Global 3- and 7-mm VLBI Observations of OJ287

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Abstract. We present here the results obtained from global mm VLBI observations at 43 GHz and 100 GHz of the BL Lac object OJ287. The visibility data at 43 GHz reproduced a multi-component structure for OJ287 consisted of a core and other three components. Assuming that they are superluminal components, the zero separation of them is in quite good agreement with the increase of total flux density. The proper motions of these components are in the range 0.2–0.4 mas per year which are consistent with known proper motions for OJ287. The visibility data at 100 GHz show solely a strong point source and, a new component, if present, must be very weak or within the noise level of the present VLBI.

1. Introduction

A non thermal variable point source at radio frequencies and absence of line in optical are the main signatures of BL Lac objects. Their high luminosity at millimeter wavelengths put them as an obvious candidate for millimeter VLBI. As a remarkable member of BL Lac objects, OJ287, presents evidence of superluminal motion as well as prolific variability time scale, spanning from a long periodic variability of 11.6 year (Sillanpää\textit{ et al.}, 1988) to short time scale variability of days or hours. The VLBI superluminal components have been associated with variability of about several months to year. The nature of underlying galaxy is not known, Kinman (1975) and Hutchings\textit{ et al.} (1984) detected a nebulosity that might be a galaxy. The red shift was measured from a single emission line as $z = 0.306$ (Miller\textit{ et al.}, 1978; Sitko and Junkkarinen, 1985). The first indication of superluminal motion on OJ287 was obtained from polarization data at 5 GHz VLBI observations (Roberts\textit{ et al.}, 1987). Thus far 3 superluminal components were followed from 1981 to 1986, all components appear to move along the same rectilinear trajectory at structural position angle of $-100^\circ$ with no evidence for bending. Recent global VLBI observations at 3 mm (1988 and 1989) have shown an unresolved source with a linear size less than $10^{17}$ cm (Bååth\textit{ et al.}, 1992).

Throughout this paper we will assume the standard Friedmann cosmology with $H_0 = 100$ h km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. At redshift of 0.306, an angular size of 1 mas corresponds to a linear distance of 2.8 h$^{-1}$ pc.
2. Observations

The observations of OJ287 at 100 GHz were carried out on 20 April 1990 using VLBI Mk III and processed on the correlator of the Haystack Observatory. The fringes were detected for the following antennas: Hat Creek (California), Kitt Peak (Arizona), SEST (Chile) and Onsala (Sweden). The Global Fringe Fitting was applied to fit delays and rates to find fringes (BÅÅTH, 1991). The data have then worked on Caltech package and the convoluting beam was 72 × 48 microseconds of arc at PA −13°.

The 43 GHz observations were obtained on 8 April 1991. The data were recorded on Mk III with bandwidth of 56 MHz and correlated at MPIfR in Bonn. Each VLBI scan length had a duration of 13 min. After fringe fitting the data were segmented to the length corresponding to the coherence time of 26 sec and then proceeded with edition of data using Caltech Package. The visibility data were obtained from antennas at Effelsberg (Germany), Onsala (Sweden), Haystack (Massachusetts), OVRO (California) and Pie Town (New Mexico). The beamwidth was 0.35 × 0.10 mas at PA = −17°. More details of observations and data analysis are described by KRICHBAUM et al. (1990) for 7 mm data and BÅÅTH et al. (1992) for 3 mm data.

3. Discussion

Now global VLBI observations at 100 GHz have been carried out for 3 epochs, each observing session was separated by a period of one year. The first and second epoch map of OJ287 showed an unresolved source (BÅÅTH et al., 1992). The third epoch (1990.3), the present data, includes a Southern antenna on the array giving a more circular beam, and further emphasizing the compact structures. The result of the observation is qualitatively very similar to the previous maps, showing no other structure than an unresolved source. Figure 1 shows the visibility data at 100 GHz. All baselines give an almost constant average correlated flux density of ~1.7 Jy, indicating a point source. Rigorously, nor the amplitudes are all equal and neither the phases are all zeroes as expected for a point source. The short observation time and the sparseness of the data do not allow us to go much further than this. A new component, if present, must be very weak and within the noise level of present VLBI. On the other hand 43 GHz VLBI data show a better \( \nu \) \( \nu \) coverage and by far a longer observation time. The visibility data are in Fig. 2. It is clear that a single component or even 2 component model does not suffice to reproduce the main features of the visibility curves. For instance, the maximum flux density is always less than ~1 Jy, except for the short baseline Onsala-Effelsberg where the flux density reaches a maximum around 1.5 Jy indicating some extended component or a presence of more than one component. Figure 3 shows the Gaussian component model of OJ287 at 43 GHz. The appearance of the source is shown by a multicomponent structure, with an indication of sinusoidal bending (changing of the sign of \( dPA/\Delta r \)). Thus the new components in the sub parsec region do not seem to follow a fixed rectilinear
trajectory, as suggested from VLBI maps made at centimeter wavelength where a set of single superluminal sources appears moving along a structural position angle of $-100^\circ$ (ROBERTS et al., 1987; GABUZDA et al., 1989). So, the disposal of the components at 43 GHz indicates a scenario as follows. Initially new components emerging from the core follow a curved trajectory in the sub-parsec region and then at distances greater than 1 milliarcsecond they proceed moving straight outward at fixed position angle of $-100^\circ$ as seen from VLBI components obtained at centimeter wavelengths. The present status of microarcseconds resolution VLBI, probing structure on the sub-parsec/parsec scale of AGN sources, has revealed a much more complex structure than seen at larger scale. Motion along a curved path in the sub-parsec/parsec scale is not uncommon and has been found in 3C273 (KRICHBAUM et al., 1990), 3C345 (KRICHBAUM and WITZEL, 1992), 3C84 and 1803+78 (KRICHBAUM, 1990). Idealized models explaining the curved path exist as a precession of the central source of energy, or like a Kelvin-Helmholtz instability giving rise to a helical path (HARDEE, 1987, 1990), or still a motion along curved path reflecting a magnetic field structure. Although all three interpretations are applicable to the present data, the precessing jet has been ruled out for other sources because it has been shown that each single component is actually moving in a curved path. In the case of OJ287 the influence of magnetic field might play an important role as depicted from VLBI polarization which is known to present high degree of polarization.
Fig. 2. The visibility data of OJ287 at 43 GHz (epoch 1991.3). The measured visibility amplitudes, phases and closures phases are superimposed with 4 component model.

The size of the components increases towards outer components, suggesting that the components are not constrained by a narrow jet, instead, a simple estimate of the observed opening angle, using the component A, gives a value of 42°. It is larger than the observed opening angles obtained for BL Lac (30°, MUTEL et al., 1990) or for 3C345 (27°, BIRETTA et al., 1986). This rather large observed opening angle must put the jet rather away from the line of sight and near the direction which maximizes the velocity of the components. This agrees with the results obtained by MUTEL et al. (1990) for the BL Lac, that the BL Lac sources do not necessarily need to be aligned to the observer’s line of sight. By polarization arguments CATHORNE and WARDLE (1988) also showed that the motion of OJ287 components is intrinsically slow.

Unless the components are confined in a fixed curved path, the large opening angle, as suggested from size and distribution of components in the map, may indicate that the opening angle near the flaring region is greater, leading to a free jet due to steep pressure gradient. To allow for components with straight motion at
Fig. 3. Gaussian component model of OJ287 at 43 GHz corresponding to the parameters listed on Table 1. The contours are 0.5, 2, 4, 8, 16, 32, 64 and 90% of the peak flux density (0.71 Jy/beam).

distances greater than 1 mas from the core, collimation or reconfinement must occur. Within the helical path geometry, some fine tunings of helical parameters are required to reconcile the curved and the straight portion of the motion.

Let us now do some additional comments concerning to the morphology seen at 43 GHz. Despite of its multi-component structure, the only component that could be seen at 100 GHz is the outer component (A), the component at 0.28 mas (B) might just be starting to brighten up at the time of 100 GHz VLBI observations (assuming that the proper motion is about 0.3 milliarcseconds per year). Another point is that, there is a higher number of new components emerging from the core as compared to only 3 components seen at 5 GHz VLBI during the 1981–86 period. It might be acceptable for an active source like OJ287, and finally, the components B and C (separation of ~0.13 mas between them) would appear merged if they were placed at the position of component A. The component A may be itself a merged component as we will see later, its size is 0.66 mas (see Table 1).

As we mentioned before an additional component could be included on the map of 100 GHz by extrapolating the position of the component derived from the model
Table 1. OJ287 at 3 mm and 7 mm. P.A. is the position angle of the component at radius $r$, while the Axis is the major axis of the elliptical Gaussian which has a position angle of $\Phi$. The axial ratio is given by ratio.

<table>
<thead>
<tr>
<th>Freq. [GHz]</th>
<th>Epoch</th>
<th>Flux [Jy]</th>
<th>$r$ [mas]</th>
<th>P.A. [°]</th>
<th>Axis ratio</th>
<th>$\Phi$ [°]</th>
</tr>
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<tr>
<td>43</td>
<td>1991.35 core</td>
<td>0.807</td>
<td>0.000</td>
<td>0</td>
<td>0.076</td>
<td>0.59</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>0.227</td>
<td>0.157</td>
<td>-82</td>
<td>0.077</td>
<td>0.75</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>0.389</td>
<td>0.282</td>
<td>-129</td>
<td>0.289</td>
<td>0.51</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>0.449</td>
<td>0.720</td>
<td>-75</td>
<td>0.656</td>
<td>0.46</td>
</tr>
<tr>
<td>100</td>
<td>1990.39 core</td>
<td>1.750</td>
<td>0.000</td>
<td>0</td>
<td>0.003</td>
<td>0.60</td>
</tr>
<tr>
<td>A</td>
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<td>0.100</td>
<td>0.430</td>
<td>-78</td>
<td>0.040</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Fig. 4. The light curve of OJ287 at 22 GHz and 37 GHz. This figure is adapted from Teräsranta et al. (1992). The additional data from 1990 to 1991 was provided by Teräsranta. The filled diamond represents the 37 GHz data and the arrows indicate the zero-separation time of the components A, B and C. The epoch of 43 GHz and 100 GHz observations are also indicated.

Fitting of 43 GHz data. Although the two component fitting at 100 GHz gives a smoother fit to the visibility data, an independent identification of the components seen at 43 GHz may come from variability of the total flux. The relationship between radio burst and the appearance of a new component has provided a good constraint to identify a structural change on the map. The light curve at 22 GHz and 37 GHz (Fig. 4) shows an increase of flux density from 2 Jy to 7 Jy in about 1.5 months, if the zero separation of the outer component is placed at the beginning of May 1989, then the angular speed is about 0.37 mas per year. In addition, before the total intensity has decreased considerably another radio outburst is seen starting on about middle of August and beginning of September. Although it gives rise to a somewhat high value of the proper motion (0.43 mas per year, assuming a non curved
trajectory), the short period of time between outbursts provides a further support that the outer components may be merged at distance about 1 mas or less. There is also an indication of the merging of the knots on the early VLBI maps made at centimeter wavelengths (GABUZDA et al., 1989). The corresponding births for other two inner components B and C give the proper motions of 0.25 mas per year and 0.23 mas per year respectively, well within the known values of proper motions for OJ287.

Briefly we can say that the structure at 100 GHz is solely dominated by a single strong core component and the morphology at 43 GHz is a multi component structure. Some points of these differences can be put as follows: 1) the sensitivity and \(\mu\)-coverage at 43 GHz are better than those at 100 GHz, although a similar ratio of flux density between each component and core should be detected at 100 GHz, 2) the two components, B and C, at 43 GHz could not have appeared as new separated component at 100 GHz, and 3) the spectrum of components A, B and C must be steep.

4. Summary

The VLBI observations at 43 GHz revealed a complex structure in the inner 1 mas of the OJ287 map. The appearance of the map shows 3 components aligned in a sinusoidal structure with the size of each component increasing towards outer component. The components were also identified with major radio outbursts giving a proper motion in the range of 0.23 to 0.43 mas/year.

We thank T. P. Krichbaum and his collaborators for 43 GHz VLBI data and L. B. Bååth and his collaborators for 100 GHz VLBI data. C. E. Tateyama thanks the scholarship granted by CNPq-Conselho Nacional de Desenvolvimento Científico e Tecnológico to pursue a Post-doctoral training at Nobeyama Radio Observatory. He also thanks S. Kamenova for many invaluable helps and he also wants to express his gratitude to M. Morimoto.

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