flux density at the highest frequency. However, the lack of significant variability and the small source size may suggest that E2 is likely a blend of the true source core and the jet base.

No core candidate is found in J2203+1007.

In J0037+0808 and J1735+5049, the core component is located roughly midway between the outer components. In J1335+5844, on the other hand, the compact and most luminous hotspot is the one closest to the core component, opposite to what is expected from projection and relativistic time dilation effects. Such asymmetry is found in a relatively large fraction ($\sim 52$ per cent) of GPS/CSS sources (Dallacasa et al. 2013) and suggests a strong interplay between the radio emission and the environment. The very compact size of the hotspot in J1335+5844 and J1735+5049 is likely due to the interaction between the radio emission and an inhomogeneous, dense medium, which confines the component by reducing the adiabatic expansion and enhances its luminosity by amplifying the radiative losses. The presence of an inhomogeneous ambient medium enshrouding young radio sources was found in the HFP radio galaxies J0428+3259 and J1511+0518, where free–free absorption from an ionized medium was detected only in front of one of the two lobes (Orienti & Dallacasa 2008b).

4.2 The magnetic field

The direct measurement of the magnetic field from observable quantities is a difficult task to perform. A way to bypass the problem is to assume that a radio source is in minimum energy conditions, which means that the energy stored in relativistic particles is approximately equal to the magnetic energy. The equipartition magnetic field $H_{\text{eq}}$ is then obtained by

$$H_{\text{eq}} = \left( \frac{c_{12} L}{V} \right)^{2/7},$$

where $L$ is the radio luminosity, $V$ the volume and $c_{12}$ a constant that is tabulated in Pacholczyk (1970) and depends on the spectral index and the upper and lower cut-off frequencies. In the case of the HFP components, we assume an average spectral index $\alpha = 0.7$, a lower
Figure 3. VLBA observations of J1735+5049 at (a) 1.6 GHz, (b) 2.2 GHz, (c) 4.6 GHz, (d) 8.1 GHz, (e) 15 GHz and (f) 22 GHz. On each image we provide the peak flux density in mJy beam$^{-1}$ and the first contour intensity (f.c.) in mJy beam$^{-1}$, which corresponds to three times the off-source noise level measured on the image plane. Contours increase by a factor of 2. The restoring beam is plotted in the bottom left corner of each panel.

cut-off frequency $v_1 = 10$ MHz and an upper cut-off frequency $v_2 = 100$ GHz. The radio luminosity is obtained by

$$L = \frac{4\pi D_L^2}{(1+z)^2} \int_{v_1}^{v_2} S(v) \, dv.$$  
(2)

We approximate the volume of the source components to a prolate ellipsoid that is homogeneously filled by relativistic plasma:

$$V = \frac{\pi}{6} \left( \frac{D_L}{(1+z)^2} \right)^3 \theta_{\text{maj}} \theta_{\text{min}}^2,$$  
(3)

where $D_L$ is the luminosity distance, $\theta_{\text{maj}}$ and $\theta_{\text{min}}$ are the major and minor angular sizes, respectively, and $z$ is the redshift. If in equation (1) we consider the luminosity and volume derived from equations (2) and (3), we obtain equipartition magnetic fields ranging between 20 and 180 mG (see Table 4), similar to the values derived for the components of other HFP sources studied earlier (Orienti & Dallacasa 2008b, 2012).

If the spectral peak is produced by synchrotron self-absorption (SSA), we have an independent way to compute the magnetic field by using observable quantities only. In this case the magnetic field, $H$, in Gauss, is

$$H = \frac{v_p^2 \theta_{\text{maj}}^2 \theta_{\text{min}}^2}{f(\alpha) S_p (1+z)},$$  
(4)

where $v_p$ is the peak frequency in GHz, $S_p$ is the peak flux density in Jy, $\theta_{\text{maj}}$ and $\theta_{\text{min}}$ are the major and minor angular sizes of the source component in mas respectively and $f(\alpha)$ is a function that depends slightly on $\alpha$ and is $\sim$8 (see e.g. Kellermann & Pauliny-Toth 1981; O'Dea 1998).

The magnetic fields are computed for the source components with a well-sampled spectrum and hence with an accurate estimate of the peak parameters. In equation (4), we consider the peak flux density and peak frequency obtained by the fit to the spectra (Table 3) and the angular sizes measured from the images (Table 2). Following the approach by Readhead (1994), we consider component angular sizes that are 1.8 times larger than the full width at half-maximum derived by the Gaussian fit. In the case of the southern component of J1335+5844, the component size was measured directly from the image due to the complex structure of the emitting region.

The magnetic fields obtained for the source components range from a few mG up to 1.8 G (Table 4). In half of the components, such values usually agree with the equipartition magnetic fields within a factor of $\sim$2–4. In the other components, the difference between the magnetic field values obtained with the two approaches may be larger than an order of magnitude. In the case of the northern component of J1735+5049 and both the components of J2203+1007, the magnetic field computed from the peak parameters is much higher than the equipartition magnetic field. In the work by Orienti & Dallacasa (2008b), such a large difference was found in one of

Figure 3. VLBA observations of J1735+5049 at (a) 1.6 GHz, (b) 2.2 GHz, (c) 4.6 GHz, (d) 8.1 GHz, (e) 15 GHz and (f) 22 GHz. On each image we provide the peak flux density in mJy beam$^{-1}$ and the first contour intensity (f.c.) in mJy beam$^{-1}$, which corresponds to three times the off-source noise level measured on the image plane. Contours increase by a factor of 2. The restoring beam is plotted in the bottom left corner of each panel.

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the components of J0428+3259 and J1511+0518, where the spectral peak was interpreted as due to free–free absorption (FFA) by an ionized thermal medium, rather than in terms of pure SSA. This explanation was supported by the analysis of the optically thick part of the spectra, which could be accurately described by a FFA model only.

In the case of J1335+5844 and J1735+5049, the large values of the magnetic field seems to reflect a non-homogeneous synchrotron component. The angular size estimated from the images refers to blended components that cannot be adequately resolved by these VLBA observations. Therefore, the estimated angular size should be considered an upper limit. As a consequence, the magnetic field derived from observational parameters is largely overestimated because it depends strongly on the angular size ($H \propto \theta^4$, while $H_{eq} \propto \theta^{-6/7}$). The optically thick spectral index $\alpha_b > -2.5$ supports the inhomogeneity of the source components, rather than the presence of FFA.

4.3 Physical properties and radio source evolution

In the context of evolutionary models, it is important to constrain the physical properties of young radio sources and how they evolve in time/size. However, observational information must arise from samples of genuinely young radio sources, without the contamination of other populations of objects like blazars, which may temporarily match the selection criteria of GPS/HFP samples (see e.g. Tinti
Table 3. Spectral parameters of the source components. Column 1: source name; column 2: source component; column 3: peak frequency; column 4: peak flux density; columns 5 and 6: spectral index computed in the optically thick and optically thin part of the spectrum, respectively.

| Source | Comp | \(v_p\) (GHz) | \(S_p\) (mJy) | \(\alpha_b\) | \(\alpha_t\) |
|-------|------|--------------|--------------|-----------|-----------|
| J0037+0808 | E | 4.8 \pm 0.5 | 233 \pm 2 | -0.7 | 0.7 |
| | W | 5.8 \pm 1.0 | 10 \pm 4 | -1.4 | 1.4 |
| Tot | 5.6 \pm 0.5 | 276 \pm 2 | -0.8 | 0.4 |
| J1335+5844 | N | 10.9 \pm 0.2 | 440 \pm 7 | -0.9 | 0.4 |
| | S | 3.3 \pm 0.5 | 432 \pm 10 | -1.7 | 1.4 |
| Tot | 5.6 \pm 0.5 | 679 \pm 2 | -0.7 | 0.5 |
| J1735+5049 | N | 6.3 \pm 0.5 | 271 \pm 2 | -2.0 | 1.1 |
| | S | 8.9 \pm 0.5 | 653 \pm 1 | -0.2 | 0.2 |
| Tot | 7.1 \pm 1.0 | 887 \pm 6 | -0.4 | 0.4 |
| J2203+1007 | E | 4.8 \pm 0.6 | 181 \pm 2 | -0.6 | 0.7 |
| | W | 3.8 \pm 0.5 | 100 \pm 3 | -0.9 | 1.4 |
| Tot | 4.5 \pm 0.5 | 264 \pm 3 | -0.7 | 0.8 |

Table 4. Physical parameters of the source components. Column 1: source name; column 2: source component; column 3: radio luminosity; column 4: volume; columns 5 and 6: equipartition magnetic field and magnetic field from observational parameters, respectively (see Section 4.2).

| Source | Comp | \(L\) (erg s\(^{-1}\)) | \(V\) (cm\(^3\)) | \(H_{eq}\) (mg) | \(H\) (mg) |
|-------|------|-----------------|---------------|-------------|-----------|
| J0037+0808 | E | 9.3 \times 10^{25} | 1.4 \times 10^{24} | 86 | 9 |
| | W | 2.2 \times 10^{24} | 1.4 \times 10^{24} | 57 | 55 |
| J1335+5844 | N | 3.9 \times 10^{24} | 2.4 \times 10^{24} | 111 | 268 |
| | S | 1.5 \times 10^{24} | 4.5 \times 10^{17} | 19 | 55 |
| J1735+5049 | N | 3.2 \times 10^{24} | 7.9 \times 10^{26} | 39 | 1800 |
| | S | 1.7 \times 10^{24} | 2.6 \times 10^{15} | 165 | 37 |
| J2203+1007 | E | 3.7 \times 10^{24} | 3.2 \times 10^{24} | 52 | 200 |
| | W | 1.4 \times 10^{24} | 8.2 \times 10^{15} | 30 | 988 |

et al. 2005; Torniainen et al. 2005; Orienti et al. 2007; Hancock et al. 2010).

For a correct identification of the nature of the radio source, it is important to have the proper classification of the radio morphology. However, this is most difficult in the smallest objects, where self-absorption changes the source morphology with frequency (see e.g. J1335+5844, Section 3.1). The secure detection of the core component is a crucial requirement for classifying a source as a genuine CSO.

With the aim of determining the physical properties during the early stages of the radio emission, we built a sample of \textit{bona fide} young radio sources with an unambiguous detection of the core region (Table 5). The sources were selected from HIP, GPS and CSS samples by Fanti et al. (1990, 2001), Dallacasa et al. (1995, 2000), Snellen et al. (1998), Stanghellini et al. (1998), Peck & Taylor (2000) and Stanghellini, Dallacasa & Orienti (2009) in order to span a wide range of linear size, from a few pc up to tens of kpc, for high-luminosity radio sources. To derive the intrinsic physical parameters, we selected only those sources with information on the redshift (either spectroscopic or photometric). Information on the core components was retrieved from multifrequency, high-resolution, high-sensitivity observations presented by Peck & Taylor (2000), Snellen et al. (2000b), Stanghellini et al. (2001),...
Table 5 - continued

| Source | z     | LLS   | \(\log L_{\text{core}}\) | \(\log L_{\text{tot}}\) | \(v_p\) | Ref |
|--------|-------|-------|----------------|----------------|-------|-----|
| 3C 216 | 0.6702 | 56.120 | 26.764 | 28.364 | 0.066 | m   |
| 3C 237 | 0.877  | 9.301  | 24.605 | 28.751 | 0.094 | m   |
| 3C 241 | 1.617  | 10.268 | 25.300 | 28.973 | 0.104 | m   |
| 3C 277.1| 0.31978| 7.392  | 25.095 | 27.350 | <0.132|m   |
| 3C 298 | 1.43732| 21.297 | 27.096 | 28.361 | 0.195 | m   |
| 3C 309.1| 0.905  | 17.215 | 27.177 | 28.833 | <0.076|m   |
| 3C 346 | 0.16201| 22.056 | 25.124 | 26.782 | <0.045|m   |

Figure 6. Rest-frame peak frequency versus largest linear size for the sources of the selected sample (Table 5). The solid line represents the best linear fit (see Section 4.3). Arrows represent upper limit to the peak frequency.

Orienti et al. (2004), Rossetti et al. (2006), Orienti & Dallacasa (2008b, 2010, 2012) and Dallacasa et al. (2013).

For the aforementioned sample, in Fig. 6 we plot the peak frequency (rest frame) versus the largest linear size, LLS. The relation between the rest-frame peak frequency and LLS, obtained by minimizing the chi-square error statistic, is

\[
\log v_p = (-0.21 \pm 0.04) - (0.59 \pm 0.05) \times \log LLS,
\]

which is in good agreement with the relation found by O’Dea (1998). The HFP sources studied in this paper are in the top left region of Fig. 6. Interestingly, in the HFP sources departing significantly from the relation – J0650+6001, J1335+5844 and J1735+5049 – the total spectrum is dominated by a bright and very compact component, as in J1335+5844 (see Fig. 5), the peak of which is above 5 GHz, while no significant contribution to the spectrum from more extended features (mini-lobes) is present. The lack of diffuse emission in HFP sources may be a consequence of both the high magnetic field (see Table 4), which causes severe radiative losses, and the short source lifetime, which prevents the formation of extended features.

4.3.1 Luminosity: core versus total

To investigate the contribution of the core component to the total luminosity, in Fig. 7 we plot the luminosity of the core at 5 GHz versus the source total luminosity at 375 MHz (source rest frame). For those sources without observations at 375 MHz and for the

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Core luminosity at 5 GHz versus the source total luminosity at 375 MHz (rest frame) for the sources of the selected sample (Table 5). \textit{Filled circles} refer to galaxies, while \textit{empty triangles} are quasars. The solid line represents the best linear fit for the whole sample, while the dashed and dotted lines represent the best fit considering either quasars or galaxies, respectively (see Section 4.3.1).

GPS/HFP sources with spectra that are absorbed at that frequency, the 375-MHz flux density was extrapolated from the optically thin part of the spectrum. In cases in which the flux density of the core at 5 GHz was not available, the 5-GHz flux density was extrapolated assuming a flat spectral index (\(\alpha = 0\)).

We performed a linear fit on the data displayed in Fig. 7, first considering the whole sample and subsequently separating galaxies and quasars. If we consider the whole sample, we obtain

\[
\log L_{\text{core}} = (6.51 \pm 3.17) + (0.67 \pm 0.11) \times \log L_{\text{tot}},
\]

which is similar to the relations derived for CSS/GPS objects (Dallacasa et al. 2013) and for FR I/FR II radio sources (e.g. Giovannini et al. 2001; Zirbel & Baum 1995; Yuan & Wang 2012).

If we consider the galaxies only, we obtain

\[
\log L_{\text{core,gal}} = (12.28 \pm 3.26) + (0.45 \pm 0.12) \times \log L_{\text{tot,gal}},
\]

while for the quasars we find

\[
\log L_{\text{core,q}} = (11.94 \pm 6.64) + (0.50 \pm 0.23) \times \log L_{\text{tot,q}}.
\]

Interestingly the slope derived for quasars (dashed line in Fig. 7) is similar to the one derived for the galaxies (dotted line in Fig. 7) and both are flatter than that of the whole sample. However, there is a clear offset in the distribution of \(L_{\text{core}}\), which is generally higher in quasars than in galaxies. If we combine galaxies and quasars, we obtain an artificially steepening of the slope that is likely due to the dominance of the latter at high luminosities.

4.3.2 Total luminosity versus linear size

To determine how the luminosity evolves as the source grows, in Fig. 8 we plot the total luminosity at 375 MHz (source rest frame), \(L_{\text{tot}}\), as a function of LLS. Quasars are mainly the most luminous and largest objects, while galaxies are found at lower luminosity and smaller linear size. This arises from selection effects: in pc-scale sources, the emission is dominated by small components like the core or very compact hotspots. As a consequence, the overall spectrum is flat and the source does not match the selection criteria of CSS/GPS samples. Two outstanding examples are the HFP...
The core luminosity spans roughly the same range of values for both pc-scale and kpc-scale sources, although small objects have, on average, lower core luminosity, while quasars are mostly in the upper right region, likely due to boosting effects (see Section 4.3.1 and Fig. 7).

To investigate how the core luminosity evolves as the source grows, we repeat the same statistical analysis performed for studying the evolution of the source total luminosity. As in Section 4.3.2, we consider only galaxies and we divide the data points into five bins on the basis of their $LLS$, each bin containing an equal number of objects. Crosses represent the median values and the error bars represent the standard deviation.

The median values suggest an increase of core luminosity with size for sources up to a few kpc, similar to that found for the total luminosity, although the poor statistics does not allow us to confirm the peak around 1–10 kpc.

Interestingly, for the large sources ($LLS > 10$ kpc) the core luminosity seems unrelated to the linear size, indicating a different evolution for core and total luminosity. The different behaviour may be related to the influence of the surrounding medium, which is supposedly the basis of the total source luminosity evolution but should not affect the core luminosity significantly. However, a larger number of objects should be considered to confirm this result. Furthermore, we must keep in mind that the core luminosity depends strongly on the resolution of the observations. If the resolution is not adequate then the core emission may be highly contaminated by the jets, causing an overestimate of its luminosity.

4.3.4 Core dominance versus linear size

To investigate whether the prominence of the core luminosity depends on the source size, we plot the ratio of core luminosity to total luminosity, $L_{\text{core}}/L_{\text{tot}}$, versus the source size $LLS$ (Fig. 10). No clear trend is found between $L_{\text{core}}/L_{\text{tot}}$ and $LLS$; $L_{\text{core}}/L_{\text{tot}}$ spans a large range of values for both pc-scale and kpc-scale objects. Among the HFP sources, those with the highest ratio are J0650+6001 and J0951+3451, the core emission of which is contaminated by the presence of an additional contribution of the jet that cannot be

Figure 8. Total luminosity at 375 MHz (rest frame) versus the largest linear size for the sources of the selected sample (Table 5). Filled circles refer to galaxies, while empty triangles are quasars. Crosses represent the median values of the total luminosity and $LLS$, for galaxies only, separated into different bins (see Section 4.3.2). Error bars are the standard deviations.

Figure 9. Core luminosity versus the largest linear size for the sources of the selected sample (Table 5). Filled circles refer to galaxies, while empty triangles are quasars. Crosses represent the median values of the core luminosity and $LLS$, for galaxies only, separated into different bins (see Section 4.3.3). Error bars are the standard deviations.

Sources J1335+5844 and J1735+5049, which were excluded from the COINS sample of CSO candidates by Peck & Taylor (2000) due to their flat overall spectrum, although they turned out to be genuinely young radio sources (see Section 3.1). On the other hand, when the sources grow on larger scales the contribution from the lobes dominates, making the overall spectrum steep enough to enter in the samples selected on the basis of the spectral shape.

In order to prevent significant contamination from selection and boosting effects, in the following statistical analysis we consider only galaxies. We divide the galaxies on the basis of $LLS$, using five different bins containing an equal number of objects. Median values are plotted as crosses and the error bars represent their standard deviation. Fig. 8 suggests that the total radio luminosity increases with $LLS$ up to about 1–10 kpc. As the source grows further away, the total luminosity progressively decreases. These results are in agreement with model predictions (e.g. Fanti et al. 1995; Snellen et al. 2000a), in which the source expansion is influenced by the surrounding ambient medium. The smaller sources are supposed to reside within the innermost dense and inhomogeneous interstellar medium, which may favour radiative losses. As the source grows, it experiences a less dense environment and the adiabatic losses dominate, causing a decrease in the source luminosity.

The presence of large asymmetries, both in luminosity and arm length, mainly among the most compact objects (Saikia et al. 2003; Orienti & Dallacasa 2008c; Dallacasa et al. 2013), indicates that during its growth one of the jets may interact with a dense cloud. In this case its expansion is highly decelerated, while its luminosity is enhanced due to severe radiative losses, making these objects common in flux-limited samples. The asymmetric flux density distribution in J1335+5844 and J1735+5049 and their very compact hotspots may be the result of a strong interaction between a newly born radio source and an inhomogeneous medium.

4.3.3 Core luminosity evolution versus linear size

In Fig. 9 we plot the core luminosity versus the source linear size. The core luminosity spans roughly the same range of values for both pc-scale and kpc-scale sources, although small objects have, on average, lower core luminosity, while quasars are mostly in the upper right region, likely due to boosting effects (see Section 4.3.1 and Fig. 7).

To investigate how the core luminosity evolves as the source grows, we repeat the same statistical analysis performed for studying the evolution of the source total luminosity. As in Section 4.3.2, we consider only galaxies and we divide the data points into five bins on the basis of their $LLS$, each bin containing an equal number of objects. Crosses represent the median values and the error bars represent the standard deviation.

The median values suggest an increase of core luminosity with size for sources up to a few kpc, similar to that found for the total luminosity, although the poor statistics does not allow us to confirm the peak around 1–10 kpc.

Interestingly, for the large sources ($LLS > 10$ kpc) the core luminosity seems unrelated to the linear size, indicating a different evolution for core and total luminosity. The different behaviour may be related to the influence of the surrounding medium, which is supposedly the basis of the total source luminosity evolution but should not affect the core luminosity significantly. However, a larger number of objects should be considered to confirm this result. Furthermore, we must keep in mind that the core luminosity depends strongly on the resolution of the observations. If the resolution is not adequate then the core emission may be highly contaminated by the jets, causing an overestimate of its luminosity.
resolved even with very-long-baseline interferometry observations. The HFP source with the smallest ratio is J1335+5844, which is also the largest object among the HFPs considered in this article, and the contribution from its hotspots is very dominant. Again, the largest sources explore a wider range of ratios as a consequence of an increased contribution of the extended emission, which is continuously built as the source expands and ages. For the same reason, the absence of objects in the bottom left part of Fig. 10 is likely due to the lack of significant extended features in the smallest sources, making the core contribution a relatively high fraction of the source total luminosity.

5 SUMMARY

We presented multifrequency VLBA observations of four high-frequency peaking radio sources. The sources are characterized by a two-sided structure and the radio emission is dominated by hotspots/lobes. The core region is unambiguously detected in J1335+5844 and J1735+5049, while in J0037+0808 we suggest that the central region is the core, although observations at higher frequencies are needed to confirm its nature.

The availability of multifrequency observations covering both optically thick and optically thin parts of the spectrum allowed us to derive the peak parameters for the main source components. The spectral peaks are above a few GHz, reaching $\sim 10$ GHz in the most compact hotspot of J1335+5844. Assuming that the spectral peak is produced by synchrotron self-absorption, we computed the magnetic field by means of observable quantities. For half of the source components, these values of the magnetic field agree with the equipartition magnetic field, within a factor of a few. However, in four components the magnetic field derived from observable quantities is more than an order of magnitude higher than the equipartition one. Such a discrepancy may either be caused by an inhomogeneous component, not properly resolved by the observations presented here, or it may indicate the presence of free–free absorption that modifies the optically thick part of the spectrum, as it was observed in other HFP galaxies (Orienti & Dallacasa 2008b), or it may bear witness to a situation where the radio emission is far from being in minimum energy condition.

To investigate possible changes in the physical properties as the source grows, we built a sample of bona fide young radio sources spanning linear sizes from a few pc to tens of kpc. The sources presented in this article sample the small linear size tail of the distribution.

We confirm the empirical correlation between peak frequency and linear size and the relation between core luminosity and source total luminosity. If we consider the source total luminosity as a function of the linear size, we find two different relations depending on the source size: sources smaller than a few kpc increase their luminosity as they grow, while larger sources progressively decrease their luminosity, in agreement with the evolutionary models. The smallest sources reside within the innermost region of the host galaxy, where the dense and inhomogeneous ambient medium favours radiative losses. As the radio source expands on a kpc scale, it experiences a smoother and less dense ambient medium and adiabatic losses dominate. The asymmetric radio structures of J1335+5844 and J1735+5049 provide additional support to the idea that the ambient medium may influence the source growth even during the first evolutionary stages.

Different behaviour for sources smaller or larger than a few kpc is also found for the core luminosity evolution. The former progressively increase their core luminosity, reaching a peak at about a few kpc, while for larger sources the luminosity seems unrelated to the size. Such a trend may be partially contaminated by the inhomogeneous resolution of the observations, which depends on the source linear size. For the smallest sources, the core properties are measured on the mas scale, while for the largest sources the core luminosity is derived on a region unresolved on arcsec scales, which may contain some contribution from the jet base.

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APPENDIX A: VLA OBSERVATIONS OF BRIGHT HFP RADIO SOURCES

A1 VLA observations

Multifrequency VLA observations of 13 of the 55 candidate HFPs from the bright HFP sample (Dallacasa et al. 2000) were carried out on 2006 November 19 in C configuration, using filler time. The observing bandwidth was chosen to be 50 MHz per intermediate frequency (IF). Separate analysis for each IF in the L, C and X bands was carried out to improve the spectral coverage of the data, as was done in previous works (Dallacasa et al. 2000; Tinti et al. 2005; Orienti et al. 2007, 2010). We obtained flux density measurements in the L (IFs at 1.465 and 1.665 GHz), C (4.565 and 4.935 GHz), X (8.085 and 8.465 GHz), K (22.460 GHz) and Q (43.340 GHz) bands. Each source was typically observed for 50 s at each band, cycling through the frequencies. Therefore, the flux density measurements can be considered almost simultaneous. About 3 min were spent on the primary flux density calibrator 3C 48, while secondary calibrators, chosen to minimize the telescope slewing time, were observed for 1.5 min at each frequency every ~20 min.

Data reduction was carried out following the standard procedures for the VLA, implemented in the AIPS package. In order to obtain accurate flux density measurements in the L band, it was necessary to image several confusing sources falling within the primary beam and often accounting for most of the flux density within the field of view. The final images were produced after a few phase-only self-calibration iterations and source parameters were measured using the task JMFIT, which performs a Gaussian fit on the image plane. The integrated flux density was checked with TVSTAT. The flux density measurements at each frequency and epoch are reported in Table A1. Apart from J0111+3908, which was already known to possess extended emission (Tinti et al. 2005), the other sources are unresolved with the VLA in C configuration.

The uncertainty in the amplitude calibration, σ_c, that results is within 3 per cent in L, C and X bands and 10 per cent in K and Q bands. Strong radio frequency interference affected the 1.665-GHz data, causing larger amplitude uncertainties of about 10 per cent at this frequency.

The rms noise level on the image plane is not relevant for bright radio sources like our targets. In this case, the uncertainty in the flux density, σ_S, is roughly equal to σ_c.

A2 Flux density variability

The spectra obtained by simultaneous multifrequency observations were fitted using the task discussed in Section 3.2. The peak frequency and peak flux density are reported in Table A1.

To investigate the presence of some variability, we compare the flux densities with those measured in previous epochs and reported in Dallacasa et al. (2000), Tinti et al. (2005) and Orienti et al. (2007). Following Orienti et al. (2007), we computed the variability index V, defined as

$$V = \frac{1}{n} \sum_{i=1}^{n} \frac{(S_i - S)_{\text{var}}}{{\sigma_i}_{\text{var}}}.$$
Table A1. VLA flux density and spectral parameters. Column 1: source name; columns 2, 3, 4, 5, 6, 7, 8 and 9: flux density at 1.4, 1.7, 4.5, 4.9, 8.1, 8.4, 22 and 43 GHz; columns 10 and 11: peak frequency and peak flux density, respectively; column 12: variability index computed following Orienti et al. (2007).

| Source         | $S_{1.4}$ | $S_{1.7}$ | $S_{4.5}$ | $S_{4.9}$ | $S_{8.1}$ | $S_{8.4}$ | $S_{22}$ | $S_{43}$ | $\nu_p$ | $S_p$ | $V$ |
|----------------|-----------|-----------|-----------|-----------|-----------|-----------|---------|---------|--------|------|-----|
| J0003+2129     | 93 ± 9    | 113 ± 17  | 245 ± 7   | 247 ± 7   | 206 ± 6   | 199 ± 6   | 55 ± 4  | 14 ± 2  | 5.0 ± 0.3 | 241 ± 2 | 13.6 |
| J0005+0524     | 182 ± 18  | 203 ± 30  | 203 ± 6   | 197 ± 6   | 170 ± 5   | 167 ± 5   | 93 ± 6  | 52 ± 5  | 3.0 ± 0.1 | 213 ± 1 | 2.6  |
| J0037+0808     | 113 ± 11  | 125 ± 19  | 290 ± 9   | 297 ± 9   | 288 ± 9   | 285 ± 9   | 156 ± 11 | 83 ± 8  | 7.0 ± 0.1 | 290 ± 1 | 2.0  |
| J0111+3906     | 437 ± 44  | 578 ± 87  | 1326 ± 40 | 1350 ± 40 | 969 ± 30  | 930 ± 28  | 290 ± 20 | 100 ± 10 | 5.1 ± 0.5 | 1244 ± 4 | 0.4  |
| J0116+2422     | 104 ± 10  | 121 ± 18  | 242 ± 7   | 243 ± 7   | 234 ± 7   | 230 ± 7   | 135 ± 13 | 73 ± 7  | 6.7 ± 0.1 | 240 ± 2 | 0.5  |
| J0428+3259     | 173 ± 17  | 208 ± 31  | 500 ± 15  | 510 ± 15  | 503 ± 15  | 497 ± 15  | 231 ± 16 | 94 ± 9  | 6.5 ± 0.1 | 516 ± 2 | 2.0  |
| J0625+4440     | 127 ± 13  | 130 ± 20  | 144 ± 4   | 146 ± 4   | 145 ± 4   | 122 ± 8   | 90 ± 9  | 5.1 ± 1.0 | 149 ± 1 | 530.8 |
| J0642+6758     | 210 ± 21  | 257 ± 39  | 383 ± 11  | 381 ± 11  | 339 ± 10  | 322 ± 10  | 160 ± 11 | 71 ± 7  | 4.9 ± 0.2 | 378 ± 7 | 7.4  |
| J0646+4451     | 746 ± 75  | 922 ± 138 | 2855 ± 86 | 2991 ± 90 | 3490 ± 105 | 3500 ± 105 | 2676 ± 187 | 1623 ± 162 | 10.4 ± 0.1 | 3524 ± 1 | 7.7  |
| J0650+6001     | 569 ± 57  | 685 ± 103 | 1199 ± 36 | 1197 ± 36 | 1044 ± 31 | 1022 ± 31 | 523 ± 37 | 249 ± 25 | 5.5 ± 0.1 | 1146 ± 3 | 1.4  |
| J0655+4100     | 242 ± 24  | 258 ± 39  | 363 ± 11  | 368 ± 11  | 369 ± 11  | 370 ± 11  | 333 ± 23 | 213 ± 21 | 7.5 ± 0.1 | 389 ± 1 | 4.8  |
| J2136+0041     | 4191 ± 419 | 5256 ± 788 | 10100 ± 303 | 10079 ± 302 | 9111 ± 273 | 8847 ± 265 | 4792 ± 335 | 2749 ± 275 | 6.2 ± 0.1 | 9600 ± 5 | 43.0 |
| J2203+1007     | 121 ± 12  | 156 ± 23  | 313 ± 9   | 311 ± 9   | 249 ± 7   | 239 ± 7   | 73 ± 5  | 24 ± 2  | 4.9 ± 0.2 | 300 ± 1 | 0.4  |

where $S_i$ is the flux density at the $i$th frequency measured at one epoch, $\overline{S}_i$ is the mean value of the flux density computed by averaging the flux density at the $i$th frequency measured at all available epochs, $\sigma_i$ is the rms of $S_i - \overline{S}_i$, and $m$ is the number of sampled frequencies. We prefer to compute the variability index for each epoch instead of considering all epochs together, in order potentially to detect small outbursts.

Significant variability is found in the sources J0625+4440 and J2136+0041, which were already classified as blazars and removed from the sample (Orienti & Dallacasa 2008a). The sources still considered as young radio source candidates do not show significant variability.

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