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VERA frequent monitoring of the Parsec-scale jet in the BL Lac Object OJ 287 simultaneous with gamma-ray flares during 2011-2012

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We present a kinematic study of the parsec-scale radio jet in the most studied BL Lac object OJ 287, during γ-ray flares to explore the relation between parsec-scale radio jet activity and γ-ray emission. VLBI observations were carried out toward OJ 287 from 2010 November to 2012 September at 22 GHz using the VLBI Exploration of Radio Astrometry (VERA). 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 seems 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 apparent 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 the new jet component unresolved at 22 GHz in the innermost region.

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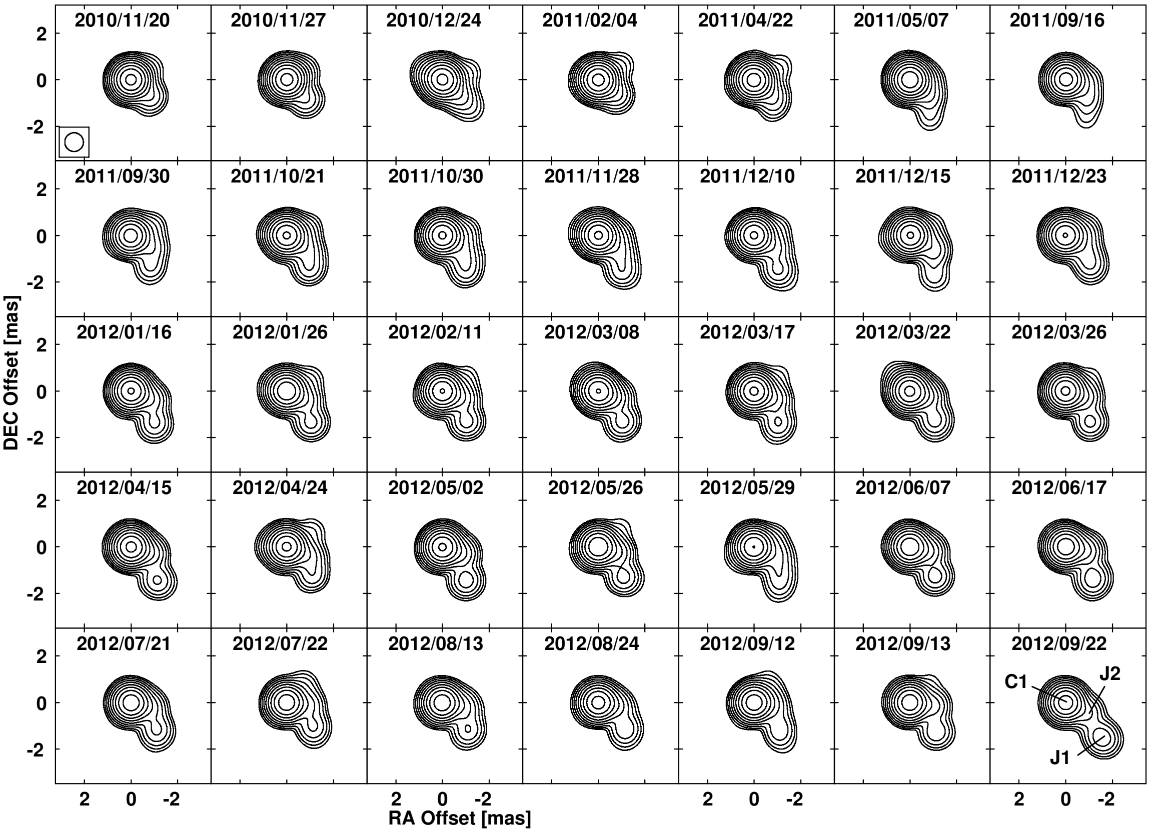

Figure 1: Sequence of VERA 22-GHz images of OJ 287 from 2010 November to 2012 September. Images are convolved with a circular beam size (FWHM) of 0.8 mas, which corresponds to the typical minor axis of synthesized beam in our observations. Contours start at 9 mJy beam^{-1} (typical 3 σ level), increasing 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. On the images, 1 mas corresponds to 4.5 pc.

1. Observational Results

1.1 Parsec-scale Structure of OJ 287

The 22-GHz images of OJ 287 (figure 1) show a southwest oriented core-jet structure with a linear size of 1–2 pc, consistent with other VLBI images observed in 2011 and 2012 [1][7]. The core-jet structure is represented by the three components : the core component (C1), the jet component (J1) and the inner jet component (J2) located between C1 and J1. The components C1 and J1 could be identified as 'C' and 'j' of the VLBA 43-GHz images[1]. Then, the innermost jet components 'a', 'm', 'n', 'o' and 'p' could be included into the components C1 or J1 because the angular resolution of our images is 5 times lower than that of the VLBA 43-GHz images.

1.2 Radio Light Curve

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 2). The second and

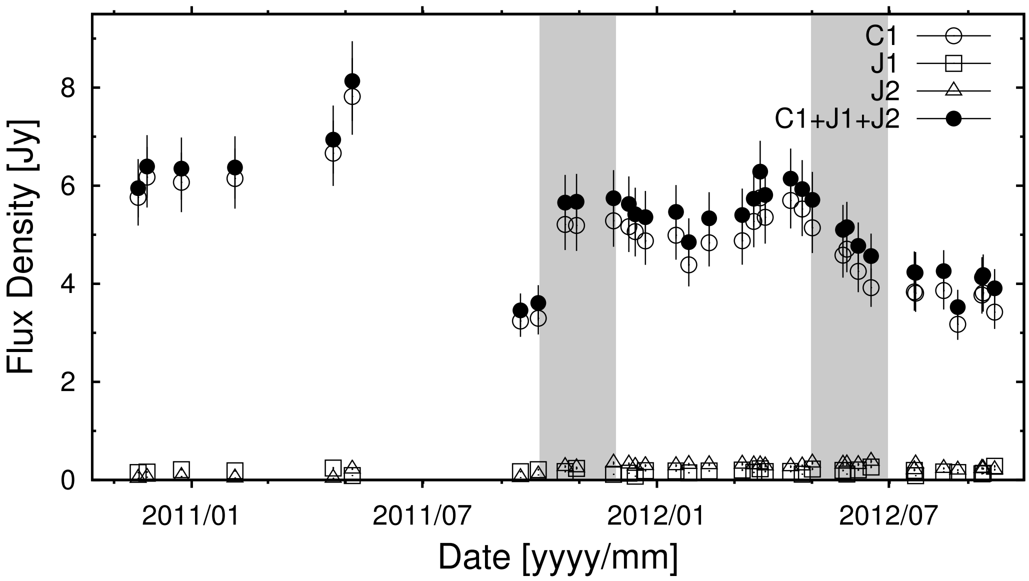

Figure 2: Light curve of each component in OJ 287 at 22 GHz observed with the VERA. The error on the flux density is 10%. The γ-ray flaring periods are indicated with gray rectangles.

third radio flaring events seem to be connected with the flares detected at γ-ray, X-ray, optical and infrared in 2011 October and 2012 March [3, 4, 2, 6, 5].

1.3 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 direction, in agreement with the previous 43-GHz VLBA images[1]. From 2010 November to 2011 April, the relative position of J1 was at the position $(x,y) \simeq (-0.8, -0.7)$ in Figure 3a and then moved with a PA of $\sim -160^\circ$ until 2011 November. The motion of J1 sharply changed direction to backward in 2011 November, just after the second radio flare. Then, J1 showed the northward motion again in 2012 July, and the motion of J1 switched the direction to the South-West in 2012 September. The apparent average radial velocity from 2010 November to 2011 November is estimated 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).

2. Discussions

The relative motion between the component C1 and J1 should be affected by both positions of the components C1 and J1, and thus the direction variation of the relative position could be due to wobbling behavior of either or both of C1 and J1. The component C1 could include contribution from the innermost jet components. No newborn jet component was seen in our VLBI images at the period the jet direction varied. However, the relative position of the component J1 from 2011 November to 2012 August moved backward and forward along a line at a position angle of $\sim -20^\circ$, nearly parallel to the ejection direction of the inner jet component 'a' detected by the

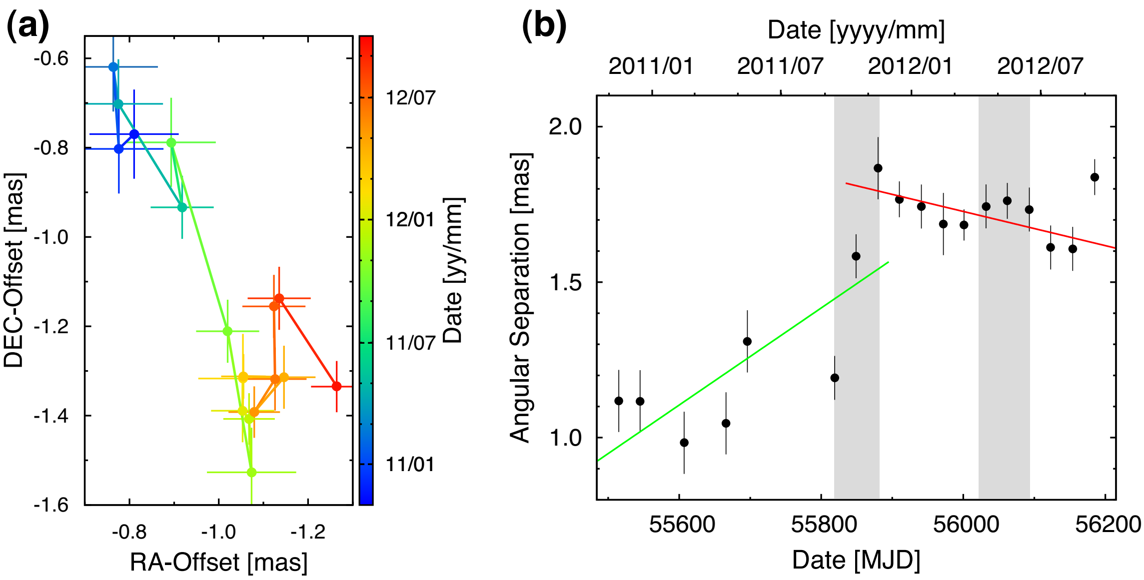

Figure 3: (a) Relative motion of the jet component J1 with respect to the core component C1. At the distance of OJ 287, 1 mas yr^{-1} corresponds to 19c. (b) Time variation of the angular separation between the components C1 and J1, The two lines represent a weighted rectilinear fit to the data points 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.

VLBA 43 GHz monitoring[1]. This fact supports the core wobbling hypothesis, which means that the direction variation could be caused by the ejection of a new component, which is not be resolved with our observations. In order to confirm our result, measurements of the absolute proper motions of the components with the phase referencing VLBI observations are necessary.

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