PROCEEDINGS OF SCIENCE

Multi-frequency VLBI follow up of a strong γ-ray flare in the blazar 3C 273

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We present results of a 5-month long VLBA campaign to observe the blazar 3C 273 between 5 and 43 GHz. This campaign started shortly after the detection of a strong γ-ray flare by the *Fermi* large area telescope in August 2009. Based on the data acquired during the campaign, we detected a flare in the parsec-scale radio core of 3C 273. The core flux density at 43 GHz increased by a factor of 6 over the 5-month period while its radio spectrum became inverted. The emission at 43 GHz peaked about 140 days after the γ-ray flare. Overall, these findings support a close connection between γ-ray and parsec-scale radio emission. The frequency-dependent apparent shift of the core position during the flare and changes in its physical properties are also discussed.

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1. Introduction

Even though they have been studied for over half a century quasars remain full of unanswered questions. In particular, jet acceleration and collimation mechanisms and jet composition are still debated. Achieving good resolution and being able to look through the jet absorbing medium are essential to probe physical conditions in the innermost parts of jets. VLBI allows one to achieve the best available resolution nowadays but radio waves are affected by synchrotron self-absorption. Conversely, observations in γ-rays usually have poor resolution (if compared with VLBI) but can detect radiation from the jet innermost parts because the jet medium is almost transparent to γ-rays.

In this paper, we combine radio observations from the Very Long Baseline Array (VLBA) and γ-ray data from the *Fermi* large area telescope (LAT) to investigate the strong flare that occurred in the blazar 3C 273 in August-September 2009. The following sections describe our data sets (Sect. 2), the data reduction process (Sect. 3), and the results that we derived from this combined analysis (Sect. 4). Our results include a determination of the time delay between the radio and γ-ray emission and estimates of the frequency-dependent core shift over the period of the flare. In all, these results support a close connection between γ-ray and radio emission on parsec scales.

2. Data set

2.1 Fermi data

The *Fermi* satellite which carries on board the LAT instrument [1] scans the whole sky in about 3.2 hours. This means that no major event in the energy range 30 MeV to 300 GeV can be missed. Most noticeably, *Fermi* revealed that many active galactic nuclei are bright in γ-rays and subject to occasional flares. The weekly-averaged LAT data available online[1] were used for our study. These show that a very strong flare occurred in the blazar 3C 273 in August-September 2009 (Fig. 1).

2.2 Triggered VLBA data

We triggered a series of multi-frequency (5, 8, 15, 24 and 43 GHz) follow up VLBA observations after the *Fermi* LAT telescope detected an increase of the γ-ray flux of 3C 273 by a factor of 3 in August 2009 (Fig. 1). The first observation (epoch 'A') was conducted on 28 August 2009, after which the γ-ray flux increased even more, peaking on 26 September 2009 (MJD 55100). In total, we observed four epochs, covering all stages of the γ-ray flare (Fig. 1). These epochs are labeled 'A' (28 August 2009), 'B' (25 October 2009), 'C' (05 December 2009), and 'D' (26 January 2010).

2.3 Additional VLBA data

Our triggered multi-frequency VLBA data were supplemented with 43 GHz VLBA data from the Boston University (BU) data base[2]. The calibrated *u-v* data retrieved from the BU data base were imaged and model-fitted. These allowed us to significantly expand the temporal coverage for tracing the evolution of the flux density of the radio core of 3C 273 at 43 GHz (Fig. 2).

[1] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

[2] http://www.bu.edu/blazars/VLBAproject.html

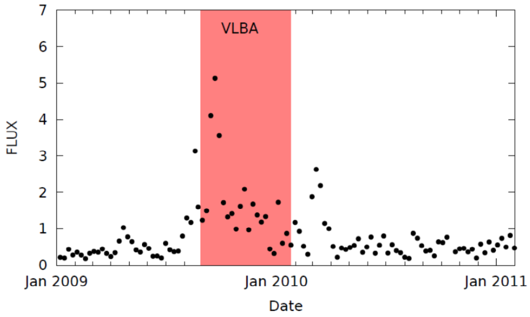

Figure 1: γ-ray light curve of 3C 273 in 2009–2010. The time span of the radio monitoring conducted with the VLBA is highlighted in red.

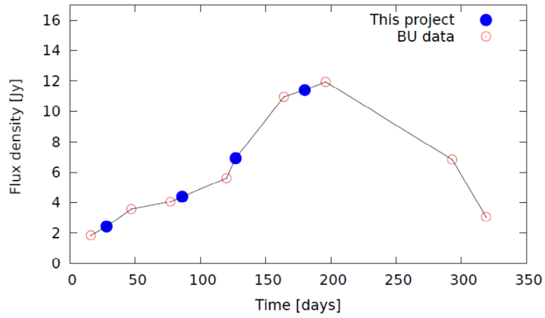

Figure 2: Evolution of the flux density of the radio core of 3C 273 at 43 GHz. The values were derived from model-fitting. Typical accuracy is 10%.

3. Data reduction

Data reduction was performed in a standard manner using AIPS [2] for a priori calibration and Difmap [5] for imaging. Special care was taken to achieve accurate amplitude calibration. Following Sokolovsky et al. [6], we first performed a full cycle of self-calibration to determine antenna-based gains averaged in time over each single observational epoch. For antennas with gain amplitude correction larger than 10% we applied these gains in AIPS and rerun the hybrid mapping procedure in Difmap. Such a technique allowed us to calibrate the amplitudes with an accuracy of 5% at 5, 8 and 15 GHz, and 10% at 24 and 43 GHz. To increase frequency coverage the 5 and 8 GHz bands were each split into two sub-bands. In all, this resulted in a total of seven frequencies (4.6, 5.0, 8.1, 8.4, 15.4, 23.8, and 43.2 GHz) available for our investigations.

Model fitting was performed in Difmap. We used a small number of elliptical Gaussian components to fit the data in each band (Fig. 3). With such a vast data set it was a challenge to tie the models at the different epochs and bands all together. We started first by modeling the data at the highest frequency (43 GHz). The derived model was then roughly checked for stability by varying the initial parameters of the fit and redoing the fit 10-15 times. Proceeding to the lower frequencies, the 43 GHz model was used as a starting point to fit the 24 GHz data, while the subsequent model derived at 24 GHz was then used as a starting point to fit the 15 GHz data, and so on. New components describing extended structures were added while going to lower frequencies. In this process, we also tried to preserve components describing the fine structure of the jet.

A similar approach was used to tie the models at the different epochs. Epoch A model at 43 GHz was taken as reference and used for adjacent epochs. After connecting all 43 GHz models all together modeling for the lower frequencies was carried out as described above. In most cases the fits for each individual frequency converged well from epoch to epoch. Such an approach made it possible to analyze the temporal evolution of the individual components. Most noticeably, the 43 GHz data revealed a new component which separated from the core after the radio flare.

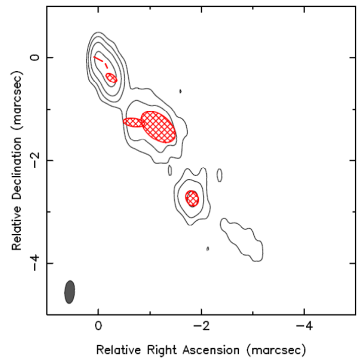

Figure 3: Total intensity map of 3C 273 at 43 GHz with components of the model overlaid.

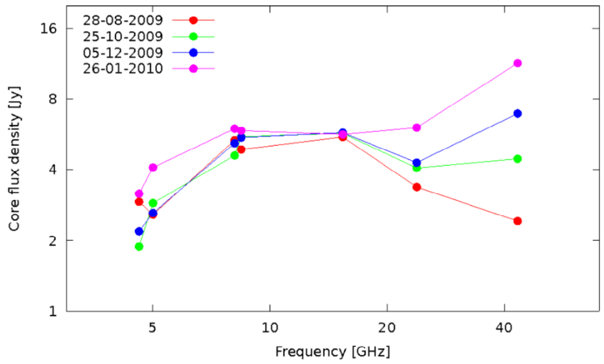

Figure 4: Spectrum of the radio core of 3C 273 reconstructed for the four observing epochs. Each epoch is shown with a different color.

4. Analysis

4.1 Time delay between the γ-ray and radio emission

By comparing peaks in the light-curves we estimate that the radio flare occurred 140–200 days after the γ-ray flare. Since the light curves show no other flares of comparable power over 2008–2010, this tends to indicate that the two flares (in the radio and at γ-rays) are related. Additionally, we made a kinematics analysis of the individual VLBI components based on the model-fitted 43 GHz data. This analysis allowed us to trace backwards a component distinct from the core in March 2010, pointing to an ejection epoch 114 ± 21 days after the γ-ray flare, in agreement with the delay estimated from the light curves. Following Pushkarev et al. [4], we assume that the flare happens simultaneously across the bands, with γ-rays escaping immediately while radio emission is completely self-absorbed at first. A highly-perturbed plasma then travels along the jet. Radio waves start to escape when reaching the $\tau \sim 1$ region where they remain absorbed only partly. The time delay may be converted into a deprojected distance along the jet, corresponding to the distance between the regions of γ-ray emission and radio emission (see [4] for details):

$$\Delta r = \frac{\beta_{\mathrm{app}} c \Delta t^{\mathrm{sour}}_{R-\gamma}}{\sin\theta} \tag{4.1}$$

where β_{app} is the apparent jet speed, c is the speed of light, $\Delta t^{\mathrm{sour}}_{R-\gamma}$ is the delay of the radio emission in the source frame (from the epoch of the γ-ray emission), and θ is the viewing angle. From Eq. 4.1, we derive a distance $\Delta r = 3.1$–3.8 pc, assuming typical values of the apparent jet speed ($\beta_{\mathrm{app}} \approx 6.5$) and viewing angle ($\theta \approx 10^\circ$). For 3C 273 this corresponds to a projected angular distance $\Delta r_{\mathrm{proj}} \approx 0.2$ mas, which is comparable to the 43 GHz radio core size.

The core radio spectrum is also affected by opacity effects. The perturbation traveling along the jet reached the apparent 43 and 24 GHz cores (corresponding to $\tau \approx 1$) at about the same time, as indicated by the increase of the flux density of 3C 273 at those frequencies (Fig. 4). However, the perturbation appears not to have reached the 15 GHz core over the period of our monitoring since the emission at this frequency and at those lower did not evolve much over this period (Fig. 4).

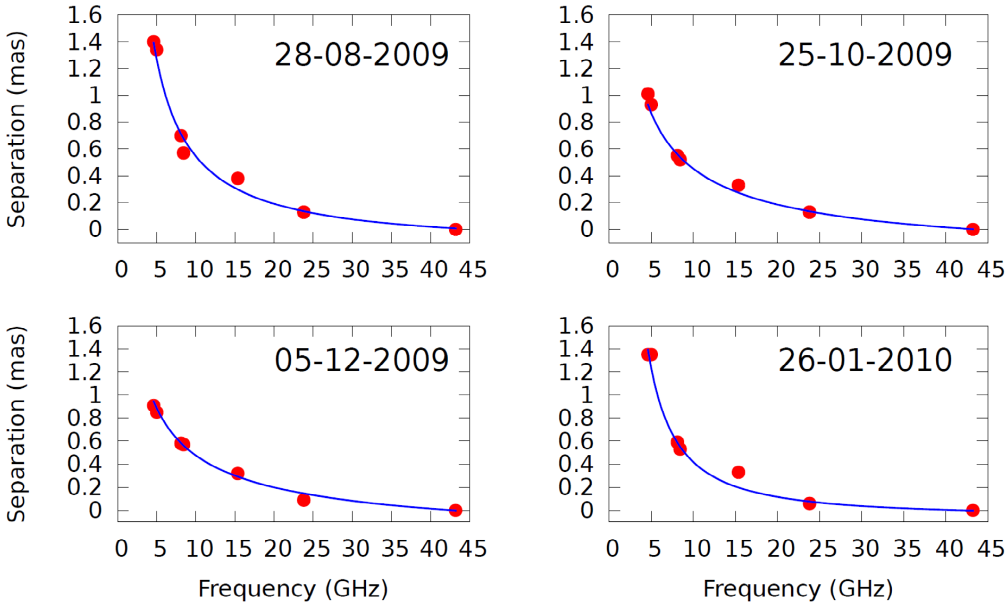

Figure 5: Core shift versus frequency for our four VLBA observational epochs in 2009–2010.

4.2 Core shift

The apparent base of the jet, commonly called the "core", is often the brightest and most compact feature seen in quasar VLBI images. The VLBI core represents the region of the jet at which its optical depth reaches $\tau_\nu \approx 1$ at a given frequency. The absolute position of the radio core relative to the central engine, $r_{\rm core}$, is frequency-dependent and varies as $r_{\rm core} \propto \nu^{-1/k}$, with $k \approx 1$ in the case of equipartition and dominating synchrotron self-absorption ([3] and references therein).

We used two different methods to estimate core shifts in 3C 273: a 2D cross-correlation method (2DCC) and a method based on alignment of optically thin components. The 2DCC method cross-correlates optically thin portions of the continuous jet taken at two different frequencies to get a displacement between the phase centers of the images. The core shift is then determined from this displacement and from the core positions as measured relative to the phase centers in the images. The second method requires the identification of a distant VLBI jet component that is visible at all frequencies. If optically thin, this component may serve as reference to align the images because its position should be independent of frequency. The two methods gave similar core shift values.

The value of the parameter k depends on the physical conditions at the jet base. Our analysis shows that k varied during the radio flare (Fig. 5) with values for epochs A, B, C, D as follows: $k_{\rm A} = 0.91 \pm 0.19$, $k_{\rm B} = 1.56 \pm 0.41$, $k_{\rm C} = 1.74 \pm 0.49$, and $k_{\rm D} = 0.70 \pm 0.09$. Such variations may be due to the evolution of particle density and/or the magnetic field distribution during the flare.

5. Summary

A flare in the sub-parsec-scale radio core of 3C 273 was detected following up a strong γ-ray flare in 2009. This supports a close connection between γ-ray and parsec-scale radio emission. The time lag between γ-ray and 43 GHz radio emission (with γ-rays leading radio) was found to be about 140 days from comparing peaks in the light curves and 114 days from kinematics estimating the birth epoch of the jet component emitted at the time of the flare. Calculating the deprojected distance between the γ-ray and radio emission zones from this time lag allowed us to locate the γ-ray emission zone 3–4 pc upstream from the apparent 43 GHz radio core. The frequency-dependent core shift ($r_{\rm core} \propto \nu^{-1/k}$) was found to vary during the flare, with k varying from 0.7 to 1.7. Such variations may result from changes in the core particle density and/or the magnetic field strength.

Acknowledgments

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