Proper motion and apparent contraction in J0650+6001

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ABSTRACT

We present a multi-epoch and multifrequency very long baseline interferometry (VLBI) study of the compact radio source J0650+6001. In VLBI images, the source is resolved into three components. The central component shows a flat spectrum, suggesting the presence of the core, while the two outer regions, with a steeper spectral index, display a highly asymmetric flux density. The time baseline of the observations considered to derive the source expansion covers about 15 yr. During this time interval, the distance between the two outer components has increased by 0.28 ± 0.13 mas, that corresponds to an apparent separation velocity of 0.39c ± 0.18c and a kinematic age of 360 ± 170 yr. On the other hand, a multi-epoch monitoring of the separation between the central and the southern components points out an apparent contraction of about 0.29 ± 0.02 mas, corresponding to an apparent contraction velocity of 0.37c ± 0.02c. Assuming that the radio structure is intrinsically symmetric, the high flux density ratio between the outer components can be explained in terms of Doppler beaming effects where the mildly relativistic jets are separating with an intrinsic velocity of 0.43c ± 0.04c at an angle between 12° and 28° to the line of sight. In this context, the apparent contraction may be interpreted as a knot in the jet that is moving towards the southern component with an intrinsic velocity of 0.66c ± 0.03c, and its flux density is boosted by a Doppler factor of 2.0.

Key words: radiation mechanisms: non-thermal – quasars: individual: J0650+6001 – radio continuum: general.

1 INTRODUCTION

The evolutionary stage of a powerful radio source originated by an active galactic nucleus is related to its linear size (LS). In this context, compact symmetric objects (CSOs), which are powerful (L1.4GHz > 1024 W Hz^-1) and intrinsically small (i.e. LS < 1 kpc) radio sources, should represent a young stage in the individual radio source life. These objects usually have a roughly symmetric structure, with core, jets and mini-lobes/hotspots, resembling a scaled-down version of the large classical radio galaxies which conversely have linear sizes of hundreds of kpc or even a few Mpc. The main characteristic displayed by young radio sources is the convex synchrotron radio spectrum that peaks at frequencies in the GHz regime. The spectral turnover is usually due to synchrotron self-absorption (SSA; Snellen et al. 2000; Orienti & Dallacasa 2008), although an additional contribution from free–free absorption has been found in the most compact objects (e.g. Kameno et al. 2000; Mutoh et al. 2002; Dallacasa & Orienti 2009).

Conclusive evidence of the genuine youth of this class of objects came from the determination of both kinematic and radiative ages.

The determination of the kinematic age is based on multi-epoch milliarcsec-scale resolution observations spanning several years, and is able to measure at which rate the hotspots are increasing their separation. Assuming that the separation velocity v_{sep} has maintained constant, the kinematic age t_{kin} can be estimated as

\[ t_{kin} = \frac{LS}{v_{sep}}. \]

From the analysis of a dozen of the most compact CSOs (LS < 20 pc; Polatidis & Conway 2003), it has been derived that the separation speed is generally in the range 0.1–0.4c, leading to kinematic ages of a few thousand years.

The radiative age can be estimated by multifrequency observations able to constrain the radio spectral shape and thus to determine at which frequency the spectral break occurs. The break frequency \( v_{br} \) is strictly related to the radiative lifetime of the synchrotron emitting electrons \( t_{syn} \). Once the magnetic field is known, for example assuming minimum total energy content corresponding to equipartition between particles and magnetic field \( (H) \) energies (Pacholczyk 1970) and following some assumptions (Murgia 2003), the radiative age can be easily estimated by means of

\[ t_{syn} = \frac{v_{br}^{1/2}}{H^{-3/2}}. \]

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Several studies aimed at estimating the radiative age in compact radio objects indicate ages between $10^7$ and $10^8$ yr (Murgia et al. 1999; Murgia 2003), in excellent agreement with the kinematic ages.

Given all the assumptions mentioned earlier, these methods do not provide the accurate source age, that can be improved either by increasing the time interval spanned by the observations or through a better sampling of the frequency coverage used to derive the radio spectrum.

Among all the CSOs studied in this framework, the radio source J0650+6001 represents a peculiar case. This source is identified with a quasar at redshift $z = 0.455$, and its optical spectrum is characterized by very weak broad lines and prominent narrow lines (Stickel & Kühr 1993). It has a non-aligned triple radio structure with a total angular size of 7 mas ($\sim$40 pc), and its total radio spectrum turns over around 5.5 GHz (Orienti, Dallacasa & Stanghellini 2007). From a previous study, no evidence of proper motion has been found (Orienti & Dallacasa 2008), although the resolution at 5 GHz (i.e. the frequency at which several observations spanning almost a decade have been performed) was not adequate to reliably estimate small changes in the component positions. However, another analysis of the position of the source components based on global very long baseline interferometry (VLBI) observations (Akujor, Porcas & Smoker 1996), indicated an apparent contraction between the central and the southern components.

In this paper, we report on the results on multi-epoch VLBI and 5-GHz Very Large Array (VLA) data of the CSO J0650+6001, and we present an interpretation to explain the radio properties of this source.

Throughout this paper, we assume the following cosmology: $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$ and $\Omega_L = 0.73$, in a flat Universe. At the redshift of the target, 1 arcsec = 5.773 kpc. The spectral index is defined as $S(v) \propto v^{-\alpha}$.

2 RADIO DATA

To determine a possible source growth, we complemented the information available in the literature for the target source J0650+6001 with archival VLBA data obtained in 1999 November at 5.0 GHz, and VLBA+Effelsberg observations at 5.0 and 8.4 GHz carried out in 2004 December (see Table 1). The data reduction was carried out by means of the National Radio Astronomy Observatory (NRAO) AIPS package. The accuracy of the amplitude calibration has been estimated to be within 5 per cent. The final images were produced after a number of phase self-calibration iterations. Amplitude self-calibration was applied only once at the end of the process using a solution interval of 30 min, i.e. longer than the scan length, to remove residual systematic errors and to fine tune the flux density scale, but not to force the individual data points to follow the model.

To construct a well-sampled light curve at 5 GHz, we complemented the information already available in the literature with archival VLA observations (see Table 2). We retrieved and analysed only data sets in which the source had been observed for at least 5 min in the $C$ band. Since the peak frequency is close to 5 GHz, observations carried out at frequencies in the range of about 4.9 and 5.0 GHz do not cause significant scatter on the determination of the light curve. Data were reduced following the standard procedure implemented in the NRAO AIPS package. Uncertainties in the determination of the flux density are dominated by amplitude calibration errors which have been found to be within 3 per cent in all the data sets considered here. VLA images were obtained after several phase-only self-calibration iterations.

3 RESULT

3.1 Radio images

Full resolution VLBI images are presented in Fig. 1. At 8.4 GHz, in addition to the full resolution image, we also produced a low resolution image using the same $uv$ range, image sampling and restoring beam of the image at 5.0 GHz, in order to produce a spectral index map of the source (Fig. 2). No VLA image is presented, since the source is unresolved on the angular scales typical of this interferometer.

For each VLBI image, we provide the observing frequency, the restoring beam plotted on the bottom left corner, the peak flux density in mJy beam$^{-1}$ and the first contour (f.c.) intensity in mJy beam$^{-1}$, which corresponds to three times the off-source noise level. Contour levels increase by a factor 2.

Flux density and angular size of each source sub-component have been measured by means of the task imfit, which performs a 2D Gaussian fit to the source components on the image plane. TVSTAT, which performs an aperture integration on a selected region on the image plane, has been used to measure the total flux density of the source, which results in agreement with the sum of the flux densities of the various sub-components. The parameters derived from the fitting procedure are reported in Table 3.

| Table 2. Multi-epoch VLA flux density at 5 GHz of the source J0650+6001. Column 1: flux density in mJy; Column 2: observing date; Column 3: reference: (1) Ulvestad & Johnston (1981); (2) Perley (1982); (3) O’Dea et al. (1990); (4) this work; (5) Dallacasa et al. (2000); (6) Tinti et al. (2005); (7) Orienti et al. (2007); (8) Orienti & Dallacasa (2008). |
|-----------------|-----------------|-----------------|-----------------|
| Flux            | Obs. date       | Ref.            |
| (GHz)           |                 |                 |
| 906             | 1979 Feb 2      | 1               |
| 830             | 1980 Nov 18     | 2               |
| 916             | 1984 Dec 30     | 3               |
| 940             | 1991 Jul 21     | 4               |
| 969             | 1993 Feb 23     | 4               |
| 1058            | 1995 Sep 24     | 4               |
| 1236            | 1998 Nov 14     | 5               |
| 1136            | 2002 Jul 3      | 6               |
| 1150            | 2003 Sep 14     | 7               |
| 1106            | 2004 Jan 28     | 7               |
| 1180            | 2006 Nov 19     | 8               |

3.2 Morphology

When imaged with the high spatial resolution provided by VLBA+Effelsberg observations, the radio source J0650+6001...
Proper motion and apparent contraction in J0650+6001

Figure 1. VLBA images at 5 GHz (top and centre panels), and at 8.4 GHz (bottom panel) of the target source J0650+6001.

shows a non-aligned triple structure, where the two main components, labelled C and S in Fig. 1, represent almost the 99 per cent of the total source radio emission, in agreement with previous observations (Xu et al. 1995; Akujor et al. 1996; Stanghellini, O’Dea & Murphy 1999; Orienti & Dallacasa 2008). Component C, accounting for 63 and 72 mJy at 5 and 8.4 GHz, respectively, possesses a flat spectrum ($\alpha = -0.05 \pm 0.15$), suggesting therefore the presence of the source core. At 8.4 GHz it is clearly resolved in the north direction, indicating the presence of a jet-like component (labelled J in Fig. 1c) that accounts for 13 mJy. Component S is located at about 16.2 pc and PA $-146^\circ$ with respect to component C, and accounts for 363 and 269 mJy at 5 and 8.4 GHz, respectively. Component N is located at about 20 pc and PA $13^\circ$ with respect to component C, and accounts for 13 and 9 mJy at 5 and 8.4 GHz, respectively. Both components S and N have a steep spectrum with $\alpha^{8.4} = 0.60 \pm 0.15$ and $\alpha^{5.0} = 0.70 \pm 0.30$, respectively. Furthermore, with a flux density ratio $S_5/S_8 = 28–30$, depending on the frequency, components N and S are very asymmetric also in their observed luminosity.

3.3 Proper motion

Decisive evidence supporting the idea that CSOs are radio sources in an early evolutionary stage has been provided by the measurements of the proper motion of the hotspots in compact CSOs (see e.g. Polatidis & Conway 2003). To date, the CSO J0650+6001 lacks...
The light curve of J0650+6001.

Table 4. Observational parameters of the components of J0650+6001. Column 1: source component; Columns 2, 3: flux density at 5 GHz from observations carried out in 1999 and 2004, respectively; Column 4: flux density at 8.4 GHz; Column 5: spectral index between 5 and 8.4 GHz; Columns 6, 7: deconvolved major and minor axis, respectively; Column 8: position angle of the major axis. Spectral index and component angular size are from observations carried out in 2004.

| Comp. | 1999 | 2004 |
|-------|------|------|
|       | $S_{5.0}$ (mJy) | $S_{5.0}$ (mJy) | $S_{8.4}$ (mJy) | $\alpha$ | $\Theta_{maj}$ (mas) | $\Theta_{min}$ (mas) | PA (°) |
| N     | 13   | 9    | 0.70 | 1.07 | 0.27 | 28 |
| C     | 830$^a$ | 644 | 662 | −0.05 | 0.50 | 0.32 | 50 |
| S     | 364  | 363  | 269 | 0.60 | 0.70 | 0.38 | 40 |

$^a$The total flux density of the northern and central components.

a proper measurement of expansion velocity. On the other hand, an apparent source contraction has been reported by Akujor et al. (1996), representing a very uncommon case among radio sources.

To derive a possible source expansion, we decided to measure the distance between components S and N from the VLBA+Effelsberg image at 5 GHz. Then we compared the result with what was reported in Xu et al. (1995), and found that the separation between these two components has increased by 0.28 ± 0.13 mas in 13.5 yr (i.e. the time interval between the two observations). We derive an apparent separation velocity of $v_{s,n} = 0.39c ± 0.18c$, that corresponds to a kinematic age of $t_{\text{kin}} = 360 ± 170$ yr. The accuracy of this separation velocity is limited, since only two-epoch observations are available with adequate resolution and at the same frequency. We do not consider the VLBA observations carried out in 1999 and 2006 (Orienti & Dallacasa 2008), since the resolution was not adequate to reliably constrain the position of the northern component.

To verify the apparent contraction reported by Akujor et al. (1996), we determined the separation between the central and the southern components from 1999 to 2006, and we compared our results with those reported by Xu et al. (1995), Britzen et al. (2007) and Orienti & Dallacasa (2008) (see Table 4). Then we modelled the data with a linear fit and obtained that the separation between components C and S has decreased by about 0.29 ± 0.02 mas in 15.6 yr (i.e. the time interval spanned by the observations), corresponding to an apparent ‘contraction’ velocity $v_{c,s} = 0.37c ± 0.02c$ (Fig. 3). This suggests that component C likely enshrouds both the core region and the jet base which cannot be resolved with the spatial resolution (∼0.6 mas) provided by the observations at the highest frequency. The observed contraction is indicative of a knot in the jet that is moving towards the southern lobe, and it is oriented with a small angle with respect to the line of sight. For this reason the flux density of component C is likely dominated by this knot whose emission is enhanced by boosting effects.

### 3.4 Flux density variability

The light curve at 5 GHz of J0650+6001 clearly indicates a steady increment of the total flux density measured by the VLA over a period of nearly 18 yr (see Section 2). The presence of flux density variability in a CSO is somewhat surprising, since young radio sources have been considered the least variable class of radio sources (O’Dea 1998). However, evidence of an increment in the flux density in the optically thick part of the spectrum may be easily explained in terms of source expansion, assuming that the spectral peak is due to SSA, as in the case of J0650+6001 (Orienti & Dallacasa 2008), the source discussed here. As the source grows, the peak shifts towards lower frequencies, while the flux density in the optically thick regime increases (Pacholczyk 1970).

In Fig. 4, together with the total VLA flux density, we report also the VLBA flux density of components C and S. In the light curve of both the total source and component C, in addition to the steady increment of the flux density, it is also present a further contribution detectable in the 1998 (VLA) and 1999 (VLBA) data. On the other hand, the light curve of component S is almost constant, with a possibly slight steady decrease, but without evidence of significant variability. This behaviour suggests that the total flux density is dominated by component C, that likely had an outburst close to the 1998–1999 observing epoch.

Figure 3. The contraction between the central and the southern components of the source J0650+6001. The line represents the best fit of $v = −0.02$ mas yr$^{-1}$.

Figure 4. The light curve of J0650+6001 at 5 GHz. Crosses indicate the source flux density from VLA data (Table 2), while triangles and squares refer to VLBI flux density of component C and S, respectively. The error bars refer to 3 and 5 per cent of the VLA and VLBI flux density, respectively (see Section 2). In addition to the VLBI data presented in this paper, we include those from Stanghellini et al. (1999), Xu et al. (1995) and Orienti & Dallacasa (2008).
4 DISCUSSION

The determination of the properties of the population of young radio sources is mainly based on the analysis of objects identified with galaxies, where boosting effects are thought to play a minor role. None the less, in some of the sources presented in Polatidis & Conway (2003), jets have been detected and also measured the proper motion of knots (e.g. in the sources J1945+7055 and J2355+4950). The target source J0650+6001 is optically identified with a quasar, and its peculiar characteristics, such as the radio emission dominated by the core component, the high flux density asymmetry between the outer components and their misalignment, may be due to orientation effects that may modify the intrinsic source properties. To verify this hypothesis, we consider a beaming model which assumes that the source is intrinsically symmetric and the different flux density displayed by components N and S is due to Doppler boosting. In this context, the flux density ratio is related to both the jet speed and its orientation $\theta$ with respect to the line of sight:

$$\frac{S_N}{S_S} = R = \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right)^{3/2},$$

where we have assumed that component S is the one on the approaching side and $\beta = v/c$, where $c$ is the speed of light. From VLBI data, we found that $R = 28 - 30$, depending on the frequency considered, and $c = 0.7 \pm 0.3$. With these values in equation (1), we find the possible combination of $\beta$ and $\theta$, reported in Fig. 5 between dotted lines. We must note that although equation (1) usually applies to jet components, it can be used also to our purpose, since components N and S are hotspot dominated and an additional contribution from extended features like lobes is marginal since their high magnetic field (Orienti & Dallacasa 2008) causes strong radiative losses at least at the frequencies considered here.

Another way to derive the ($\beta - \theta$) combination is from the measured separation velocity $v_{s,a}$ between components N and S, by means of

$$v_{s,a} = \frac{2 \beta_{s,a} \sin \theta}{1 - \beta_{s,a}^2 \cos^2 \theta}.$$

Considering $v_{s,a} = 0.39c \pm 0.18c$, as determined in Section 3.3, the resulting possible ($\beta - \theta$) combinations are reported in Fig. 5 between solid lines. Comparing the areas obtained with the two different methods, we obtain an intrinsic separation velocity $v_{s,i} = 0.43c \pm 0.04c$ and a source orientation with respect to the line of sight of $12^\circ$ and $28^\circ$.

The comparison of the flux density of the outer components may not be always appropriate. In fact, given the relativistic time dilation, we are watching the components at different stages of their evolution. This is particularly important in the case of blazars whose jets are oriented with very small angles $\theta < 5^\circ$ to the line of sight, causing a quite rapid evolution due to boosting effects. On the other hand, this effect should not be relevant for J0650+6001 if we consider that the lobes/hotspots of this source are oriented at a relatively larger angle, as also supported by the lack of flux density variability in the southern component.

Another way to determine the ($\beta - \theta$) combination is based on the comparison of the distance of the two lobes with respect to the core. However in this source, the central component is likely dominated by a knot in the jet, thus precluding the determination of the core position. The apparent contraction between components C and S clearly indicates the presence of a compact component moving towards south with apparent speed $v_{c,a} = 0.37c \pm 0.02c$. If in equation (2) we consider the apparent separation velocity computed in Section 3.3 and the same orientation as derived from Fig. 5, we find that this knot has a mildly relativistic intrinsic velocity $v_{c,i} = 0.66c \pm 0.03c$.

With the derived values we can compute the Doppler factor of the jet knot by means of

$$D = \frac{1}{\Gamma_{c,i}(1 - \beta_{c,i} \cos \theta)},$$

where $\Gamma_{c,i} = 1/\sqrt{1 - \beta_{c,i}^2}$ is the Lorentz factor.

If in equation (3) we consider that the knot in the jet in component C is moving with $v_{c,i} = 0.66c \pm 0.03c$, and it is oriented with an angle between $12^\circ$ and $28^\circ$ to the line of sight, we derive a Doppler factor $D \sim 2$, which is consistent with the peculiarly high observed flux density shown by the central component. In the case, the whole flux density of component C is attributed to a knot in the jet. We can compute the intrinsic flux density $S_{int}$:

$$S_{int} = S_{obs}D^{-3/2},$$

where $S_{obs}$ is the observed flux density. If in equation (4) we consider the observed flux density reported in Table 3, $D \sim 2$ as derived above and $\alpha = 0.7$, we find that the intrinsic flux density of component C, i.e. core+jet region, is about 50 mJy at both 5 and 8.4 GHz, in good agreement with what is expected for the central component of radio sources.

Another explanation for the misaligned source structure and its high flux density asymmetry may be caused by an inhomogeneous external environment. In fact, in the case the two jets/hotspots experience different ambient properties on the two sides of the radio source, the side hitting the most dense medium has its expansion slowed down and its radio emission enhanced, since the energy losses due to adiabatic expansion are smaller with respect to the other side. This ends up with the brighter and smaller radio component lying closer to the core. If this is the case, the model developed assuming beaming effects becomes meaningless, and the source may thus be oriented even at larger angles to the line of sight, making the estimation of the intrinsic velocity an upper limit.

**Figure 5.** The ($\theta - \beta$) plane for J0650+6001, as derived from the northern and southern components. The solid lines represent the limits derived from the apparent separation velocity ($\beta_{s,a} = 0.39 \pm 0.18$), while the dotted lines refer to limits inferred from the flux density ratio.
5 CONCLUSIONS

We have presented multi-epoch VLBI and VLA observations of the radio source J0650+6001. The source shows a peculiar triple structure, where the outer components are misaligned with respect to the central flat-spectrum region, and a high flux density asymmetry. The comparison between multi-epoch high spatial resolution observations indicated that the farthest components are increasing their distance with an apparent separation velocity \( v_{\text{sa}} = 0.39c \pm 0.18c \). Assuming that this velocity is representative of the mean separation speed, we obtain a source kinematic age of 360 \( \pm \) 170 yr. On the other hand, the distance between the central component and the southern lobe has decreased with a mean apparent contraction speed \( v_{\text{ca}} = 0.37c \pm 0.02c \). To explain these peculiar characteristics, we discussed an interpretation based on relativistic beaming effects. From this analysis, we drew a picture in which the source is oriented with an angle between 12° and 28° to the line of sight, with the southern component being the approaching side of the source. The intrinsic separation velocity is \( v_{\text{si}} = 0.43c \pm 0.04c \). The apparent contraction observed between the central and the southern components may be explained in terms of a knot in the jet that dominates the radio emission of the central component, that is moving towards the southern component with a mildly relativistic intrinsic velocity \( v_{\text{ci}} = 0.66c \pm 0.03c \), and with a Doppler factor \( D = 2 \), which causes a moderate boost of its flux density. The monitoring of the flux density variability and the study of the component separations on a longer time-scale will be crucial to better determine the nature of this source.

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