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Localization of the gamma-ray emission site using multi-waveband data and mm-VLBI

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Abstract. We perform monthly monitoring of a sample of γ-ray blazars with the VLBA at 43 GHz along with optical photometric and polarimetric observations and 2-week campaigns (once per year) with 3 VLBA epochs during each campaign. We demonstrate that the γ-ray variability is tightly connected with the variability in the mm-wave core, especially in quasars. We show that, for all sources in our sample for which a high γ-ray state was observed, the high energy events are simultaneous with an increase of the flux in the mm-wave core. We resolve features of enhanced brightness on our VLBA images that appear be responsible for the mm-wave flux increase. We also find a strong correlation between optical and γ-ray light curves, with a delay of γ-ray variations within 1-3 days, as well as a strong correlation between optical flux and degree of polarization during a high γ-ray state. We observe new examples of marked rotation of the optical polarization angle that accompanies a γ/optical flare. In 1633+382 the position angle of polarization in the core agrees with the optical PA during the rotation period. These are strong arguments in support of the conclusion that a high γ-ray state in blazars is connected with processes originating near the mm-VLBI core.

1. Introduction

Blazars were the largest class of identified γ-ray sources detected by EGRET on board the *Compton Gamma Ray Observatory* (Hartman et al. 1999). Although the main questions - the mechanism(s) of γ-ray production and the site(s) of γ-ray emission - were not answered, it became clear that γ-ray emission arises in highly relativistic jets (Jorstad et al. 2001a, Kellermann et al. 2004). A positive correlation between VLBI core flux at 22/43 GHz and γ-ray flux (Jorstad et al. 2001a) suggested that the production of the γ-ray emission takes place in the most compact region of the relativistic jet, close to the VLBI core. Moreover, examination of the coincidence of times of high γ-ray flux and ejections of superluminal knots showed that the two events are associated (Jorstad et al. 2001b). This result implied that the γ-ray flares are caused by inverse Compton scattering by relativistic electrons in the parsec-scale regions of the jet rather than closer to the central engine. This was supported by the analysis of radio light curves of γ-ray blazars indicating that the highest levels of γ-ray emission are observed during the initial (or peak) stages of high-frequency radio flares (Lähteenmäki & Valtaoja 2003). These results imply that the bulk of γ-rays are generated parsecs from the black hole (BH), near where the radio core of the jet is located (Marscher 2006). However, the opposite point of view finds support in the short timescales of γ-ray variability: that the γ-ray emission is produced closer to the black hole (BH) through inverse Compton scattering of photons from the accretion disk (Dermer & Schlickeiser 1994) or broad line regions (Sikora, Begelman, & Rees 1994).

The dramatically improved γ-ray sensitivity of the *Fermi* Large Area Telescope (LAT) has provided detailed light curves of a number of blazars. This has rekindled debates about mechanisms and sites of γ-ray production in blazars. According to Finke & Dermer 2010), a sharp break found in the γ-ray spectrum of the quasar 3C 454.3 is inconsistent with a cooling distribution and poorly fit with a synchrotron self-Compton model (SSC), but can be explained by the combination of Compton-scattered disk emission and BLR radiation. Poutanen & Stern (2010) interpret the γ-ray break as the result of opacity from photon-photon pair production on He II Lyman recombination continuum and lines, which implies that the site of γ-ray emission lies within a light-year of the BH. However, the correlation between γ-ray and radio flux has received strong confirmation from the extensive MOJAVE survey (Kovalev et al. 2009) which leads to the conclusion that γ-ray emission is tightly connected with highly relativistic radio jets (Lister et al. 2009). Multi-band observations suggest that γ-ray emission is produced as a superluminal knot moves from the BH to the mm-wave core. As it does, it encounters different sources of seed photons for inverse Compton scattering from both within and outside the jet, including the sheath of the jet (Marscher et al. 2010). Using the most recent γ-ray and mm-wave VLBA data, as well as optical photometric and polarimetric light curves, we demonstrate a close connection between high states of γ-ray emission and activity in the VLBI mm-wave core region in blazars.

2. Observations and Data Reduction

We monitor monthly a sample of bright γ-ray blazars with the VLBA at 43 GHz (7 mm). The calibrated uv-FITS files and images can be found at our website[1]. We also carried out 2-week campaigns in October 2008, October 2009, and April 2010 with 3 VLBA epochs within each campaign. We have performed the data reduction, electric vector position angle (EVPA) calibration, and brightness distribution modelling in the manner of Jorstad et al. (2005) and used their method, as well as the same cosmological parameters ($\Omega_{\rm m}=0.3$, $\Omega_\Lambda=0.7$, and $H_\circ$=70 km s^{-1} Mpc^{-1}) to calculate the proper motions, apparent speeds, and times of ejection from the 43 GHz core of moving features.

We carry out optical photometric and polarimetric monitoring of the blazars using i) the Perkins telescope of Lowell Observatory (Flagstaff, AZ), with the PRISM camera[2]; ii) the 70 cm telescope of the Crimean Astrophysical Observatory with a photometer-polarimeter; iii) the 40 cm telescope of St. Petersburg State University (Russia) with a photometer-polarimeter; iv) the 2.2 m Telescope at the Calar Alto Observatory (Almería, Spain)[3]; and v) the 1.54 m Kuiper and the 2.3 m Bok telescopes at Steward Observatory[4]. More detailed descriptions of optical observations can be found in Jorstad et al. (2010). We also use the 2 m Liverpool telescope at La Palma (Canary Islands, Spain) and the 1.1 m telescope of the Main (Pulkovo) Astronomical Observatory of the Russian Academy of Sciences at Campo Imperatore, Italy to obtain near-IR photometric measurements.

We have calculated γ-ray light curves for all sources in the sample at 0.1-200 GeV with weekly binning using the software and following the Analysis Threads provided by the FSSC. We used the response function generated by the FSSC, and created a model file that consisted of a power-law model (prefactor and index) for each source. The model file included all bright γ-ray sources within 15° of the source. We used spectral indices listed in the 11-month Fermi LAT Catalog (Abdo et al. 2010) for all sources. However, for sources in a high γ-ray state we have calculated daily γ-ray light curves with both prefactor and spectral index left as free parameters.

3. Connection between Gamma-Ray and mm-Wave Core Variability

We have calculated variability indices of the γ-ray emission, V_g, and of the flux in the core of jets, V_r, for all sources in our sample using formalism developed by Aller, Aller, & Hughes (2003), adjusted for γ-ray light curves that contain both measurements and upper limits. The radio variability index, V_r, and γ-ray variability index V_g

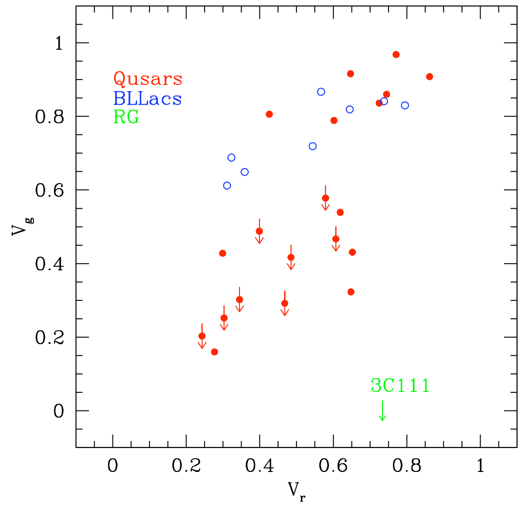

Fig. 1. Dependence between γ-ray and mm-wave core variability indices for quasars (filled circles) and BL Lac objects (open circles).

were determined as follows:

$$V_r = \frac{(S_r^{max}-\sigma_{max})-(S_r^{min}+\sigma_{min})}{(S_r^{max}-\sigma_{max})+(S_r^{min}+\sigma_{min})}$$

$$V_g = \frac{(S_\gamma^{max}-\sigma_{max})-2S_\gamma^{min\downarrow}}{(S_\gamma^{max}-\sigma_{max})+2S_\gamma^{min\downarrow}}$$

$$V_g^\downarrow = \frac{S_\gamma^{max\downarrow}-S_\gamma^{min\downarrow}}{S_\gamma^{max\downarrow}+S_\gamma^{min\downarrow}},$$

where S_r^{max} and S_r^{min} are the maximum and minimum observed fluxes in the 43 GHz core, respecively, σ_{max} and σ_{min} are their uncertainties, $S_\gamma^{max}\pm\sigma_{max}$ is the maximum detected γ-ray flux at 0.1-200 GeV, $S_\gamma^{max\downarrow}$ and $S_\gamma^{min\downarrow}$ are the maximum and minimum upper limits of γ-ray flux at 0.1-200 GeV, respectively. Figure 1 shows a good correlation between V_g and V_r for both quasars and BL Lac objects. All quasars undetected by the LAT with weekly binning have a low variability index in the mm-wave core, $V_r\ \leq$0.6, which implies that γ-ray detection of quasars strongly depends on variability of the mm-wave core. The BL Lac objects have a similar range of V_r as the quasars but a weaker dependence between variability indices. This suggests an additional mechanism for the γ-ray production in BL Lac objects, different from quasars and located outside the mm-wave radio core. Lähteenmäki & Valtaoja (2003) noted previously that BL Lac objects do not possess a clear connection between radio and γ-ray variations.

4. Analysis of Multi-waveband data for Individual Sources

Figure 2 shows the γ-ray and 43 GHz core light curves for sources in our sample that exhibited strong γ-ray activity during 2008 Summer - 2010 Spring. Visual examination of the light curves reveals that a high γ-ray state is characterized by strong variability that lasts several months.

[1] http://www.bu.edu/blazars/VLBAproject.html
[2] http://www.bu.edu/prism/
[3] http://www.iaa.es/∼iagudo/research/MAPCAT/
[4] http://james.as.arizona.edu/∼psmith/Fermi

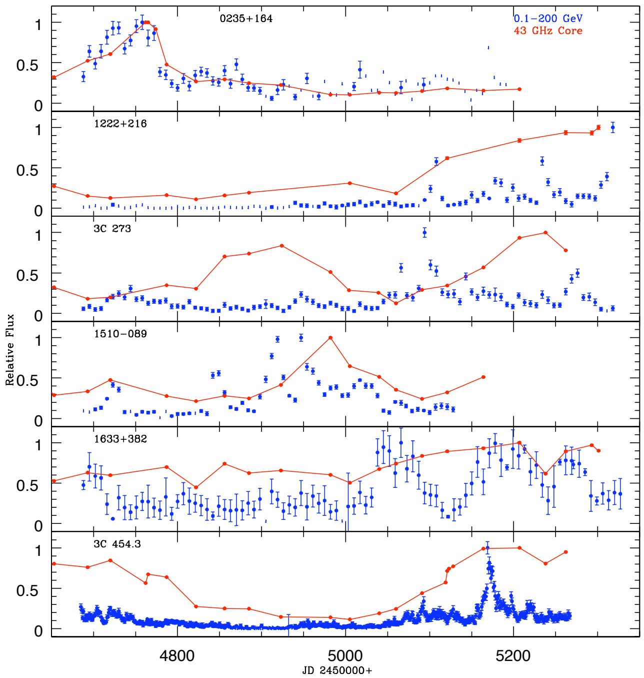

Fig. 2. Gamma-Ray and 43 GHz VLBI core (solid lines) light curves of sources from our sample exhibiting high γ-ray states.

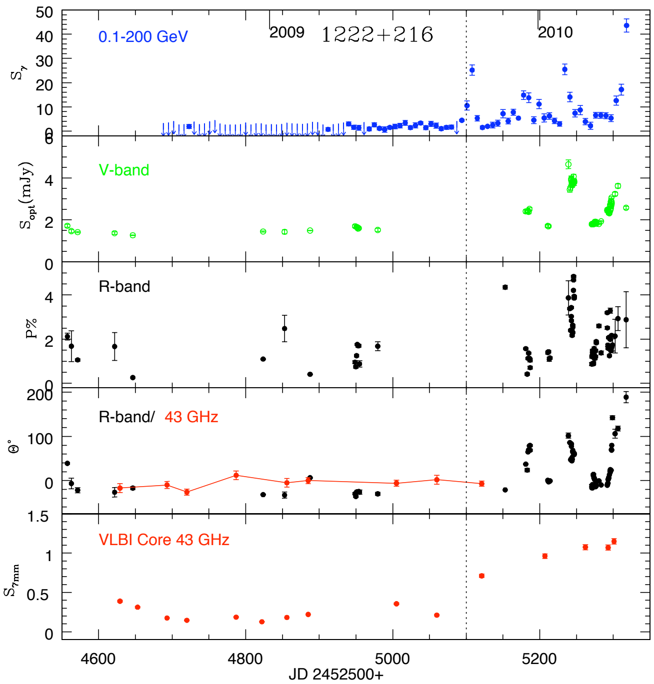

Fig. 3. Light curves in γ-ray, optical (photometric and polarimetric), and 43 GHz VLBI core of the quasar 1222+216; the fourth panel shows optical and 43 GHz core EVPAs (points connected by lines); dotted line denotes beginning of the γ-ray activity.

Table 1. Results of Gamma-Ray/43 GHz Core Correlation Analysis

Source	Max. Coeff.	Delay (days)
0235+164	0.89±0.03	−7±7
1222+216	0.64±0.04	0±7
3C273	0.40±0.05	−119±7
1510−089	0.66±0.05	−28±7
1633+382	0.55±0.04	−7±7
3C454.3	0.54±0.02	0±7

Remarkably, these prolonged periods coincide with a successive increase of flux in the mm-VLBI core region for all sources except 3C 273. We have performed a correlation analysis between the γ-ray and core light curves using weekly binned γ-ray light curves and a cubic spline approximation for core light curves. We used the latter to obtain an estimate of the core flux for each γ-ray measurement. We have calculated the correlation function between the light curves with delays running from −140 to 140 days (a negative delay indicates that the γ-ray variations lead those in the core). The correlation analysis shows statistically significant correlation between the γ-ray and mm-wave core light curves for all sources. The results are listed in Table 1. In four cases the delay between the light curves is within the uncertainties of the value, in 1510−089 the γ-ray variations precede the activity in the core by ∼30 days, and in 3C 273 the γ-ray activity leads variations in the core by ∼4 months.

4.1. Quasar 1222+216 (4C +21.35)

The quasar 1222+216 (z=0.435) was in a quiescent state from 2008 August to 2009 September (see Fig. 3): i) the γ-ray flux was below the detection level; ii) the optical magnitude was faint, V$\sim$16^m; iii) the degree of optical polarization was ≤2%; iv) the position angle of polarization was stable, close to the jet direction, $\Theta_{opt} \sim -20°$, and close to the EVPA in the core; v) the jet had a stable structure observed at many epochs, consisting of a weak core (∼0.25Jy) and a stationary feature, *St*, located ∼0.3 mas from the core (Fig. 4). The situation dramatically changed around 25 September 2009 (dotted line in Fig. 3), when the γ-ray flux increased by a factor of ∼10. This epoch coincided with an increase of the flux in the mm-wave core. The high γ-ray activity as well as brightening of the VLBI core of the quasar have been in progress for 9 months. The optical emission has shown strong variability and an increase in brightness by more than a magnitude. This was accompanied by strong variability of the degree and position angle of polarization, with an increase of p up to 6% and rotation of the optical EVPA by ∼200°. The rotation of Θ_{opt} coincided with the largest γ-ray outburst and an optical flare. Such behavior is reminiscent of that seen in BL Lac and 1510−089 (Marscher et al. 2008, 2010). Moreover, although we cannot yet make a robust conclusion that a new superluminal component was ejected from the core during the last γ-ray outburst, some indication

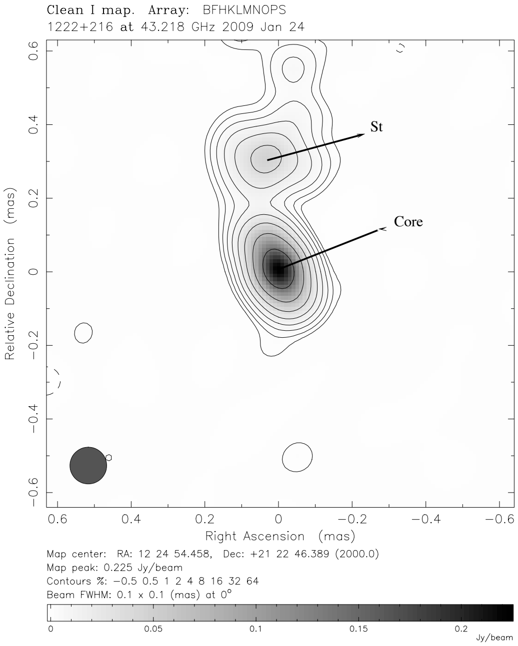

Fig. 4. Total intensity image of the quasar 1222+216 at 43 GHz during a quiescent state.

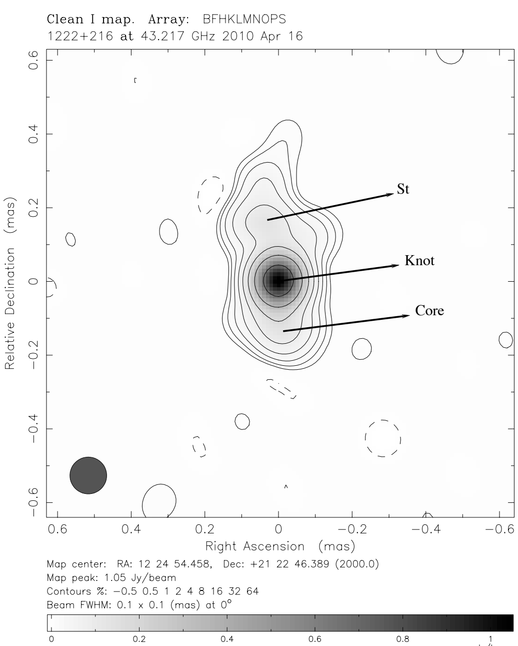

Fig. 5. Total intensity image of the quasar 1222+216 at 43 GHz during a high γ-ray state.

of the appearance of a new feature in the jet is seen on the most recent image of the quasar, taken on 2010 April 16 (Fig. 5). The γ-ray and optical light curves during RJD: 5180-5318 (RJD=JD-2450000.0) are well correlated (coefficient of correlation $\rho = 0.69 \pm 0.03$) with γ-ray variations delayed by 1±1 day, i.e. variations at both wavebands are possibly simultaneous. The variability of the degree of optical polarization strongly correlates with the optical flux behavior ($\rho = 0.60 \pm 0.04$) and leads the latter by 2±1 day. A possible scenario is as follows: propagation of a disturbance (possibly a shock) through the mm-wave core causes an increase in ordering of the magnetic field, followed by a rise in the density of relativistic electrons radiating at optical wavelengths and generation of γ-rays via inverse Compton scattering of UV/optical/IR photons from both inside and outside the jet.

4.2. Quasar 3C 273 (1226+023)

The quasar 3C 273 is one of the nearest blazars (z=0.158), which allows us to study the core region of the quasar in some detail. Figure 6 shows that the correlation between γ-ray and near-IR (H-band) light curves is very poor, although IR variations are stronger than the optical variations, which are suppressed by contamination by the big blue bump (Impey et al. 1989). A significant contribution from the BBB decreases the degree of optical polarization, which is usually under 0.5%. The increase of the optical polarization to 1.5±0.02% in 2010 Spring is therefore very significant and coincides with a γ-ray flare. We have performed a correlation analysis between the daily binned γ-ray light curve and degree of optical polarization over the period from RJD:5150 to RJD:5300 that gives a strong correlation ($\rho = 0.67 \pm 0.03$), with γ-ray variations delayed with respect to variations of degree of optical polarization by 3±1 days. This indicates that γ-ray production is strongly related to an increase in the optical synchrotron flux, probably as the result of an increase in the number of relativistic electrons that produce both optical/IR synchrotron and, through scattering, γ-ray photons. The position angle of optical polarization does not change significantly, and aligns with the jet direction during the outburst. The 43 GHz core has very low polarization and is subject to the effects of Faraday rotation (Jorstad et al. 2007). However, during an outburst some part of the core is often polarized with EVPA aligned with the jet direction, while knots downstream have EVPAs perpendicular to the jet axis (see Fig. 7). The significant delay of variations in the 43 GHz core with respect to γ-ray variations (Table 1) can be explained by the difference in time when the maximum number of relativistic electrons radiating at optical vs. mm-waves has been achieved. There are two superluminal knots ejected during a high state of γ-ray emission, $K4$ and $K5$. However, ejection of a knot also occurs during a relatively low γ-ray state in 2008 ($K3$). This raises the question about differences in properties of superluminal features associated with high γ-ray states with respect to those which are "γ-ray quiet". Table 2 lists parameters of knots determined as in Jorstad et al. (2005) showing that $K3$ is among the brightest features and decays slowly (the parameters of $K5$ are not well determined yet).

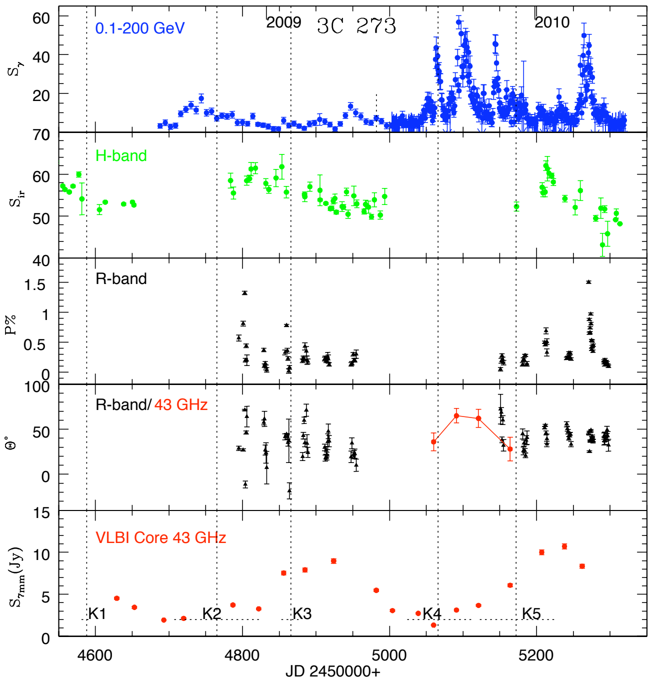

Fig. 6. Gamma-ray, H-band photometric, R-band polarimetric, and 43 GHz VLBI core light curves of the quasar 3C 273; the fourth panel shows optical and 43 GHz core EVPAs (points connected by lines); optical polarization is corrected for interstellar polarization according to Impey et al. (1989); dotted lines show the time of ejection of superluminal knots.

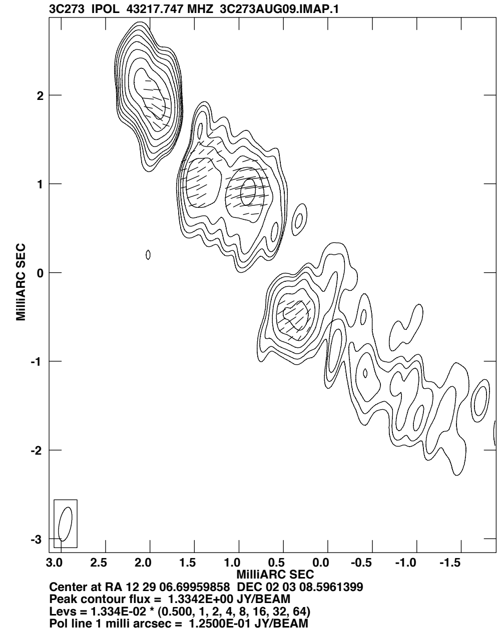

Fig. 7. Total and polarized intensity image of the quasar 3C 273 at 43 GHz during the beginning of high γ-ray activity in 2009 August, the line segments show direction of polarization.

Table 2. Parameters of Superluminal Knots in 3C 273

Knot	β_{app}	S_{max}	Γ	$\Theta_\circ$	δ
K2	7.6±1.5	0.83±0.15	9	3.6	14
K3	8.3±0.3	8.5±0.3	9	4.6	12
K4	10.7±1.4	2.8±0.2	12	3.3	16
K5	6.6±3.0	9.7±0.3	10	2.2	17

Notes: β_{app} - apparent speed in units of c; S_{max} - maximum flux in Jy; Γ - bulk Lorentz factor; $\Theta_\circ$ - angle between the centroid of knot and line of sight in degrees; δ - Doppler factor.

4.3. Quasar 1633+382 (4C +38.41)

The high-redshift (z=1.814) quasar 1633+382 displays i) modest γ-ray activity in 2008 August, which is accompanied by a minor optical flare and a small increase in optical polarization; ii) a relatively quiet period at all wavelengths from 2008 Autumn to 2009 August, during which the optical polarization drops to 1%; and iii) a dramatic increase of the γ-ray (by a factor of $\sim$10), optical (factor of $\sim$5), and 43 GHz VLBI core (factor of 2) emission starting in September 2009. During the high state the optical polarization reaches 20%. A rotation of the optical EVPA from 100° to −100° is observed, coinciding with the peak of the γ/optical flare and the maximum degree of optical polarization. The EVPA in the 43 GHz core behaves in a similar way, which implies that the polarized optical emission comes from the region close to the VLBI core, as suggested previously (Jorstad et al. 2007). Correlation between the γ-ray and optical light curves is moderately high (ρ=0.56±0.04), with a delay of $+1 \pm 1$ day; the same holds for the degree of polarization (ρ=0.55±0.05), with a delay of 0 ± 1 day.

The VLBA images (Fig. 9) reveal the appearance of a bright superluminal knot, K1, on 2009 September 14 (±43 days), moving with an apparent speed 7.8±2.2 c (Fig. 10). The knot is very bright and compact, reaching 1.4 Jy on 2010 January 10. The time of the ejection of K1, despite an uncertainty of $\sim$1 month, agrees with the pronounced γ/optical flare.

5. Conclusions

Our multifrequency data reveal a strong correlation between optical synchrotron and γ-ray emission in blazars. Analysis of optical and 43 GHz VLBA polarization and the timing of passages of superluminal knots through the core suggest that optical synchrotron emission originates in the vicinity of the mm-wave core, most likely through shocks, and that enhanced γ-ray emission is associated with this process. This implies that γ-ray flares originate near the mm-wave VLBI core.

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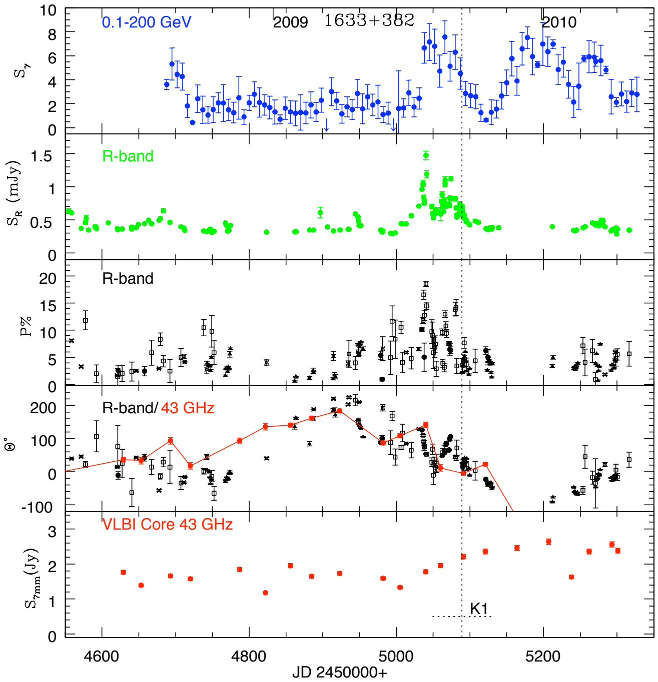

Fig. 8. Light curves in γ-ray, optical (photometric and polarimetric), and 43 GHz VLBI core of the quasar 1633+382; the fourth panel shows optical and 43 GHz core EVPAs (points connected by lines); dotted line shows the time of ejection of superluminal knot.

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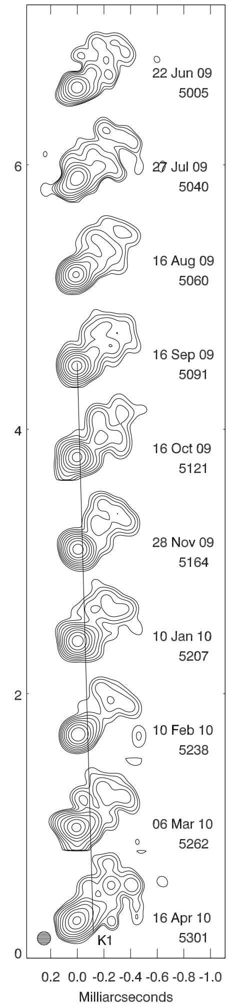

Fig. 9. VLBA images at 43 GHz of the quasar 1633+382 with convolving beam 0.1×0.1 mas, S_{peak}=2.45 Jy/Beam, and contours representing 0.25,0.5,...,64% of the peak.

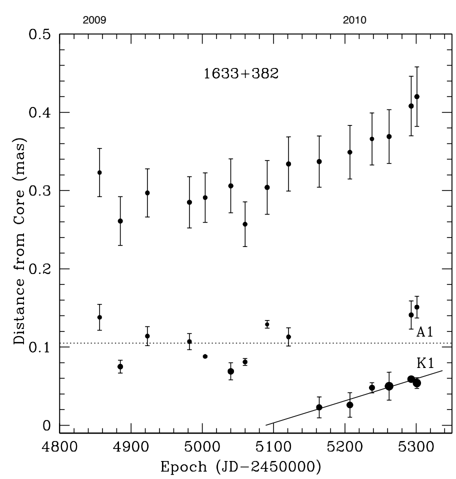

Fig. 10. Separation of knot K1 from the core.