The Inner Jet of the Quasar PKS 1510–089 as Revealed by Multi-waveband Monitoring

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As part of our comprehensive long-term multi-waveband monitoring of 34 blazars, we followed the activity in the jet of the blazar PKS 1510–089 during major outbursts during the first half of 2009. The most revealing event was a two-month long outburst that featured a number of \(\gamma\)-ray flares. During the outburst, the position angle of optical linear polarization rotated by about 720°, which implies that a single emission feature was responsible for all of the flares during the outburst. At the end of the rotation, a new superluminal knot (∼22c) passed through the “core” seen on 43 GHz VLBA images at essentially the same time as an extremely sharp, high-amplitude \(\gamma\)-ray and optical flare occurred. We associate the entire multi-flare outburst with this knot. The ratio of \(\gamma\)-ray to synchrotron integrated flux indicates that some of the \(\gamma\)-ray flares resulted from inverse Compton scattering of seed photons outside the ultra-fast spine of the jet. Because many of the flares occurred over time scales of days or even hours, there must be a number of sources of IR-optical-UV seed photons — probably synchrotron emission — surrounding the spine, perhaps in a slower sheath of the jet.

1. Introduction

There are four primary methods for probing the structure and physics of relativistic jets in blazars on parsec and sub-parsec scales: VLBI imaging in both total and polarized intensity at millimeter wavelengths, variability of the flux at radio through \(\gamma\)-ray frequencies, polarization at radio through optical wavelengths, and the spectral energy distribution (SED). In the past, efforts to study this capricious class of objects have been limited by datasets with substantial gaps in either time or frequency coverage. Starting in the mid-1990s, this situation has been greatly alleviated by the availability of instruments such as the Very Long Baseline Array (VLBA), the Rossi X-ray Timing Explorer (RXTE), and, most recently, the Fermi Gamma-ray Space Telescope. Together with concerted efforts with optical/near-infrared, millimeter-wave, and radio telescopes, these facilities now allow long-term, comprehensive multi-waveband monitoring of a number of blazars. Such programs are providing valuable insights into the processes by which jets form and propagate, as well as the locations and physics of flux outbursts in blazars [e.g., Chatterjee et al. 2008, Larionov et al. 2008, Marscher et al. 2008].

We are leading a monitoring program that provides the data needed to combine the techniques listed above in order to locate the sites of high-energy emission, determine the processes by which X-rays and \(\gamma\)-rays are produced, and infer the physical conditions of the jet, including the geometry of its magnetic field. Because of limitations in sensitivity and available observing time, such comprehensive monitoring can be mounted only for a relatively small number of objects, 34 in the case of our program. Progress toward an overall understanding of blazars therefore involves generalization of inferences drawn from the well-studied specimens into a framework that can be applied to the entire class.

We present here a rich set of observations of the quasar PKS 1510–089 (\(z = 0.361\)) that allows us to locate the sites of \(\gamma\)-ray flares, leading to inferences on the high-energy emission processes. PKS 1510–089 possesses all of the characteristics of blazars: flat radio spectrum, apparent superluminal motion — among the fastest [as high as 45c for \(H_0=71 \text{ km s}^{-1}\text{Mpc}^{-1}\) and the concordance cosmology Spiergol et al. 2007] of all blazars observed thus far [Jorstad et al. 2005] — high-amplitude and rapid flux variability at all wavebands, strong and variable optical linear polarization, and high \(\gamma\)-ray apparent...
luminosity \cite{Hartman2001}. The observations of this blazar from our program allow us to compare motions, linear polarization, and changing flux of features in the parsec-scale radio jet with flux variability of the entire source at radio, millimeter-wave, IR, optical, X-ray, and $\gamma$-ray frequencies, and with optical polarization. The relative timing of the correlated variations thus found probe the structure and physics of the innermost jet regions where the flow is accelerated and collimated, and where the emitting electrons are energized.

2. Observational Results

Figure \ref{fig:1} presents the Fermi Large Area Telescope $\gamma$-ray light curve, the R-band optical light curve, and the optical polarization as a function of time during the first half of 2009, with the data taken from the above paper. Details of our observations of PKS 1510–089 are given in \cite{Marscher2010}, which includes data from 2006 to 2009. That paper also presents 43 GHz VLBA images showing that a bright superluminal (22c) knot (A) passed through the core on JD 2454959\pm 4. Additional VLBA images (see Fig. \ref{fig:2}) reveal that another knot (B) with the same apparent speed was coincident with the core on JD 2455008\pm 8. We stress that the “core” of a blazar seen on VLBI images lies parsecs downstream of the location of the black hole \cite{Marscher2002}. There is mounting evidence that, barring optical depth effects, the core represents emission from jet plasma that has been compressed and energized by a system of one or more standing conical shocks owing to pressure mismatches between the jet and the external medium.

One of the main questions that our observational program can answer is whether the high-energy emission occurs between the central engine and core, within the core, or downstream of the core. In order to do this, we must first establish an association between a superluminal knot and high-energy flares, then analyze the timing of the flares relative to the motion of the knot. In the case of BL Lac in 2005, we employed this method to determine that there are multiple sites of X-ray and optical flares in the jet: upstream of the core where the magnetic field has a helical geometry, and within the core. Flares occur as a disturbance in the jet flow (an “emission feature”) passes through these regions \cite{Marscher2008}.

Eight major flares are apparent in Figure \ref{fig:1} which covers the first half of 2009. The figure numbers the flares. (We note that $\gamma$-ray emission was detected at an elevated level throughout the 50+ days following flare 8, but one cannot isolate distinct flares during this period.) Of particular interest is the 51-day period from JD 2454901 to 2454962 during which flares 3-8 took place. As seen in Figure \ref{fig:1} the optical polarization position angle $\chi$ rotated by $\sim 720^\circ$. (Since there is no distinction between $\chi$ and $\chi \pm 180^\circ n$, we select $n$ such that the jump in $\chi$ is minimized.) The ratio of $\gamma$-ray 0.1-200 GeV integrated flux to bolometric synchrotron flux \cite{Marscher2010} for flares 1–8 was 70, 30, 40, 40, 30, 10, 40, and 9, respectively.

Superluminal knot A passed through the core at the same time (within the uncertainties) as the very sharp (intra-day), extremely high-amplitude $\gamma$-ray and optical flare on JD 2454962. The rotation of the optical polarization vector ended at the same time. We therefore surmise that the $\gamma$-ray flares occurred upstream of and within the core. After this point, the $\gamma$-ray flux remained elevated, which suggests that $\gamma$-ray emission continued downstream of the core, as inferred previously from observations with EGRET, the VLBA, and single-dish radio antennas \cite{Jorstad2001,Latheenmaki2003}.

3. Interpretation

Although a turbulent magnetic field can produce such apparent rotations of the polarization vector by $720^\circ$ or more via a random walk \cite{Aller1985,DArcangelo2007,Jones1988}, the beginning and end of such a rotation should occur randomly, whereas the observed event matches quite closely the duration of the flux outburst. We therefore conclude that a single coherent emission feature was responsible for the entire outburst. We appeal to the same model as for BL Lac \cite{Marscher2008}: as a disturbance in the flow moves down the jet, it follows a spiral streamline \cite{Vlahakis2006}. It first travels through the acceleration and collimation zone, which possesses a tightly wound helical magnetic field. If the emission feature covers most, but not all, of the cross-section of the jet, much of the polarization is cancelled out from mutually perpendicular magnetic field orientations around the circumference. The residual polarization vector rotates as the feature executes its spiral motion.

We have performed a rough calculation of the rotation of $\chi$ in such a model, matching the parameters (probably non-unique) to the PKS 1510–089 data. The bulk Lorentz factor increases from 8 to 24 during the rotation event, causing the Doppler factor to increase from 15 to 38 for an angle between the jet axis and the line of sight of 1.4$^\circ$ \cite{Jorstad2005}. The acceleration of the jet causes an increase with time in the rate of rotation, as observed. The circulation of the centroid of the emission feature around the jet axis causes $\chi$ (corrected for relativistic aberration) to undulate with time about the trend of monotonic rotation. In the quantitative model, the core lies 17 pc downstream of the point where the outburst containing flares 3-8 began. The magnetic field is in the range of 1 to 0.2 G during the outburst.
The dichotomy in the ratio of $\gamma$-ray to synchrotron flux of the various flares suggests that different sources of seed photons dominate the inverse Compton scattering as the emission feature moves down the jet. Flares with relatively low values of this ratio can be caused by an increase in the number of GeV electrons, which causes enhanced synchrotron, synchrotron self-Compton (SSC), and external Compton (EC) emission. If SSC is the main mechanism, second-order Compton (SSC), and external Compton (EC) emissions where either the sheath produces large numbers of seed photons or electrons are accelerated to GeV energies. A single superluminal knot can be responsible for a number of flares and periods of sustained elevated $\gamma$-ray emission.

As we accumulate data for more blazars, we expect to see similar patterns of flares both before and after a disturbance passes through the core of the jet. We also hope to find deviations from this pattern that serve to provide further insight into the range of physical behavior of blazars. In both cases, we anticipate a tremendous increase in our understanding of the relativistic jets of blazars by combining the great power of monitoring the flux, polarization, and submilliarcsecond structure of these exciting objects.

4. Conclusions

We are finally at the point where the richness of our datasets is sufficient for us to draw grand inferences about the locations and physical mechanisms of $\gamma$-ray flares. If PKS 1510–089 and BL Lac are typical, it is no wonder that previous, less comprehensive monitoring programs left us confused! There are multiple sources of seed photons, some of which are quite local (as opposed to more global, such as an IR-emitting hot dust torus) and may not radiate at sufficiently high luminosities to be directly observable. These include the accretion disk and BELR — which may be important during the earliest part of a multi-flare outburst — shocks or other features in the sheath of the jet, and synchrotron radiation from the fast spine of the jet that contains the electrons that scatter the seed photons to $\gamma$-ray energies. A single superluminal knot can be responsible for a number of flares and periods of sustained elevated $\gamma$-ray emission.

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References

Aller, H. D., et al. 1985, ApJS, 59, 513
Chatterjee, R., et al. 2008, ApJ, 689, 79
D’Arcangelo, F. D., et al. 2007, ApJL, 659, L107
Ghisellini, G., Tavecchio, F., & Chiaberge, M. 2005, A&A, 432, 401
Hartman, R. C., et al. 1999, ApJS, 123, 79
Jones, T. W. 1988, ApJ, 332, 678
Jorstad, S. G., et al. 2001b, ApJ, 556, 738
Jorstad, S. G., et al. 2005, AJ, 130, 1418
Lähteemäki, A. & Valtaoja, E. 2003, ApJ, 580, 85
Larionov, V. M., et al. 2008, A&A, 492, 389
Marscher, A. P., et al. 2002, ApJ, 577, 85
Marscher, A. P., et al. 2008, Nature, 452, 966
Marscher, A. P., et al. 2010, ApJ, 710, L126
Spergel, D. N., et al. 2007, ApJS, 170, 377
Vlahakis, N. 2006, in Blazar Variability Workshop II: Entering the GLAST Era, ed. H. R. Miller et al., ASP Conf. Ser., 350, 169
Figure 1: Variation with time during the first half of 2009 of (top to bottom panels) (1) $\gamma$-ray flux (upper limits in red), (2) optical flux density (note the logarithmic scale, to fit in the very high-amplitude flare on JD 2454962), (3) degree of optical linear polarization, and (4) electric-vector position angle of optical linear polarization. Vertical dotted lines denote major $\gamma$-ray flares. From data presented by Marscher et al. [2010].
Figure 2: VLBA image of PKS 1510–089 on 16 September 2009 (JD 2455091). The resolution beam is comparable to the angular size of the longest baselines of the array in the direction of the jet. Contour levels are -1, 1, 2, 4, 8, 16, 32, and 64% of the peak intensity of 0.55 Jy/beam. The two superluminal knots discussed in the text are marked, as is the core.
Figure 3: Sketch of the model for PKS 1510−089 discussed in the text. Note the logarithmic length scale, so that various components of the nucleus can be included.