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Multi-Frequency Monitoring of the Flat Spectrum Radio Quasar PKS 1222+216 in 2008–2015

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Abstract: We analyze the broadband activity of the flat spectrum radio quasar PKS 1222+216 from 2008 to 2015 using multi-frequency monitoring which involves γ-ray data from the *Fermi* Large Area Telescope, total intensity and linear polarization observations from different optical telescopes in R band, and imaging of the inner jet structure with the Very Long Baseline Array (VLBA) at 43 GHz. During the observations, the source showed several dramatic flares at γ rays and optical bands, with the rising branch of a γ-ray flare accompanied by a rapid rotation of the polarization position angle (EVPA), a fast increase of the degree of polarization in the optical band, brightening of the VLBI core, and appearance of a new superluminal component in the parsec-scale jet. The rapid variability of the optical linear polarization may be explained by a strong turbulence in the jet plasma. We find a correlation between the γ rays, optical R band, and 43 GHz variability on a long-term scale (months and years), and a good general alignment between EVPAs in R band and at 43 GHz, while the correlation between short-term variations (days and weeks) is weaker. Synchronous activity across the bands supports the idea that the emission regions responsible for the γ-ray and optical flares are co-spatial and located in the vicinity of the mm-wave core of the parsec-scale jet. However, these connections do not completely explain the challenging behaviour of PKS 1222+216, since there are some γ-ray flares which are not accompanied by jet events, and vice versa. We need a continuation of multi-frequency monitoring along with high resolution imaging of the parsec-scale jet to understand in detail the origin of high energy emission in blazars.

Keywords: blazars; jets; VLBA; polarization

1. Introduction

The flat spectrum radio quasar PKS 1222+216 (4C+21.34; z = 0.43) ended a prolonged state of quiescence in a dramatic manner in late 2009. A series of pronounced γ-ray flares over a nearly two-year period were accompanied by millimeter-wave outbursts and optical flares, as well as a detection of $>$0.2 TeV γ-rays in June 2010 [1]. This established the object as a bona fide blazar, whose emission across most of the electromagnetic spectrum is dominated by nonthermal radiation from a compact relativistic jet pointing almost directly along the line of sight. A second prolonged period of high multi-wavelength activity began in mid-2013 [2].

We report the long-term photometric and polarimetric monitoring of PKS 1222+216 with different optical telescopes, and supplement our observations with γ-ray data from the *Fermi* Large Area Telescope and VLBA images at 43 GHz. We have used these observations to improve constraints on the location of the emission regions responsible for the optical and γ-ray flares by comparison of individual events (flares, polarization variability, jet kinematics) and cross-correlation analysis of light curves.

2. Observations and Data Reduction

Optical R-band flux densities were obtained from photometric and polarimetric observations with the 0.4 m telescope of St. Petersburg State U. (LX200) and with the 0.7 m telescope of the Crimean Astrophysical Observatory (AZT-8). The data analysis for these telescopes is described in [3]. We also used R-band photometric and polarimetric data obtained with the Perkins Telescope (BU group [4]), Liverpool Telescope, Calar Alto Telescopes [5], and Steward Observatory [6].

We used total and polarized intensity images of the quasar obtained by the Boston U. group at 43 GHz with the Very Long Baseline Array (VLBA). Each image in Stokes I, Q, and U parameters was fit by a model consisting of a number of components with circular Gaussian brightness distributions to obtain total flux densities, fractional polarization, EVPA , and relative (to the core) positions of the components. The "core" is a presumably stationary feature located at one of the ends of the portion of the jet that is visible at 43 GHz. Identification of components across the epochs is based on analysis of their distance from the core, flux density, position angle, and size. We have computed the kinematic parameters of knots (proper motion, apparent velocity, and acceleration) by fitting the position of each component over epochs by different polynomials in the same manner as described in [7].

We have derived 0.1–200 GeV γ-ray flux densities using data provided by the Large Area Telescope (LAT) of the *Fermi* Gamma-ray Space Telescope. We used the unbinned likelihood analysis implemented in the standard Fermi Science Tools software [8] for data reduction. The γ-ray light curve is constructed with four-day integration times. We used a log-parabolic spectral model of the source and a detection criterion that the maximum-likelihood test statistic (TS) should exceed 10 to provide approximately a 3σ detection level.

3. Results and Discussion

3.1. Light Curves

During 2008–2015, the quasar PKS 1222+216 exhibited two phases of high activity, with a number of optical and γ-ray flares separated by a continuous relatively quiescent state. The light curves and polarization parameters vs. time during the period from August 2008 to December 2015 are presented in Figure 1a–e.

The first major flare in the γ-ray band started on MJD 55095, with a rapid increase of flux and sharp peak on MJD 55106. The brightness of the 43 GHz VLBA-core increased to 0.64 Jy (on MJD 55121) contemporaneously with the optical flare. A number of γ-ray and optical flares occurred during the two subsequent years. The light curves in these bands contemporaneously display a series of sharp peaks, but there is no close accordance between the times and amplitudes of individual peaks. The brightness of the 43 GHz VLBA-core also varied substantially from 1.70 Jy (MJD 55622) to 0.22 Jy (MJD 55705), but more smoothly. An enlarged plot of this period is shown in Figure 2a. The interval from MJD $\sim$55800 to MJD $\sim$56430 is characterized by relatively low flux densities at γ-ray energies, optical R band and 43 GHz radio band (mean flux densities: 2.2×10^{-7} ph cm^{-2} s^{-1} in γ rays, 1.8 mJy in the optical R band, and 0.7 Jy in the 43 GHz VLBI core). Highest flux densities in all these bands were observed from MJD $\sim$56200 to MJD $\sim$56350 (7.2×10^{-7} ph cm^{-2} s^{-1} in γ rays, 2.5 mJy in the optical R band and 1.3 Jy in the 43 GHz VLBI core).

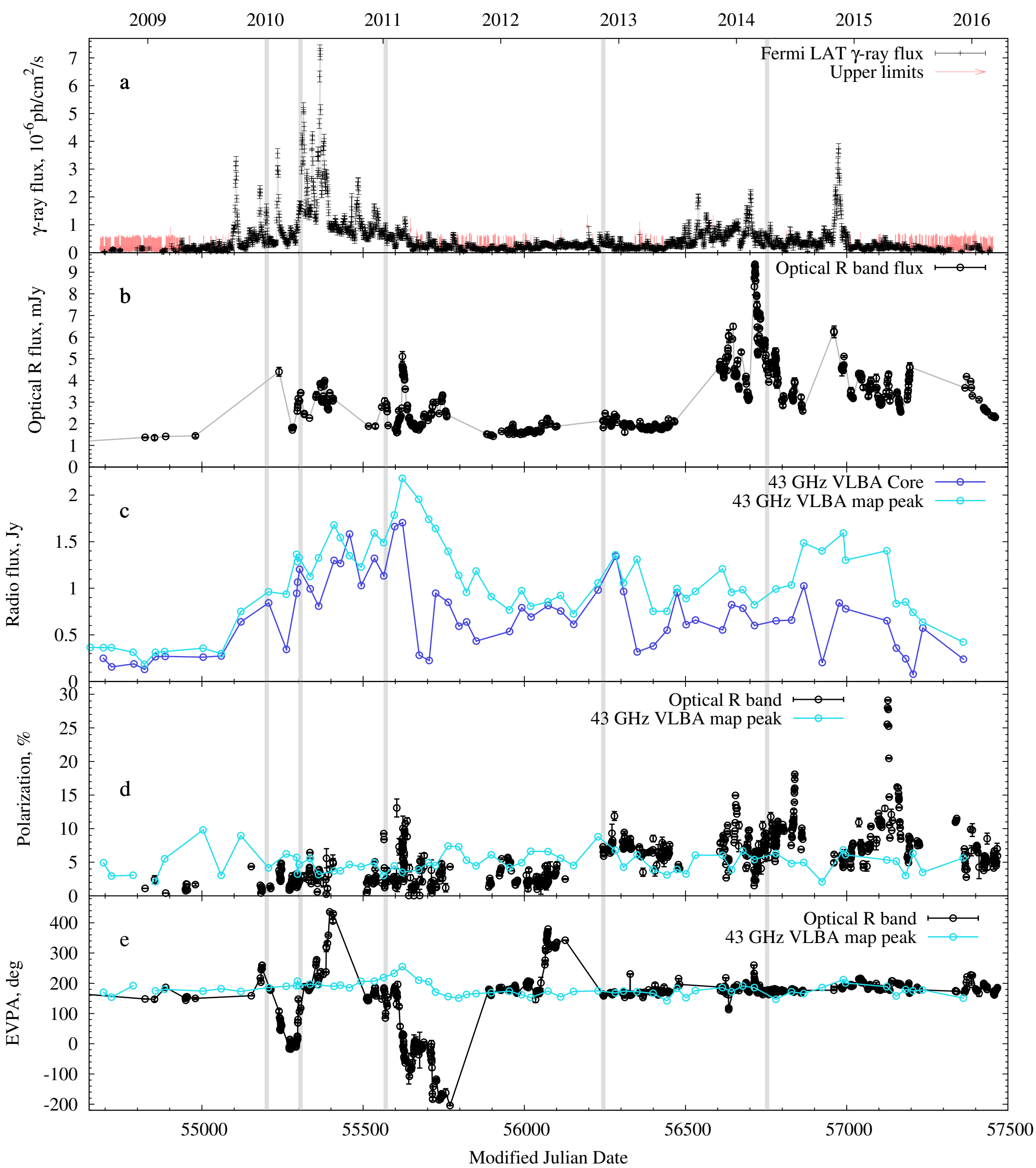

Figure 1. Light curves and polarization parameter curves. (**a**) *Fermi* LAT 0.1–200 GeV γ-ray light curve. Red arrows mark upper limits (test statistic values <10; i.e., less than ∼99.7% confidence level); (**b**) Optical light curve in R band; (**c**) Light curves in the 43 GHz radio band of the VLBI core and Very Long Baseline Array (VLBA) map peak; (**d**) Degree of polarization of the 43 GHz VLBA map peak and optical R band; (**e**) EVPA of the 43 GHz VLBA map peak and optical R band. The vertical gray bars mark ejection times of knots K1–K5.

The second phase of high activity is characterized by an increase of average flux densities and by a number of major optical and γ-ray flares (Figure 2b). When simultaneous observations are available, the bright optical flares occurred within ∼15 days of the bright γ ray flares.

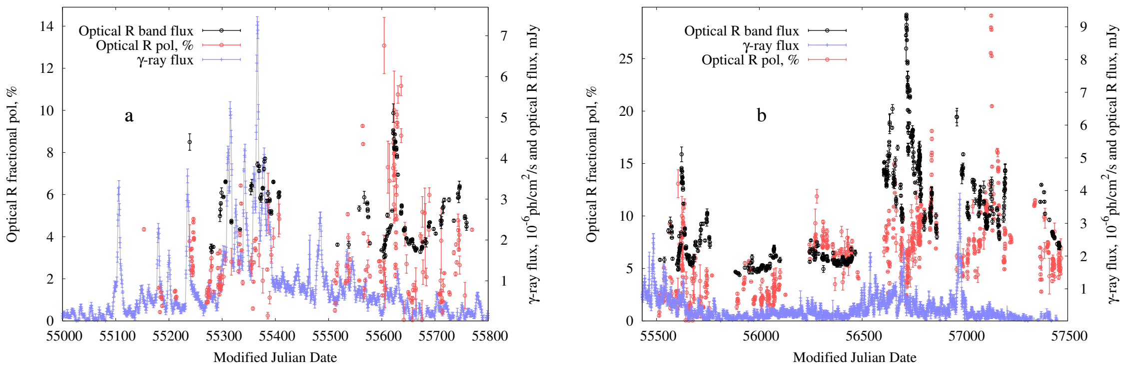

Figure 2. Light curves in γ rays, optical R band, and fractional polarization in optical R band for the periods (**a**) from MJD 55000 to MJD 55800 and (**b**) from MJD 55500 to MJD 57500.

We used the discrete correlation function (DCF, [9]) to quantify the apparent correlation between the γ-ray, optical R-band, and 43 GHz VLBI core light curves. Results are presented in Figure 3a,b. The DCF values between the γ-ray and optical data were calculated with seven-day binning. We used 30-day binning to estimate correlation coefficients between the γ-ray and 43 GHz VLBI core light curves. The DCF peaks of 0.29 ± 0.02 and 0.51 ± 0.04 correspond to the time lags of 18 and 95 days for the γ-ray–optical and γ-ray–VLBI core data, respectively.

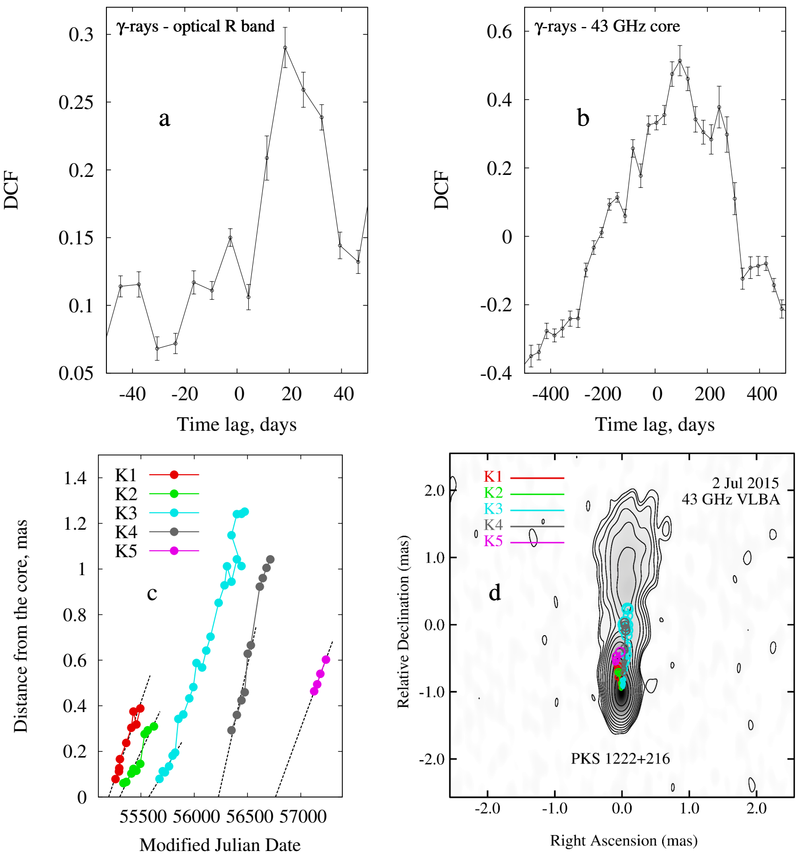

Figure 3. (**a**) Discrete correlation function (DCF) between the γ-ray and optical R-band data (7-day binning); (**b**) Discrete correlation function between the γ-ray and 43 GHz VLBI core data (30-day binning); (**c**) Distance from the 43 GHz VLBI core vs. time for knots K1–K5 (dashed lines represent linear extrapolation to zero distance from the core); (**d**) VLBA images at 43 GHz with overlaid trajectories of knots K1–K5.

3.2. Polarization

Over the entire interval of observations considered here, the quasar PKS 1222+216 displays prominent variability of the degree of optical polarization and rapid EVPA rotation.

A series of major γ-ray flares from MJD 55095 to MJD 55800 was accompanied by a fast increase of polarization degree in the optical R band and dramatic EVPA rotations (Figure 1). Starting from MJD 55180, the EVPA value in the optical R band rotated from 158° to 260° (MJD 55153 and MJD 55187), then rotated to −17° (MJD 55275), and after that rotated to 436° (MJD 55396). The optical flare on MJD 55558 is accompanied by an increase in the degree of polarization from 2% to 9% and EVPA rotation from 185° to 85°. The optical flare on MJD ∼55624 is accompanied by a high degree of polarization and rapid rotation of EVPA over 300°. This optical flare corresponds to the maximum observed VLBI core flux at 43 GHz.

After MJD 56200, only minor EVPA rotations were observed in the optical band. Meanwhile, the degree of polarization during the second phase of high activity varied dramatically (Figure 2b). Flares in the γ-ray and optical bands were accompanied by a rapid rise of the fractional polarization in the optical R band. During the optical flare on MJD 57128, the degree of optical polarization reached 29% near the time of maximum optical flux. The increase of the degree of polarization with the increase of total flux can be explained by ordering of the magnetic field in the shock-in-jet model [7,10,11].

3.3. VLBA Images

We have detected five superluminal knots in the parsec-scale jet of PKS 1222+216 at 43 GHz, with apparent speeds ranging from 9 c to 22 c. Angular distances from the core of knots K1–K5 as a function of time are shown in Figure 3c. The 43 GHz VLBI core was relatively faint (S_{core} < 0.4 Jy) before the first γ-ray flare (MJD 55100). Two superluminal knots, K1 and K2, were ejected during a series of strong γ-ray flares and rapid EVPA rotations in the optical R band (MJD ∼55201 and MJD ∼55306). The ejection of knot K3 (MJD ∼55570) is contemporaneous with the optical flare, increase of fractional optical polarization, and rotation of the optical EVPA. During the relatively quiescent period, only one knot, K4, was ejected (MJD 56245). The appearance of knot K4 coincided with the maximum of averaged flux densities in the γ-ray and optical R bands (peak-to-mean ratio of 3.3 at γ-ray energies and 1.4 in the optical R band for the period from MJD ∼55800 to MJD ∼56430). Knot K5 coincided with the VLBI core on MJD ∼56753 after the brightest optical flare and a series of γ-ray flares.

A new knot, K6, appeared in 2015 after the second phase of high activity. Further observations are required to estimate the time of ejection of knot K6 and compare this with the time of bright flares in γ-ray and optical bands in MJD ∼55700. We also detected a stationary component, A1, located 0.14 ± 0.04 mas from the core.

Figure 3d shows the VLBA image at 43 GHz (12 July 2015) with the trajectories of the components overlaid. The direction of the jet changed with time. The position angles of knots K1 and K2 with respect to the core were about +10°. The position angles of knots K3 and K4 were −7° and −4°, respectively. Knot K5 appeared with a position angle of about +10°. Knot K6 emerged with position angle ∼28° after the second phase of high activity.

The optical R-band EVPA has a preferred direction near 0°, which coincides with the EVPA values of the VLBA map peak at 43 GHz and the jet flow direction (Figures 1e and 3d).

4. Conclusions

During the period of observations from August 2008 to December 2015, the quasar PKS 1222+216 exhibited high activity, with a number of flares in the optical and γ-ray bands. This activity was apparent from radio to γ-ray frequencies. The fine structure of the light curves does not show detailed correspondence, but many optical flares (or polarization maxima) occurred close in time to bright γ-ray flares. The highest DCF values of 0.29 ± 0.02 and 0.51 ± 0 .04 correspond to time lags of 18 and 95 days for the γ-ray–optical and γ-ray–VLBI core data, respectively. We have detected five superluminal knots in the parsec-scale jet at 43 GHz with apparent speeds ranging from $9c$ to $22c$. The ejection times of knots K1, K2, K3, and K5 were close to the times of γ-ray and/or optical flares, and to intervals of significant EVPA rotations and variations in fractional polarization in the optical band. Knot K4 was ejected contemporaneously with the local increase of γ-ray and optical R-band flux densities within the continuously quiescent period. The direction of the parsec-scale jet fluctuated from $+10^{\circ}$ to -4° and to -7° after the first phase of high activity, then to $+28^{\circ}$ after the second active phase. We also found a preferred direction of EVPA in the optical R band near 0°, which is close to the EVPA values of the VLBA map peak at 43 GHz and the average jet flow direction. The rapid variability of the optical linear polarization may be explained by strong turbulence in the jet plasma [12]. The multi-wavelength behaviour of the quasar PKS 1222+216 presented here is evidence that many optical and γ-ray flares originate in the vicinity of the millimeter-wave core of the parsec-scale jet [12]. Despite the correlations and contemporaneous events found among the bands, these connections do not explain the entire complex broadband activity of the source; significant details remain to be interpreted. Continued monitoring at multiple wavelengths, with perhaps even closer sampling than for the data reported here, along with more sophisticated theoretical models, are required to understand the complex behavior of the quasar PKS 1222+216.

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