Astrophysical Phenomena Revealed by Space VLBI
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High-Frequency Observations of Blazars

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Abstract

We report on the results of high-frequency VLBA observations of 42 γ-ray bright blazars monitored at 22 and 43 GHz between 1993.9 and 1997.6. In 1997 the observations included polarization-sensitive imaging. The cores of γ-ray blazars are only weakly polarized, with EVPAs (electric-vector position angles) usually within 40° of the local direction of the jet. The EVPAs of the jet components are usually within 20° of the local jet direction. The apparent speeds of the γ-ray bright blazars are considerably faster than in the general population of bright compact radio sources. Two X-ray flares (observed with RXTE) of the quasar PKS 1510$-$089 appear to be related to radio flares, but with the radio leading the X-ray variations by about 2 weeks. This can be explained either by synchrotron self-Compton emission in a component whose variations are limited by light travel time or by the Mirror Compton model.

1 Introduction

The operation of the VLBA has enabled us to make high dynamic-range, fine-resolution images of strong compact radio sources at frequencies of 22 and 43 GHz. This allows significant advancements in our exploration of the regions in the jets of blazars closer to the central engine than has heretofore been possible.

In order to explore the properties of the jets of γ-ray bright blazars at the highest possible resolution, the first four authors monitored 42 EGRET-detected blazars with the VLBA, mostly at 22 and 43 GHz.

Starting in 1997, near the end of the project, observations were carried out in dual-polarization mode so that polarized intensity images could be made. Here we describe the salient results obtained thus far from this study.

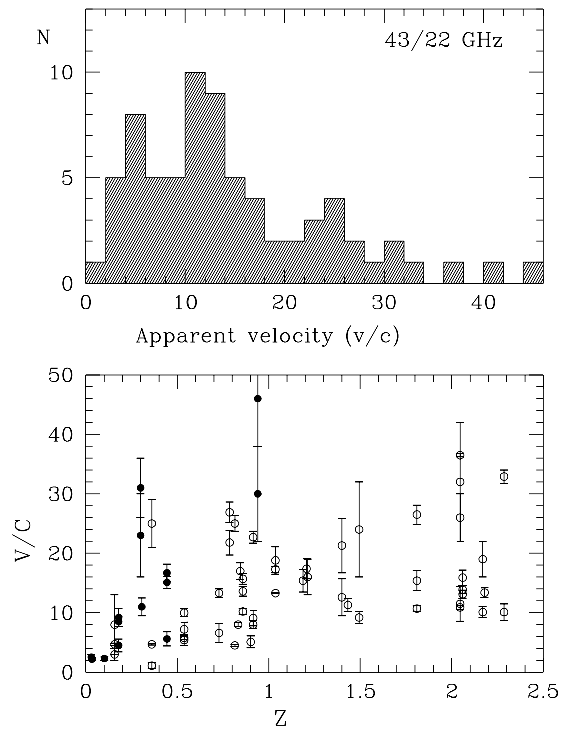

Figure 1: *Top panel:* Histogram of apparent velocities of jet components with proper motions detected (72 components in 33 sources). *Bottom panel:* Correlation plot of apparent velocities vs. redshift. BL Lac objects are denoted by filled circles, quasars by open circles.

In addition, starting in December 1996, three of us (APM, SGM-J, and MFA) began a campaign of weekly X-ray monitoring of the rapidly variable quasar PKS 1510−089 with the *Rossi* X-ray Timing Explorer (*RXTE*) to accompany the regular monitoring of the radio emission at 14.5, 8.0, and 4.8 GHz at the University of Michigan Radio Astronomy Observatory (UMRAO). The purpose is to determine whether the X-ray and radio variations are related in this object, which in the past has shown no significant time lags across radio frequencies (Tornikoski et al. 1994). We discuss preliminary results from this ongoing project below.

2 Results of the γ-Ray Blazar Monitoring Program

In the jets of the γ-ray blazar sample, we have found 26 stationary components in 20 sources and 72 moving components in 33 sources. Standing features are therefore quite common close to the core. The apparent velocity distribution of the moving components is given in Figure 1. The apparent speeds range from sub-c (Mkn 421) to $> 40c$ (0235+164) for $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.1$. The peak of the apparent velocity distribution is at $11c$, but there is a long high-velocity tail to the distribution: 13 of the sources (18 components) show motions at speeds exceeding $20c$. The distribution of apparent velocities of the general population of bright, flat-spectrum radio sources is quite different (Pearson et al. 1998), heavily weighted toward low speeds.

In general, for blazars in which more than one superluminal component is detected, the apparent velocities are not the same. For example, in PKS 0528+134 the speeds range from 4 to $13c$. If the separation from the core is deprojected in a crude fashion (e.g., by assuming that the fastest component is moving at the optimal angle for superluminal motion — the result does not depend strongly on the details of the deprojection scheme), there is a positive correlation of apparent speed with linear distance from the core for the sample.

Many of the jets of the γ-ray blazars are strongly bent. Examples are shown in Figure 2. Furthermore, a number of the jets of γ-ray blazars are quite broad within a few mas of the core, which suggests that they are being viewed nearly end-on.

The high apparent velocities, correlation of apparent velocity with distance from the core, strong apparent bending, and broad features in the jet, are all expected for a sample that is biased toward objects with relativistic jets that lie very close to the line of sight near the core. In such cases, the Doppler boosting of the high-energy emission will be maximal and the projection effects will be amplified compared with jets that, for example, lie at angles that maximize the proper motions. Seen in projection, jets pointing nearly at us appear broader and more strongly bent than do jets that lie at larger angles to the line of sight. Furthermore, the proper motion is less than its maximum value for such jets. If the jet bends, it will almost always bend away from the line of sight, since there is a very limited range in direction in which it could be to point even closer to the line of sight. Components farther down the jet will then have higher proper motions.

The polarized intensity images shown in Figure 2 are representative

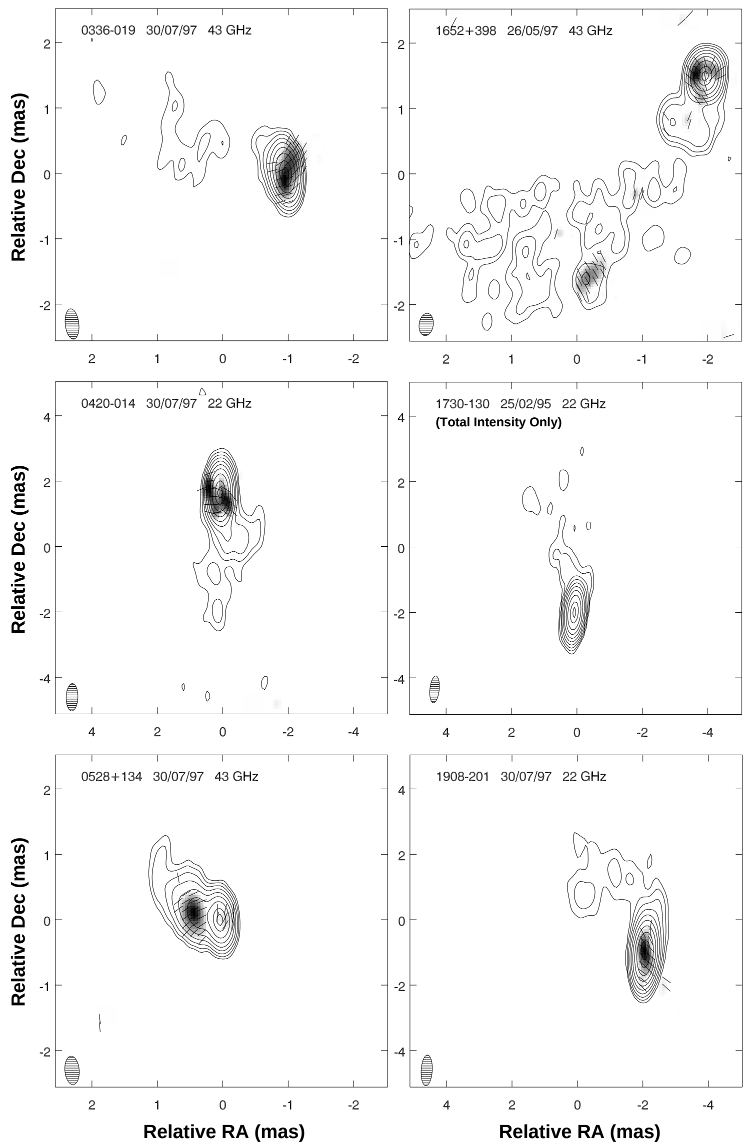

Figure 2: VLBA images of 6 blazars with strongly bent jets. The contours correspond to factors of 2 in total intensity, with the highest at 64%. The gray-scale shows polarized intensity, while the lines indicate the direction of the electric vectors. The maximum total intensities in Jy beam^{-1} (fractional polarizations of the cores) are: 0336−019: 1.73 (1.9%); 0420−014: 3.00 (0.5%); 0528+134: 1.74 (0.7%); 1652+398 (Mkn 501): 0.23 (1.2%); 1730−130: 7.81 (no polarized intensity image); 1908−201: 2.41 (1.4%).

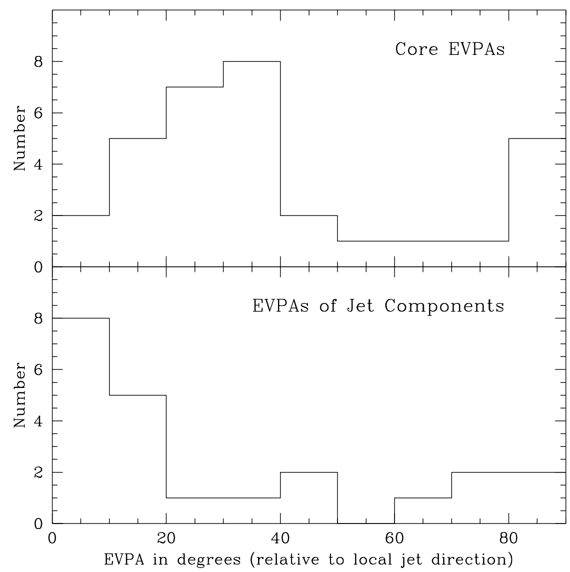

Figure 3: *Top panel:* Histogram of polarization electric-vector position angles (EVPAs), minus the local direction of the jet axis, of the cores of 32 of the blazars in the sample (4 other sources had core polarizations below the detection threshold). *Bottom panel:* The same for 22 jet components with significant polarization detected.

of the entire sample. The core polarizations are very low — all less than 6% and most less than 3%, with 25% (9 blazars) less than 1%. The electric-vector position angles (EVPAs) have a rather broad distribution relative to the local jet direction (see Figure 3, top panel), although there is a deficit of EVPAs between 40° and 80°. The EVPAs of the cores therefore tend to favor orientations somewhat parallel to the jets, but still at oblique angles, although 16% have EVPAs transverse to the jet. The substantial number of oblique EVPAs might suggest further bending closer to the central engine (so that the fields would be transverse to the inner jet direction), which can be tested with higher frequency or space-VLBI observations at 22 or 43 GHz. The distribution of the EVPAs of the jet components (see Fig. 3, bottom panel) is even more uneven, favoring magnetic fields that are either parallel or transverse to the jets. There is essentially no difference between the polarization properties of BL Lac objects and quasars, unlike what is found at 5 GHz (Cawthorne et al. 1993).

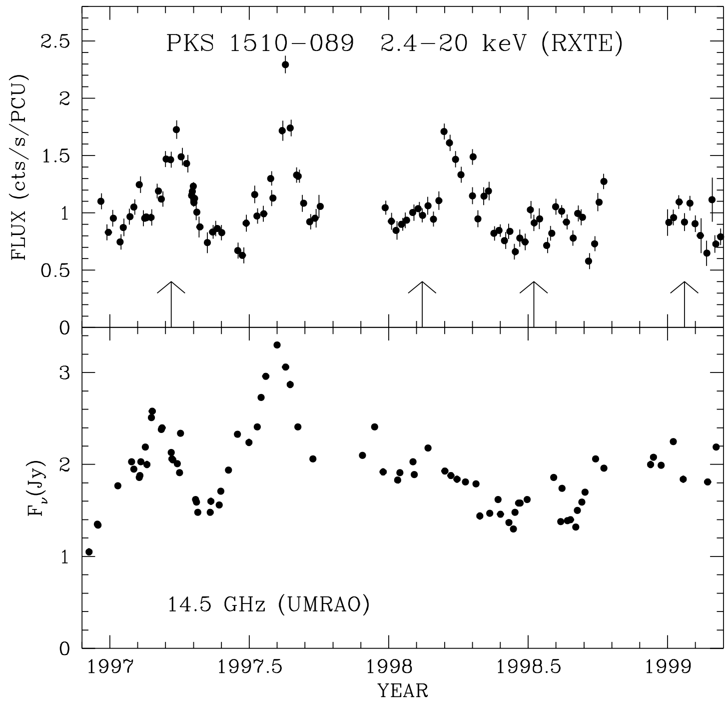

Figure 4: *Top panel:* X-ray light curve (flux is in photon counts per second per detector) of PKS 1510−089. *Bottom panel:* Radio light curve at 14.5 GHz. In the two major flares in 1997, the radio variations led the X-ray by about 2 weeks. The arrows indicate epochs of extrapolated zero separation between superluminally moving knots and the core.

3 Nearly Simultaneous X-Ray and Radio Flares in PKS 1510−089

Figure 4 shows the 2.4–20 keV X-ray and 14.5 GHz radio light curves of the quasar PKS 1510−089. In 1997 there were two strong flares at each waveband. It is noteworthy that the timescale of the flares was many weeks, which allowed good time sampling despite the fact that observations occurred only weekly. The second flare has a very similar profile at both wavebands. It is apparent from Fig. 4 that the radio variations *led* the X-ray by about two weeks. Of course, this needs to be confirmed with further observations, especially in light of the early-1998 X-ray flare that had no strong radio counterpart; we are continuing to monitor the source through early October 2000.

How can the radio lead the X-ray flare? There are two possibilities.

One is the "Mirror Compton" model of Ghisellini & Madau (1996), in which the synchrotron flare first scatters off one or more clouds near the jet so that the relativistic electrons in the jet see the flare blue-shifted and time-delayed and scatter these photons to X-ray and γ-ray energies. This predicts that longer time delays should correspond to weaker X-ray flares. The other possibility is that the X-rays are synchrotron self-Compton (SSC) emission from the jet. If the variations are limited by light-travel effects, then the electrons receive most of the synchrotron photons (which they will subsequently scatter to high energies) time-delayed. In this case the X-ray peak cannot occur any later than when the synchrotron flare has decayed to about 60% of its peak value (Sokolov & Marscher 2000), a condition that is satisfied by the two flares in PKS 1510−089 in 1997.

4 Conclusions

The association of high-energy emission with the relativistic jets in blazars is demonstrated by the coincidence of γ-ray (Marchenko-Jorstad et al., these proceedings) and X-ray flares with radio flares and/or superluminal ejections. The properties of the γ-ray blazars are consistent with a population that is more strongly beamed than the general population of strong, compact radio sources (Lister & Marscher 1999). The stronger beaming of the γ-rays occurs in the case of Compton scattering of photons from outside the jet because of the blue-shifting of these seed photons in the jet frame. In the SSC case, the extra beaming comes from the K-correction owing to the steeper spectral index (typically ~ -1) of the γ-ray emission relative to the radio emission (~ 0).

The polarization of the cores and jets of both quasars and BL Lac objects favors magnetic fields that lie transverse to the jet direction, although there are many sources in which the core polarizations are oblique by 20–40°. There is no significant difference between the polarization properties of BL Lac objects and quasars at 22 or 43 GHz.

The images shown here reveal cores that are still nearly unresolved. In order to explore the nature of the cores of blazar jets and to understand the production of energy and acceleration of relativistic electrons in the jets, we need the angular resolution provided by VLBI with antennas in space, as well as multiwavelength monitoring missions and campaigns. In addition, continued theoretical effort, especially 3D relativistic MHD simulations, is needed to interpret the results.

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