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Relationship between High-Frequency Emission and the Radio Jet in Blazars

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Abstract. The combination of VLBA and X-ray/γ-ray monitoring of blazars reveals some strong connections across the electromagnetic spectrum. In 3C 279 and PKS 1510−089, the nature of the X-ray variability changes as the projected direction of the compact jet swings. Outbursts in the radio, IR, or optical precede flares at high energies, and ejections of superluminal radio knots often accompany the flares. In 3C 120, in which the X-rays probably come from a corona above an accretion disk, the emergence of superluminal radio knots follows dips in the X-ray emission, as in microquasars. The delay implies that the core seen on high-frequency VLBA images is at least 0.4 pc from the central engine. Despite the undersampling of γ-ray variations by the *Compton* Gamma Ray Observatory's *EGRET* detector, there is strong evidence that γ-ray flares occur near the beginning of radio outbursts and superluminal ejections. It therefore appears that the high-energy emission is generated in the radio jet, at or downstream of the core seen on VLBA images. The VLBA, preferably combined with a space antenna, is therefore the perfect companion to the upcoming *GLAST* γ-ray mission.

1. Introduction

The superb monitoring capability of the VLBA serves as an excellent probe of the jets of blazars on ultra-fine scales. There is potential for similar information from multiwaveband variability, but in order to take advantage of this, we need to locate the sites of the higher frequency variability relative to the features seen on the radio images. Until recently, it was thought that the former were closer to the central engine than the VLBI core, and hence inaccessible to direct imaging. However, combined VLBA and higher frequency monitoring by the author and collaborators suggests that the emission regions across wavebands are co-spatial, or at least nearly so. This unleashes a probe of great value in our quest to understand the physics of the exotic relativistic plasma jets that wreak the nonthermal havoc we observe as the fireworks of quasar emission.

Below I summarize some of my collaboration's main findings through August 2003. Particularly interesting are (1) the appearance of a "reverse" time delay, which means that variations at lower frequencies are observed in advance of those at X-ray or γ-ray energies, and (2) a possible relation between changes in the projected position angle of the jet and those seen in the X-ray variability properties.

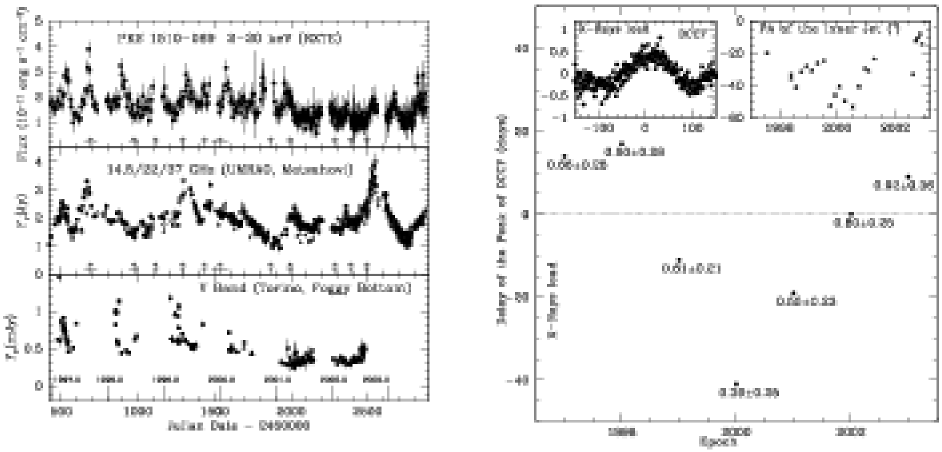

Figure 1. *a. (left)* X-ray and radio light curves of PKS 1510−089 from our long-term program. Arrows show times (horizontal lines: uncertainties) of known ejections of superluminal radio knots; some ejections may have been missed by the more limited time coverage prior to 1998.3 owing to extremely rapid motions (as high as 48c for $H_0 = 65$ km s^{-1} Mpc^{-1}). Only superluminal ejections before 2002.5 are included. *b. (right):* Delay of peak in the discrete cross-correlation function (DCCF) of the 14.5 GHz and X-ray light curves for each year of observation; positive values correspond to radio leading. The value of the DCCF peak is given, with those above ∼ 0.5 corresponding to very high levels of significance. *Left inset:* DCCF for all the data. *Right inset:* Direction of the pc-scale jet as a function of time.

2. The Quasar PKS 1510−089

A prime example of reverse time delay occurs in the quasar PKS 1510−089 (see Fig. 1b, upper left inset). Over a nearly 7-year period, the X-ray/radio correlation is strong, with a broad peak in the discrete cross-correlation function (DCCF) occurring at a lag of 8 days, with the radio variations leading those in the X-ray. Given the large amount of data involved, the level of the peak, ∼ 0.5, is highly significant. The breadth of the peak reflects not only the weeks-long timescale of a typical flare, but also the changing time lag. The radio and X-ray light curves in 1997, 1998, and 2003 are extremely well correlated, with the radio variations leading the X-ray by 9–17 days. In 1999–2001, the correlation is generally somewhat weaker and the lag is in the opposite sense, while in 2002 the correlation is strong but at zero lag. During the period of weakest correlation, the direction of the jet is considerably farther to the south, while the intervals of strongest correlation—with reverse time lags—correspond to the northernmost direction of the jet (see the upper right inset to Fig. 1b). If we can contime the project for another few years (i.e., if RXTE survives that long and if the time allocation panels are kind to us), we should be able to determine whether this trend between jet direction and the nature of the X-ray/radio correlation persists.

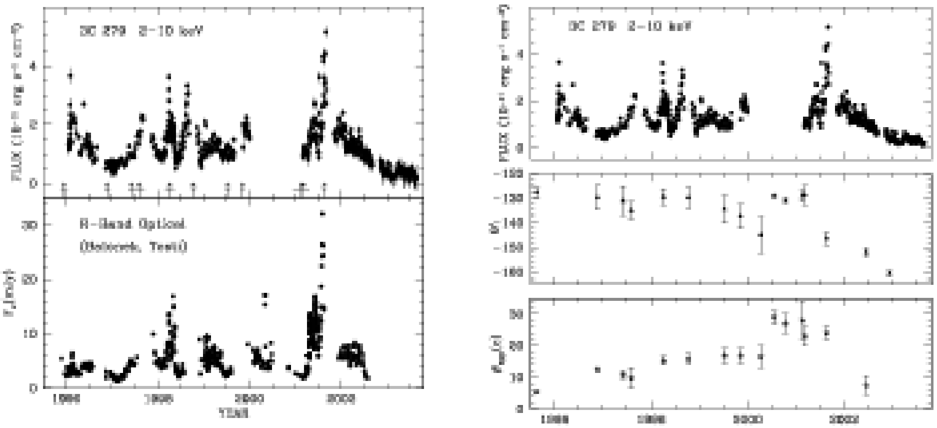

Figure 2. *a. (left):* RXTE and optical (mostly from T. Balonek & G. Tosti) light curves of 3C 279. Arrows show times of known ejections of superluminal radio knots (observations by Jorstad et al., in prep); any ejections in mid-1996 may have been missed owing to a dearth of VLBA observations during this time period, and no information is yet available for ejections after 2002.5. (Ejections during 2000 when the source was not observed with RXTE are not shown in the plot.) *b. (right):* Repeat of the X-ray light curve (*top*), angle of jet close to the core (*middle*), and apparent speed of superluminal knots (for $H_0 = 65$ km s^{-1} Mpc^{-1}) vs. date of extrapolated coincidence with the core (*bottom*).

The reverse time lag can only be explained if the X-rays are produced in the radio jet—in the core or a bit downstream—rather than closer to the central engine. Furthermore, it indicates that the flares are light-travel limited. In this case, it is difficult to understand why the profiles are usually sharply peaked, since light-travel limited flares should have ~ flat tops unless the decay time equals the light-travel time across the emitting region.

3. The Quasar 3C 279

In 3C 279, the overall light curve (Fig. 2a) suggests an R-band/X-ray correlation. This is verified by the DCCF, which indicates a strong (peak in DCCF ≈ 0.8, $> 99.999\%$ confidence) R-band/X-ray correlation at 0–3 day lag, with the optical leading the X-ray. Since the seed photons that are scattered to X-ray energies could be predominantly from IR or optical wavelengths, the cause of this reverse lag could be either light-travel delays (which tend to occur in synchotron self-Compton models for jets aligned very close to the line of sight; Sokolov & Marscher 2003) or frequency stratification (e.g., Georganopoulos & Marscher 1998).

As shown in Fig. 2b (middle panel), the apparent direction Θ of the milliarcsec-scale jet of 3C 279 swung by over 30° during our RXTE monitoring. Furthermore, the apparent speed of the radio knots increased from $5c$ in 1996 to $26 \pm 3c$ in 2001—when the activity was most violent—before decreasing precipitously in 2002 as the X-ray flux declined monotonically to the lowest levels seen during our program. If this relationship is confirmed by further observations, relating the emission properties to projected direction and apparent speed can lead to a determination separately of the Lorentz factor and angle to the line of sight of the jet.

4. Superluminal Ejections and High-Energy Emission

In an extensive VLBA study of 42 γ-ray bright blazars—about 60% of the total number known—Jorstad et al. (2001) found a statistical connection between times of high γ-ray flux and the epochs of (extrapolated) coincidence of new superluminal radio knots with the compact core. The timing indicates that superluminal ejections occur prior to the peak of a γ-ray flare. This is consistent with the finding of Lähteenmäki & Valtaoja (2003) that γ-ray flares occur during the rising portion of mm-wave outbursts.

While there appears to be an association of superluminal ejections with X-ray flares in PKS 1510−089 and 3C 279 (see Figs. 1 and 2), the relationship falls short of a one-to-one correspondence. Ejections can be missed because of inadequate time coverage and rapid decay (e.g., from extreme radiative energy losses), while flares can be canceled out by superposed decays of previous X-ray events or missed owing to the 8-week RXTE sun-avoidance gap. We hope that our more intensive monitoring since late 2001 will allow us to identify short-lived events and to measure time lags more accurately.

5. Where is the Radio Core?

In the radio galaxy 3C 120, we (Marscher et al. 2002) found that the emergence of superluminal radio knots is preceded, by about four weeks, by a dip in the X-ray flux, as in microquasars (Mirabel et al. 1998; the timescales, however, are much shorter). The X-ray emission is similar to that of black hole binary systems, so that it is reasonable to assume that the X-rays originate near the accretion disk. The 4-week delay then corresponds to the time it takes for the energy from a disturbance in the accretion flow to reach the radio core seen in VLBA images at 43 GHz. From this, we conclude that the core is $\gtrsim 0.4$ pc from the central engine. Since 3C 120 is a low-luminosity object, it is probably fairly small—the mass of its black hole is several $10^7\ M_\odot$ (Wandel et al. 1999; Marshall et al. 2003)—so that the core is probably parsecs from the central engine in powerful quasars and FR II radio galaxies.

6. Implications

Prior to the high-energy/radio timing studies, most blazar scientists operated under the working assumption that higher frequency emission occurs closer to the central engine than the position of the compact, high-frequency radio core. The implication of the results presented above is that the most intense, variable, nonthermal phenomena take place in the radio jet imaged by the VLBA at short wavelengths. But the timescales of variability are often $\lesssim 1$ day or shorter, which requires regions smaller than a few tens of light-days even for cases of strong relativistic beaming. This is reconciled by noting that the jets with the highest Lorentz factors, $\gtrsim 20$, must be intrinsically very narrow, with half-opening angles $\lesssim 0.5^\circ$; otherwise, they would all appear fat. In this case, a conical jet has a transverse radius of only $\lesssim 10$ light-days at a distance of 1 pc from its apex. If the thickness of the emission region is similar to its radius, variations on timescales less than a day are possible for objects with Lorentz factors $\gtrsim 10$ at such a location. The timescale of variability can therefore be very misleading as an indicator of the site of emission.

As pointed out by Lähteenmäki & Valtaoja (2003), placing the site of the high-energy emission so far from the central engine poses a problem for models in which the γ-rays result from upscattering of broad emission-line photons by electrons in the jet (e.g., Sikora et al. 1994). Since the broad-line region (BLR) is thought to be within 1 pc of the central engine, the angle of scattering is not as favorable as assumed in the models. Case studies should be carried out on some γ-ray blazars during the *GLAST* era to measure the size of the BLR as well as the placement of the γ-ray emission region relative to the radio core.

One of the obvious items on the agenda is to confirm the reverse-lag tendency in more objects. This will be possible when the wide-field, highly sensitive *GLAST* γ-ray observatory is deployed in a few years. Detailed γ-ray light curves will finally be available for many objects. This instrument, coupled with the VLBA—including, if possible, one or more space-based antennas—will allow us to map the variable emission from radio frequencies to high energies armed with the knowledge of where the radiative action is taking place in the jet.

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References

Georganopoulos, M., & Marscher, A. P. 1998, ApJ, 506, L11

Jorstad, S. G., et al. 2001, ApJ, 556, 738

Lähteenmäki, A., & Valtaoja, E. 2003, ApJ, 590, 95

Marscher, A. P., et al. 2002, Nature, 417, 625

Mirabel, F., et al. 1998, A&A, 330, L9

Sikora, M., Begelman, M. C., & Rees, M. J. 1994, ApJ, 421, 153

Sokolov, A. S., & Marscher, A. P. 2003, in High Energy Blazar Astronomy, ed. L.O. Takalo & E. Valtaoja, ASP Conf. Ser., 299, 153

Wandel, A., Peterson, B. M., & Malkan, M. A. 1999, ApJ, 526, 579