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Mapping Blazars' Inner Jets Through Multiwavelength Observations

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Abstract

Being dominated by non-thermal emission from aligned relativistic jets, blazars allow us to elucidate the physics of extragalactic jets, and, ultimately, how energy is extracted from the central black hole in radio-loud AGNs. Crucial information is provided by blazars' spectral energy distributions from radio to gamma-rays, their trends with luminosity, and correlated multifrequency variability. I will review recent results from multiwavelength monitorings of blazars which provide us with a close look to jets' inner regions.

1 The Spectral Energy Distributions (SEDs) of Blazars

Blazars are radio-loud Active Galactic Nuclei characterized by polarized, highly luminous, and rapidly variable non-thermal continuum emission (Angel & Stockmann 1980) from a relativistic jet oriented close to the line of sight. The radio through gamma-ray spectral energy distributions (SEDs) of blazars exhibit two broad humps (Figure 1). The first component peaks at IR/optical in "red" blazars and at UV/X-rays in their "blue" counterparts, and is most likely due to synchrotron emission from relativistic electrons in the jet (e.g., Ulrich, Maraschi, & Urry 1997). The second component, extending from X-rays to gamma-rays, has less well understood origin. It could be due to inverse Compton (IC) scattering of ambient photons, either internal (synchrotron-self Compton, SSC; Tavecchio, Maraschi, & Ghisellini 1998) or external to the jet (external Compton, EC; e.g., Sikora 1994). In the following discussion I will assume the synchrotron and IC scenarios, keeping in mind, however, that a possible alternative for the production of gamma-rays is provided by the hadronic models (proton-induced cascades; e.g., Rachen 1999).

Red and blue blazars are just the extrema of a continuous distribution of SEDs. Recent multicolor surveys (Laurent-Muehleisen et al. 1998; Perlman et al. 1998) found sources with intermediate spectral shapes, and trends with bolometric luminosity were discovered (Sambruna, Maraschi, & Urry 1996; Fossati et al. 1998). In the more luminous red blazars the synchrotron and IC peak frequencies are lower, the

Compton dominance (ratio of the synchrotron to IC peak luminosities) is larger, and the luminosity of the optical emission lines/non-thermal blue bumps is larger than in their blue counterparts (Sambruna 1997). A possible interpretation is that the different types of blazars are due to the different predominant electrons' cooling mechanisms (Ghisellini et al. 1998). In this context, red blazars, where large external radiation fields are observed, are EC-dominated at γ-rays, while in blue blazars the higher energies are produced via SSC. While there are caveats to this picture (Urry 1999), it is clear that the spectral diversity of blazars' jets cannot be explained by beaming effects *only* (Sambruna et al. 1996; Georganopoulos & Marscher 1998), but require instead a change of physical parameters and/or a different jet environment.

2 Correlated Multiwavelength Variability: Testing the Blazar Paradigm

Correlated multiwavelength variability provides a way to test the cooling paradigm since the various synchrotron and IC models make different predictions for the relative flare amplitudes and shape, and the time lags (see Sambruna 1999 for a review). Here I summarize recent results for a few prototypical objects of both the red and blue types.

2.1 Results for Red Blazars

One of the best monitored red blazars is 3C279. From the simultaneous or contemporaneous SEDs in Figure 1a, it is apparent that the largest variations are observed above the synchrotron peak in IR/optical (not well defined) and the Compton peak at GeV energies, supporting the synchrotron and IC models. The GeV amplitude is roughly the square of the optical flux during the earlier campaigns, supporting an SSC interpretation (Maraschi et al. 1994) or a change of the beaming factor δ in the EC models, while in 1996 large variations were recorded at gamma-rays but not at lower energies (Wehrle et al. 1998). During the latter campaign, the rapid decay of the GeV flare (Figure 2a) favors the EC model (Wehrle et al. 1998). Note the good correlation, within one day, of the EGRET and RXTE flares, which provides the first evidence that the gamma-rays and X-rays are cospatial (Wehrle et al. 1998).

Another candidate for future gamma-ray monitorings is BL Lac itself. In 1997 July it underwent a strong flare at GeV and optical energies (Bloom et al. 1997). The gamma-ray light curve shows a strong

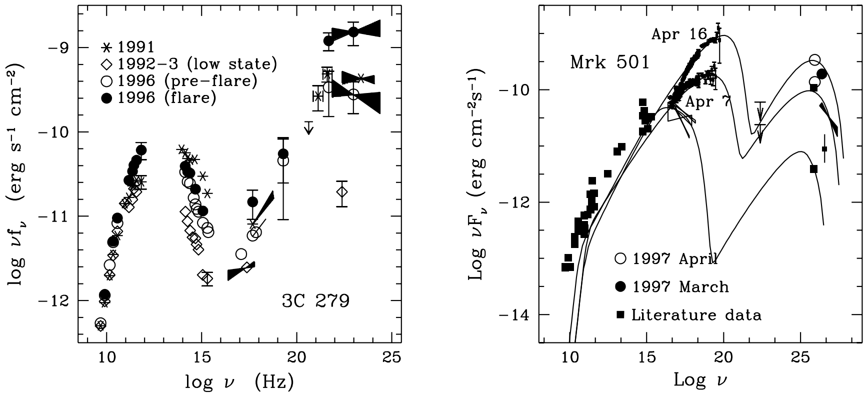

Figure 1: Spectral energy distributions (SEDs) of 3C279 [*(a), Left*] and Mrk 501 [*(b), Right*]. Data are from Maraschi et al. (1994), Wehrle et al. (1998), and Pian et al. (1998). Blazars' SEDs typically have two broad humps, the first peaking anywhere from IR/optical (in red blazars like 3C279) to hard X-rays (in blue blazars like Mrk 501) and due to synchrotron emission from a relativistic jet. The second component, extending to gamma-rays, is less well understood. A popular explanation is inverse Compton scattering of ambient seed photons off the jet's electrons.

flare possibly anticipating the optical by up to 0.5 days; however, the poor sampling does not allow firmer conclusions. The SED during the outburst is best modeled by the SSC model from radio to X-rays, while an EC contribution is required above a few MeV (Sambruna et al. 1999). A similar mix of SSC and EC is also required to fit the SEDs of PKS 0528+134 (e.g., Sambruna et al. 1997).

2.2 Results for Blue Blazars

Mrk 501, one of the two brightest TeV blazars, attracted much attention in 1997 April when it underwent a spectacular flare at TeV energies (Catanese et al. 1997; Aharonian et al. 1999; Djannati-Atai et al. 1999). This was correlated to a similarly-structured X-ray flare observed with RXTE, with no delay larger than one day (Krawczynski et al. 2000). These results are consistent with an SSC scenario where the most energetic electrons are responsible for both the hard X-rays (via synchrotron)

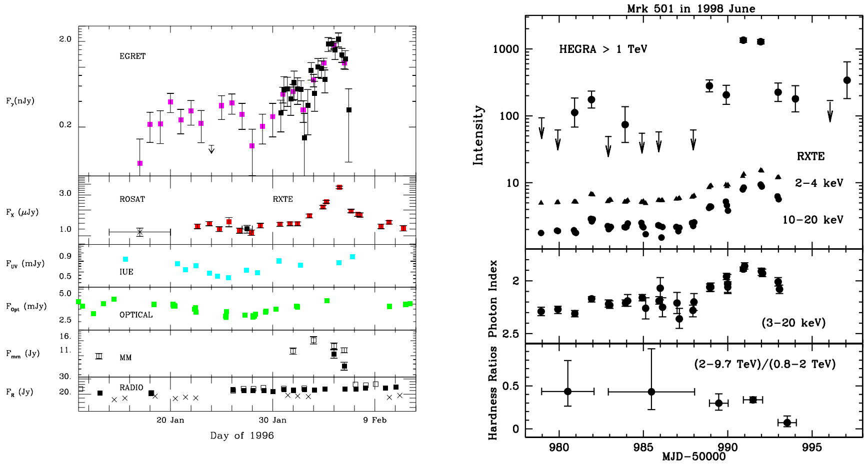

Figure 2: Multiwavelength light curves of 3C279 in 1996 January [*(a), Left*] and of Mrk 501 in 1998 June [*(b), Right*]. Data from Wehrle et al. (1998) and Sambruna et al. (2000).

and the TeV (via IC).

Figure 1b shows the SEDs of Mrk 501 during the 1997 April TeV activity, compared to the "quiescent" SED from the literature. An unusually flat (photon index, $\Gamma_X \sim 1.8$) X-ray continuum was measured by SAX and RXTE during the TeV flare (Pian et al. 1998; Krawczynski et al. 2000), implying a shift of the synchrotron peak by more than two orders of magnitude. This almost certainly reflects a large increase of the electron energy (Pian et al. 1998), or the injection of a new electron population on top a quiescent one (Kataoka et al. 1999). Later RXTE observations in 1997 July found the source still in a high and hard X-ray state (Lamer & Wagner 1998), indicating a persistent energizing mechanism.

An interesting new behavior was observed during our latest 2-week RXTE-HEGRA monitoring of Mrk 501 in 1998 June (Sambruna et al. 2000), when 100% overlap between the X-rays and TeV light curves was achieved (Figure 2b). A strong short-lived ($\sim$ two days) TeV flare was detected, correlated to a flare in the X-rays, with energy-dependent amplitude. As in 1997, large X-ray spectral variations are observed, with the X-ray continuum flattening to $\Gamma_X = 1.9$ at the peak of the TeV flare, implying a similar shift to ≥ 50 keV of the synchrotron peak. However, while in 1997 the TeV spectrum hardened during the flare (Djannati-

Atai et al. 1999), as it did in the X-rays, we did not observe significant variability in the TeV hardness ratios during the flare (Figure 2b, bottom panel); instead the spectrum softens 1-2 days later. The correspondence between the X-ray and TeV spectra is no longer present during the 1998 June flare.

3 Acceleration and Cooling in Blue Blazars

X-ray monitorings of blue blazars are a powerful diagnostic of physical processes occurring in these sources. This is because in these objects the X-rays are the high-energy tail of the synchrotron component where rapid and complex flux and spectral variability is expected depending on the balance between escape, acceleration, and cooling of the emitting particles (Kirk et al. 1998).

An ideal target for X-ray monitorings is PKS 2155–304, one of the brightest X-ray blazars. Interest in this source was recently revived due to a TeV detection (Chadwick et al. 1999) during a high X-ray state (Chiappetti et al. 1999). ASCA and SAX observations detected strong X-ray variability, with the softer energies lagging the harder energies by one hour or less (Chiappetti et al. 1999; Kataoka et al. 2000; Zhang et al. 1999), and are consistent with a model where the electron cooling dominates the flares. This implies magnetic fields of $B \sim 0.1-0.2$ Gauss (for $\delta \sim 10$), similar to Mrk 421 (Takahashi et al. 1996).

A new mode of variability was discovered during our RXTE monitoring of PKS 2155–304 in 1996 May, as part of a larger multifrequency campaign. The sampling in the X-rays was excellent (Figure 3), and complex flux variations were observed, with short, symmetric flares superposed to a longer baseline trend. Inspection of the hardness ratios (the ratio of the counts in 6–20 keV over the counts in 2–6 keV) versus flux shows that different flares (separated by vertical dashed lines in Figure 3) exhibit hysteresis loops of opposite signs, both in a "clockwise" and "anti-clockwise" sense (labeled as C and A in Figure 3, respectively). Applying a correlation analysis to each flare separately, we find that the C loops corresponds to a soft lag (softer energies lagging) and the A loop corresponds to a hard lag (harder energies lagging), of the order of a few hours in both cases.

We interpreted the data using the acceleration model of Kirk et al. (1998). Here loops of both signs are expected depending on how fast the electrons are accelerated compared to their cooling time, t_{cool}. If

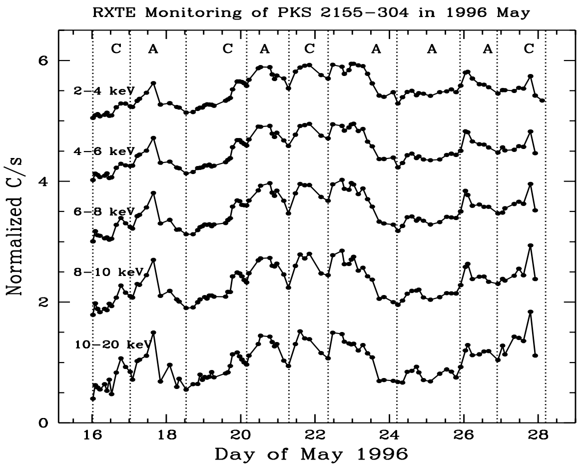

Figure 3: RXTE intensive monitoring of PKS 2155–304 in 1996 May. Energy-dependent X-ray light curves, normalized to their average intensity and arbitrarily shifted. The vertical dashed lines mark portions of the light curves characterized by "clockwise" (C) or "anti-clockwise" (A) hysteresis loops in the hardness ratio versus intensity diagrams. This complex spectral behavior is a powerful diagnostic of the acceleration and cooling processes in the jet.

the acceleration is instantaneous (i.e., $t_{acc} << t_{cool}$), cooling dominates variability and, because of its energy dependence, the harder energies are emitted first, with C loops. If instead the acceleration is slower ($t_{acc} \sim t_{cool}$), the electrons need to work their way up in energy and the softer energies are emitted first, with A loops. A close agreement between the RXTE light curve and the model is found by increasing t_{acc} by a factor 100 going from a C to an A loop, when t_{acc} becomes similar to the duration of the flare, and by steepening the electron energy distribution. Thus we reach the important conclusion that we are indeed observing electron acceleration, and together with cooling this is responsible for the observed X-ray variability properties of PKS 2155–304.

4 Summary and Future Work

Recent multiwavelength campaigns of blazars expanded the current available database, from which we are learning important new lessons. Detailed modeling of the SEDs of bright gamma-ray blazars of the red and blue types tend to support the current cooling paradigm, where red sources are EC-dominated and blue sources are SSC-dominated at gamma-rays. However, several observational biases are present, including the limited EGRET sensitivity and currently small number of TeV blazars (5). A more definite test of the blazar paradigm awaits the higher sensitivities of future missions (GLAST, AGILE in GeV and HESS, VERITAS, MAGIC, CANGAROO II in TeV). Broader-band, higher quality gamma-ray spectra will also be available, allowing a better location of the IC peak, a more precise measure of the spectral shape at gamma-rays, and its variability. More correlated X-ray/TeV monitorings are necessary, in which RXTE and SAX have crucial roles, to add to the current knowledge of the variability modes of single sources.

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Corrections to VSOP Symposium Proceedings

* In the contents, the author list for the paper starting on page 79 is incomplete and should read
  "Ignas Snellen, Wolfgang Tschager, Richard Schilizzi et al."

* In the preface, "Orian-KL" should be "Orion-KL"!!!

* The caption to Color Figure 3 refers to the source 1928+734, which should be 1928+738.

* In the summary section on page 49 (Murphy et al.), the sentence
  "In that time, we have observed a variety of
  structural changes in the inner jet region near the region."
  should read
  "In that time, we have observed a variety of
  structural changes in the inner jet region near the core."

* In the references on page 175 (Fomalont et al.) and page 182 (Moellenbrock et al.) "Fomalont et al. 2000" should be updated to
  "Fomalont, E.B., Frey, S., Paragi, Z., Gurvits, L.I., Scott, W.K., Edwards, P.G., Hirabayashi, H., 2000, ApJS, 131, 95"

* On page 217 (Lovell et al), the fourth line of the final paragrpah of section 1 should say "(see figure on page xviii)"

* In the references on page 233 (Sambruna) an extraneous "439" was introduced during the editing process into the reference for Catanese 1999.

* In the First Author List on page 327 (in the Index), the following line is missing
  Junor, W.   13