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High-resolution polarization imaging of the *Fermi* blazar 3C 279

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Ever since the discovery by the *Fermi* mission that active galactic nuclei (AGN) produce copious amounts of high-energy emission, its origin has remained elusive. Using high-frequency radio interferometry (VLBI) polarization imaging, we could probe the magnetic field topology of the compact high-energy emission regions in blazars. A case study for the blazar 3C 279 reveals the presence of multiple γ-ray emission regions. Pass 8 *Fermi*-Large Area Telescope (LAT) data are used to investigate the flux variations in the GeV regime; six γ-ray flares were observed in the source during November 2013 to August 2014. We use the 43 GHz VLBI data to study the morphological changes in the jet. Ejection of a new component (NC2) during the first three γ-ray flares suggests the VLBI core as the possible site of the high-energy emission. A delay between the last three flares and the ejection of a new component (NC3) indicates that high-energy emission in this case is located upstream of the 43 GHz core (closer to the black hole).

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1. Introduction

Fermi has brought about a revolution via the discovery of GeV emission from active galaxies (AGN). Studies over the past few years suggest that rapid γ-ray flares are produced in regions close to the central black hole (1; 2; 3; 5) where the particle acceleration is most efficient (in some cases γ-rays appear to also come from larger distances (6; 7; 8)). High-resolution VLBI imaging allows us to probe jet morphology changes on scales $\leq$1000 R_g, distances where the jets are likely still accelerating and are potential sites of γ-ray emission. We present an investigation of parsec-scale jet morphology evolution of the blazar 3C 279 during an episode of extreme γ-ray flaring activity in 2013 – 2014, using 43 GHz very long baseline interferometry (VLBI) images. A detailed study of the event is presented in (4). The γ-ray bright flat spectrum radio quasar (FSRQ) 3C 279 (z = 0.538, 9) has an extremely bright and polarized jet pointed close to our line-of-sight at $\leq 2^\circ$ (10).

2. Results

2.1 Gamma-ray variability

Gamma-ray photon flux and photon index variations in the source were investigated using the *Fermi*-LAT (Large Area Telescope, 11) data. To explore the GeV variability properties, we generated the constant uncertainty (15%) light curve above the de-correlation energy (E_0) using the adaptive binning analysis method (12). The light curve is produced by modeling the spectra for each time bin by a simple power law, N(E) = N_0 $E^{-\Gamma}$, N_0 : prefactor, and Γ : power-law index. The details of observations and data reduction can be found in (13).

The source displays multiple modes of flaring activity as can be seen in Fig. 1. Bright flares, labelled as “1" to “6" are superimposed on the long-term outburst. An increase in the source brightness from a flux level F (E >219 MeV) $\sim 3.3\times10^{-7}$ photons cm^{-2} s^{-1} was observed on JD$'$[1] $\sim$1610. Later in the end of the outburst on JD$'$ $\sim$1850, the source faded to the same brightness level. The brightness level of the source before and after the outburst is marked via a solid green line in Fig. 1 (top). Similar variations were observed in the γ-ray photon index as well. The spectrum was softer (Γ = 2.7) before and after the outburst, while significant hardening was observed during the flares.

2.2 Jet morphology variations

The 7 mm VLBA observations of 3C 279 were used to investigate the morphological changes on parsec-scales. The VLBI data were observed in the course of the monthly monitoring of bright γ-ray blazars at 43 GHz program[2]. The standard data reduction tasks were performed using the Astronomical Image Processing System (AIPS) and Difmap (Shepherd 1997). The details of the observations and data reduction can be found in (14).

Figure 2 shows a super-resolved image of the 3C 279 jet convolved with a beam size of 0.1 mas. In the source frame, 1 mas corresponds to 6.3 parsec. To study the evolution of the jet morphology, we fitted the total intensity of the jet using circular Gaussian components. The

[1] JD$'$ = JD - 2455000

[2] VLBA-BU-BLAZARS, http://www.bu.edu/blazars

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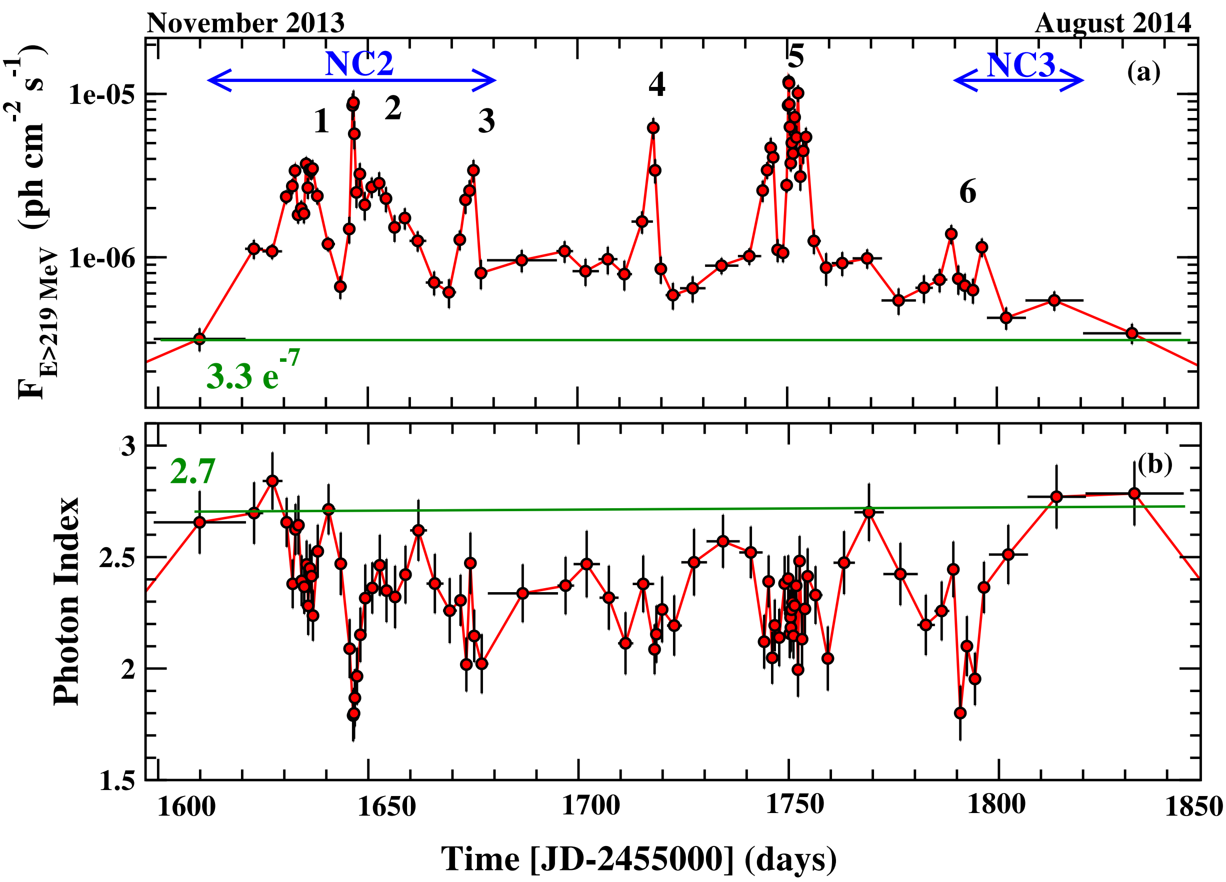

Figure 1: Gamma-ray photon flux and photon index variations observed in 3C 279 using the *Fermi*-LAT at 219 MeV to 300 GeV. The rapid γ-ray flares are labeled as “1" to “6". The blue horizontal arrows mark the period of ejection of components NC2 and NC3 (see Section 2.2 for details).

evolution of the components as a function of time is shown in Fig. 3. We fix the coordinates of the core to (0,0) to study the kinematics of individual components. The solid lines in Fig. 3 shows the best-fitted linear functions, which provide the angular velocity of the components. Given the angular speed, one can get an estimate of the apparent speed. We found that the new components (NC1 to NC3) have an average apparent speed of $\sim$20 c. Back-extrapolation of the components' motion was used to determine the ejection time or core separation time of the new components (NC1, NC2, and NC3). Our calculations suggest that NC1 was ejected on JD′[3] 1558^{-28}_{+15}, NC2 on 1638^{-27}_{+40}, and NC3 on 1810^{-19}_{+26} days. The ejection periods for NC2 and NC3 are shown in Fig. 1.

2.3 Multiple energy dissipation sites in 3C 279

Because of the superposition of multiple modes of flaring activity in 3C 279, it quite challenging to establish a connection between component ejection and flaring behavior of the source. Interestingly, the component “NC2" is ejected from the core during the first three (“1" to “3") γ-ray flares. The horizontal blue arrows in Fig. 1 mark the ejection period of NC2 and NC3. A continuous decay in the source brightness after the next three flares (“4" to “6") is followed by the

[3] JD′ = JD - 2455000

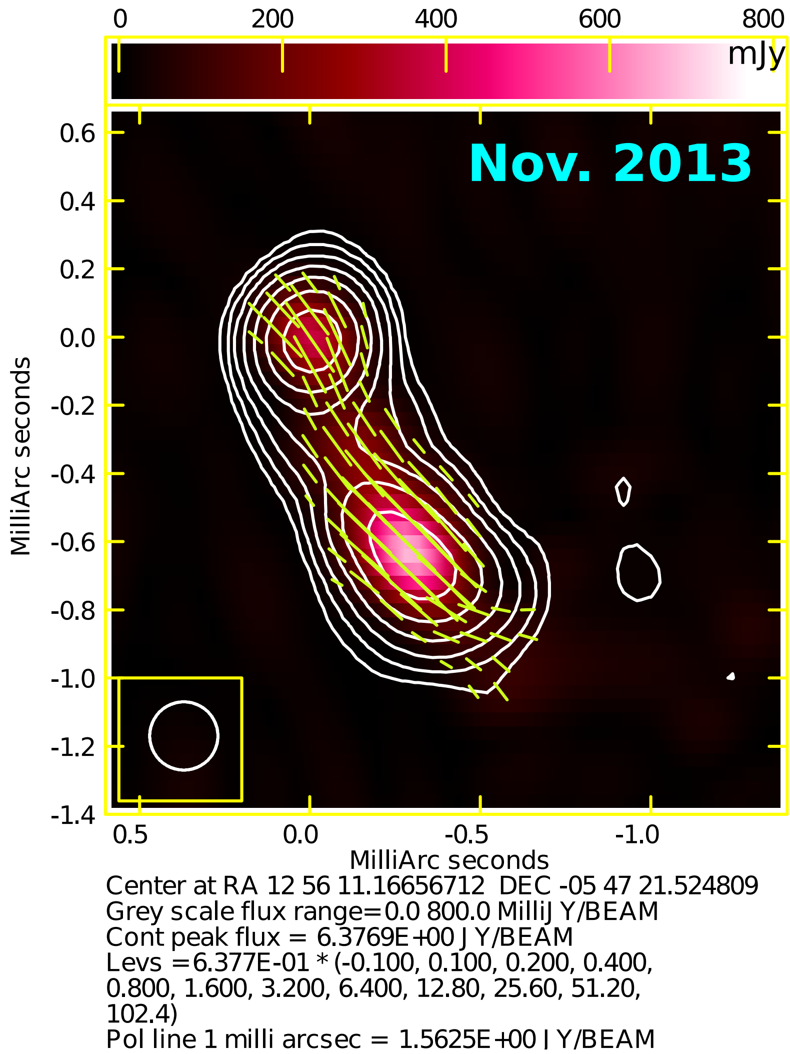

Figure 2: An example composite image of 3C 279 convolved with a beam size of 0.1 mas (circle in the bottom left corner). The contours represent the total intensity while the color scale is for polarized intensity image of 3C 279 . The line segments (length of the segments is proportional to fractional polarization) marks the EVPA direction.

ejection of NC3. Ejection of NC2 during the first three flares indicates that the γ-ray flares have to be produced either at the VLBI core or very close to the core region; otherwise, there should be a delay between the high-energy flares and the component ejection, which is not observed. A delay between the last three flares (4 to 6) and the ejection of NC3 suggests that γ-ray are produced upstream of the VLBI core (closer to the central engine). Our analysis therefore indicate multiple sites of high-energy dissipation in 3C 279.

3. Future Perspectives

VLBI is the only current technique capable of viewing directly the parsec- and subparsec-scale regions of jets in AGNs. Using VLBI, we are currently able to achieve an angular resolution of

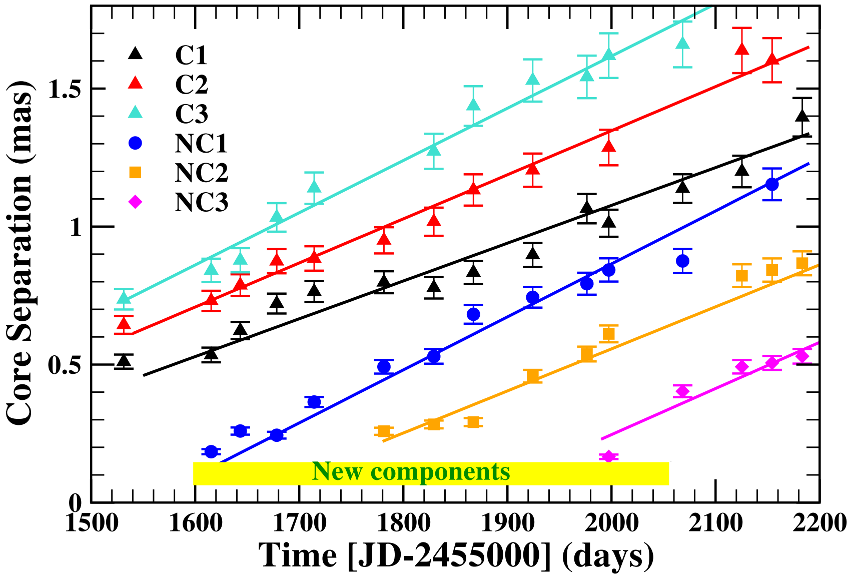

Figure 3: The 43 GHz jet kinematics i.e., temporal evolution of circular Gaussian components in 3C 279. The trajectories of the components can be well fitted using a linear function (shown using the solid lines).

$\sim$20 μas which makes it the most promising technique to probe the high-energy dissipation sites. The *Fermi* mission will continue observing the GeV sky at least for next couple of years. The TeV missions are on their way to probe the most energetic part of the electromagnetic spectrum. High-energy polarization observations (*AMEGO*, *IXPE*, etc.) will be of extreme importance in understanding the high-energy dissipation mechanisms.

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