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APPARENT INWARD MOTION OF THE PARSEC-SCALE JET IN THE BL LAC OBJECT OJ287 DURING THE 2011-2012 γ-ray FLARES

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ABSTRACT

We present a kinematic study of the parsec-scale radio jet in OJ 287, one of the most studied BL Lac objects, during γ-ray flares, to explore the relation between parsec-scale radio jet activity and γ-ray emission. The 22-GHz light curve of OJ 287 show three obvious flare events around 2011 May, 2011 October, and 2012 March. The second radio flare occurred during the γ-ray flaring period, and the third radio flare seemed to precede the γ-ray flare by one month. One jet component moved outward with respect to the core component with an apparent superluminal speed ($\sim 11c$) from 2010 November to 2011 November. Then it changed direction, moving apparently inward in 2011 November, when the γ-ray flare occurred. The observed apparent inward motion of the jet at 22 GHz could be caused by a new jet component, unresolved at 22 GHz, in the innermost region.

Key words: jgalaxies: active — galaxies: jets — galaxies: individual (OJ 287) — radio continuum: galaxies — gamma rays: galaxies

1. INTRODUCTION

OJ 287 is one of the most studied BL Lac objects, and is known to show a strong variability across a wide range of wavelengths (Abdo et al., 2010). However, in spite of vigorous observations at various bands, the mechanism of such flares in OJ 287 still remains unclear.

Very Long Baseline Interferometry (VLBI) monitoring toward BL Lac objects allows us to identify the location of the flaring event at parsec scales. Recent reports of long-term (> 15 years) VLBI monitoring observations revealed a swinging jet (Agudo et al., 2012) and parallel trajectories of jets (Tateyama, 2013) on sub-milliarcsecond scales. Agudo et al. (2011) reported a strong correlation between the millimeter radio and γ-ray emissions from their monthly VLBI monitoring program during 2008–2010. Agudo et al. (2011) also suggested that the γ-ray emitting site is located at a distance > 14 pc from the central engine. The time scale of the radio flux variability seen in AGNs is often shorter than one month (Lazio et al., 2001; Kadota et al., 2012), and therefore it is important to carry out frequent VLBI monitoring observations on a time intervals of weeks.

2. OBSERVATIONS AND DATA REDUCTIONS

We collected VLBI data for OJ 287 at 22 GHz from 2010 November to 2012 September with the VLBI Exploration of Radio Astrometry (VERA). Data reduction including calibration, data flagging, fringe fitting, self-calibration and imaging, was done using the NRAO AIPS package. By using the AIPS task `JMFIT` on the images, we estimated the position and flux density of each component by fitting three Gaussians: C1, J1 and J2.

The data collected by *Fermi*-LAT (Atwood et al., 2009; Ackermann et al., 2012) from 2010 November 1 (MJD 55501) to 2012 October 31 (MJD 56231) were analyzed with the `ScienceTools` software v9r32p5 using an unbinned maximum-likelihood method implemented in the tool `gtlike`, with the `P7REP_SOURCE_V15` instrument response functions and following the standard procedures described in the LAT documentation[1].

Throughout the paper, we adopt a Λ-CDM cosmology with $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 0.27$ and $\Omega_\Lambda = 0.73$ (Komatsu et al., 2009), and hence 1 mas corresponds to 4.5 pc, and 1 mas yr^{-1} corresponds to 19 c at the

[1]http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/

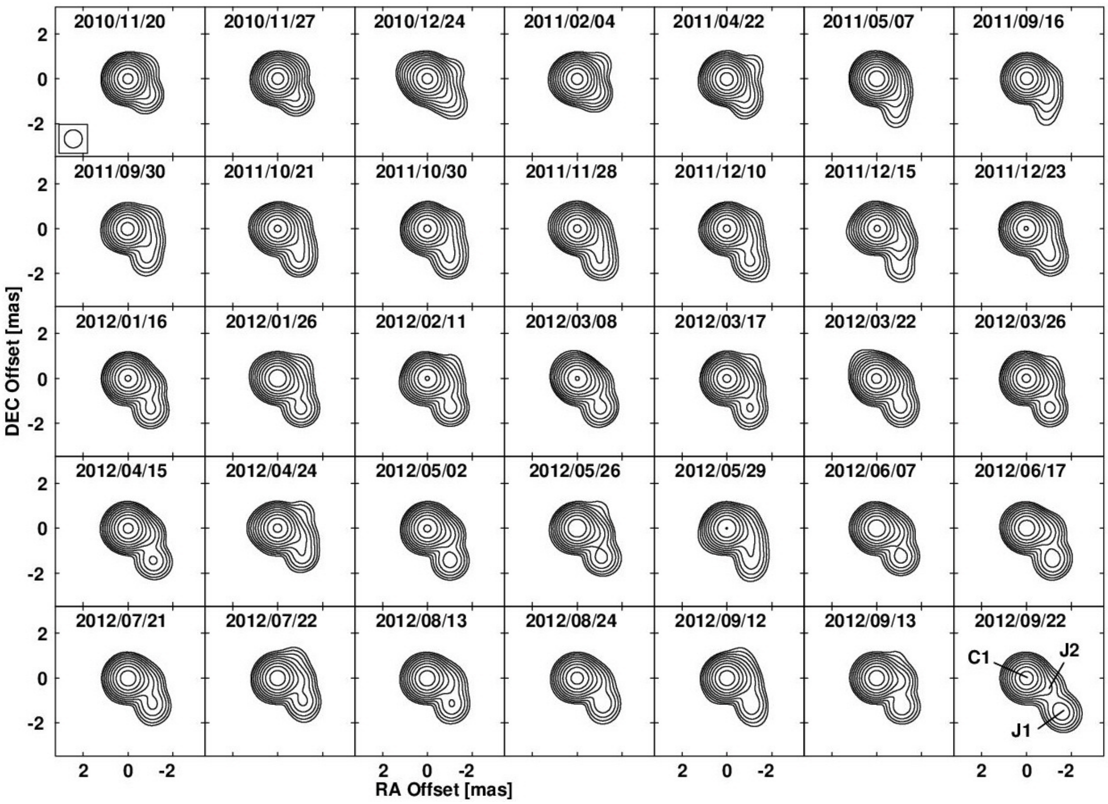

Figure 1. Sequence of VERA 22-GHz images of OJ 287 from 2010 November to 2012 September. Images are convolved with a circular beam size (FWHM) of 0.8 mas, which corresponds to the typical minor axis of synthesized beam in our observations. Contours start at 9 mJy beam^{-1} (typical 3 σ level), increasing by a factor of 2. The structure can be resolved into three components, the core component (C1), the jet component (J1) and the inner jet component (J2) located between C1 and J1.

distance of OJ 287.

3. RESULTS

3.1. Parsec-scale Structure

The 22-GHz images of OJ 287 (Figure 1) show a south-west oriented core-jet structure with a linear size of 1–2 pc, consistent with other VLBI images observed in 2011 and 2012 (Agudo et al., 2012; Tateyama, 2013). The core-jet structure is represented by the three components described above: C1, J1 and J2. The components C1 and J1 are identified as ‘C’ and ‘j’ in the VLBA 43-GHz images by Agudo et al. (2012). We did not resolve the inner jet components ‘a’, ‘l’, ‘m’, ‘n’, ‘o’ and ‘p’ visible on the VLBA 43-GHz images of Agudo et al. (2012), due to the lower resolution of the 22-GHz VERA observations. These inner components are thus included in components C1 or J2.

3.2. Radio and γ-ray Light Curves

The 22-GHz VERA light curve of the C1 component of OJ 287 reveals three flaring periods during 2011–2012, in 2011 May, 2011 October and in 2012 March (Figure 2a). The second and third radio flaring events seem to be connected with flares detected at γ-ray, X-ray, optical and infrared in 2011 October and 2012 March (Escande & Schinzel, 2011; Larionov et al., 2011; D’Ammando et al., 2011; Stroh & Falcone, 2013; Pihajoki et al., 2013). The γ-ray light curve of OJ 287 for the period from 2010 November to 2012 October (Figure 2b) revealed two pronounced γ-ray flares, in 2011 October Escande & Schinzel (2011) and 2012 April (D’Ammando et al. 2014, in prep.), with daily peak fluxes of 1.0×10^{-6} and 7.2×10^{-7} photons (E $>$ 0.1 GeV) cm^{-1} s^{-1} on 2011 October 27 and 2012 April 16, respectively. The second radio flaring event took place during the first γ-ray flaring period. On the other hand, the third radio flaring event preceded the second γ-ray flare by $\sim$ 30 days.

3.3. Radio Jet Motion

The relative motion of J1 with respect to C1 is shown in Figure 3a. From 2010 November to 2012 September, J1 moved from the core toward the south-west, in agreement with the previous 43-GHz VLBA images of Agudo et al. (2012). From 2010 November to 2011 April, the relative position of J1 was at $(x, y) \simeq (-0.8, -0.7)$ in Figure 3a and then moved with a PA of $\sim -160°$ until 2011 November. The motion of J1 sharply changed direction to the opposite in 2011 November, just after the second radio flare. Then, J1 showed a northward motion again in 2012 July, switched direction to the south-west in 2012 September. The apparent average radial velocity from 2010 November to 2011 November was es-

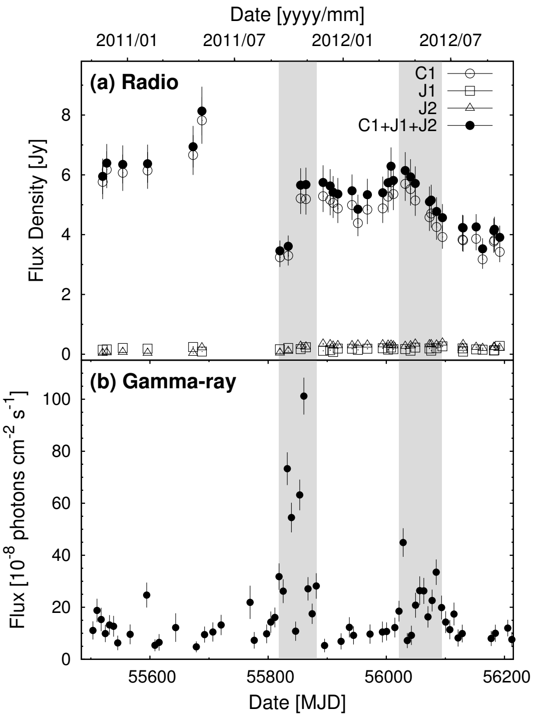

Figure 2. (a) Light curve of each component in OJ 287 at 22 GHz observed with the VERA. The error on the flux density is 10%. (b) Light curve of γ-rays (0.1–100 GeV) with 7-day time bins observed using the *Fermi* LAT. Only points with $TS > 10$ are reported. The γ-ray flaring periods are indicated with gray rectangles ($> 2.5 \times 10^{-7}$ photons cm^{-2} s^{-1}).

timated using a linear fit, giving (0.57 ± 0.09) mas yr^{-1}, which corresponds to a projected apparent superluminal speed of (11 ± 2) c in the plane of sky (Figure 3b, the green line). The apparent inward motion is (-0.2 ± 0.1) mas yr^{-1}, which corresponds to (-4 ± 2) c (Figure 3b, the red line).

4. DISCUSSION

We discuss possibilities for the apparent inward motion between C1 and J1 as follows: (1) a temporary positional shift due to an unresolved emerging jet component and the core component, and (2) a highly curved jet trajectory across the line of sight.

Scenario 1 implies the combination of a newly emerging jet component and a core, not resolved by the synthesized beam. A new jet component could have been ejected in the period when the apparent inward motion was seen. No newborn jet component was found in the 22-GHz VERA images, but the relative position of J1 from 2011 November to 2012 August moved backward and forward along a line at a PA of $\sim -30°$, nearly parallel to the direction of the innermost jet components 'C', 'o', 'p' and 'n' in the 43-GHz VLBA images of Agudo et al. (2012). The rapid change of the brightest part in the innermost region can cause a rapid positional change of the intensity-weighted core center, resulting in a core wobbling behavior. These observed characteristics support the idea that component C1 in the 22-GHz VERA images include contributions from the innermost jet components. It suggests that the apparent inward motion of C1 could be produced by the appearance of a new component moving along the jet but still too close to the core component to be resolved by our observations, or too faint to be detected due to the limited dynamic range of the 22-GHz VERA images. The apparent inward motion was detected in the high state period of γ-rays, as shown in Figure 2b. This is similar to the pattern seen in bright TeV γ-ray source Mrk 421 Niinuma et al. (2012). It may suggest that the γ-ray flare is closely related to a new jet ejection event.

In scenario 2, the projected separation between the core and the jet components appeared to decrease due to a highly curved jet trajectory across the line of sight. If the apparent inward motion of J1 is due to a highly curved trajectory, the flux density of J1 would show time variability due to a Doppler factor variation of geometrical origin. Our radio light curve of J1, however, indicates a constant flux density of J1 (Figure 2a) during the inward motion. Thus, there is no observational evidence for the highly curved motion of J1.

5. CONCLUSIONS

We have performed frequent VLBI monitoring of OJ 287 at 22-GHz from 2010 November to 2012 September, and compared the results with the γ-ray light curve obtained by the LAT on-board *Fermi* during the same period. The 22-GHz light curve of OJ 287 shows three radio flare events in 2011 May, 2011 October and 2012 March. The second radio flare took place during the γ-ray flaring period in 2011 October and the third radio flares seemed to precede the γ-ray flare in 2012 April by ~ 30 days, unlike the previous behavior observed during the γ-ray flare in 2009. We detect an apparent inward motion of the parsec-scale jet in OJ 287 during the period from 2011 November to 2012 August, and we note that two γ-ray flares also occur during the same period.

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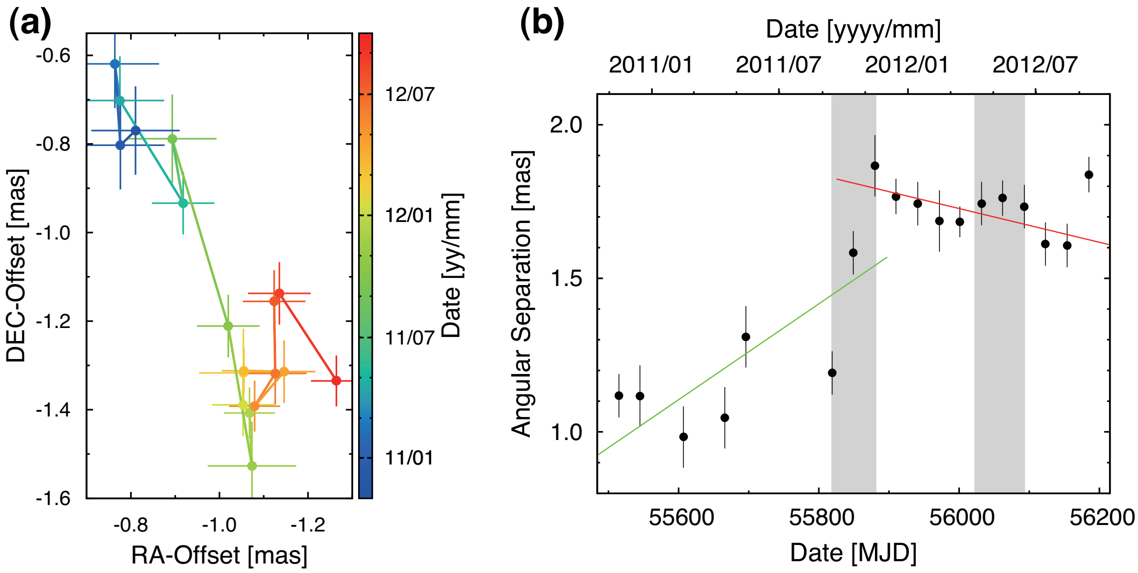

Figure 3. (a) Relative motion of the jet component J1 with respect to the core component C1. (b) Time variation of the angular separation between the components C1 and J1, The two lines represent a weighted rectilinear fit to the data points from 2010 November to 2011 November (green line) and from 2011 November to 2012 August (red line). The γ-ray flaring periods are indicated with gray rectangles. Each point in (a) and (b) is monthly averaged, with the exception of January, March, June, July and August in 2011.

assistance in observations.

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