Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring
ASP Conference Series, Vol. TBD, 2000
B.M. Peterson, R.S. Polidan, and R.W. Pogge

Time Delays of Blazar Flares Observed at Different Wavebands

Alan P. Marscher

Institute for Astrophysical Research, Boston University, 725 Commonwealth Ave., Boston, MA 02215

Abstract. Correlated variability at different frequencies can probe the structure and physics of the jet of a blazar on size scales much smaller than can be resolved by telescopes and interferometers. I discuss some observations of frequency dependent time lags and how these place constraints on models for the nonthermal emission in blazars. The time lags can be either positive (high frequency variations leading those at lower frequencies) or negative, while simultaneous flares are also possible.

1. Introduction

The jets of blazars are the sites of extremely exotic and interesting physical phenomena: Continuous ejection of highly collimated, extremely energetic, magnetized plasmas at highly relativistic bulk speeds, rapid and sporadic acceleration of ultrarelativistic particles, probable production of electron-positron pairs, formation of multiple shock waves, synchrotron radiation at very high intensity, and inverse Compton scattering of synchrotron photons to KeV, MeV, GeV, and even TeV energies. As a consequence, we observe a dazzling display of cosmic fireworks across the electromagnetic spectrum, as well as the illusion of faster-than-light motion of bright blobs of radio-bright plasma. If we can determine how jets in blazars can do such things at amazingly high efficiency, we will solve some of the most outstanding puzzles of the universe.

Fortunately, very long baseline interferometry (VLBI) with the Very Long Baseline Array (VLBA) can image the jets in blazars at resolutions as high as 0.1 milliarcseconds, which corresponds to 0.07 pc in Mkn 501 (redshift $z = 0.034$), 0.14 pc in BL Lac ($z = 0.069$), 0.6 pc in 3C 279 ($z = 0.538$), and 0.9 pc in PKS 0528+134 ($z = 2.06$). (These numbers are calculated for a Hubble constant $H_0 = 65$ km s^{-1} Mpc^{-1} and either $q_0 = 0.1$ or a flat universe with Ω(baryons) = 0.3 and $\Omega(\Lambda) = 0.7$.) However, time scales of variability indicate that most of the interesting action occurs on even smaller scales.

How can we probe these ultrafine scales to unlock the secrets of blazars? The most promising method is multiwaveband monitoring: There is a wealth of information in the frequency-dependent timing of correlated variations in brightness and polarization. Unfortunately, proper multiwaveband monitoring is very difficult and the theoretical models are not yet worked out to sufficient precision to allow unambiguous interpretations.

Here I present some recent results of multiwaveband monitoring that is fairly intensive in time coverage but, unfortunately, not so intensive in frequency coverage. This will serve to illustrate the power and practical difficulties of tapping the rich potential of such studies. I will then discuss the characteristics of frequency-dependent variability expected according to various proposed emission models. I will conclude by mentioning what is needed in order to exploit the technique more fully.

2. Multiwaveband Observations

There have been a number of cases in which the multiwaveband time sampling has been good enough to provide strong constraints on models. Of course, there have been many more in which the coverage was not good enough to do this despite concerted efforts on the part of the investigators. My advice to those found in this situation is to publish their data (e.g., in the electronic *Blazar Data Journal*) with a minimal amount of interpretation: It just is not worth the valuable time of an active scientist to try to apply theoretical models to a dataset that is too incomplete to draw firm conclusions. (Of course, we all do it anyways, which is one reason why there is so much old data that has still not been published!) Here, I will examine a few of the campaigns that have borne fruit. There are a number of others (e.g., the exquisite correlations of X-ray and TeV variations in Mkn 421 and Mkn 501) that I will not discuss except perhaps in passing, owing to space limitations.

2.1. PKS 1510−089

My colleagues (M. Aller, S. Jorstad, and I. McHardy) and I have been observing the quasar ($z = 0.361$) PKS 1510−089 with RXTE, the University of Michigan Radio Astronomy Observatory (UMRAO), the VLBA (43 GHz polarization-sensitive imaging), and Lowell Observatory's 1.8 m Perkins Telescope. The radio and X-ray results are shown in Figure 1. The X-ray and 14.5 GHz radio variations in 1997 were about as well-correlated (Fig. 2) as one could expect theoretically: The maximum value of the discrete cross-correlation function is 0.7 at a *negative* time lag of 16 days, i.e., the radio variations led the X-ray by $\sim$ 16 days (the peak of the dccf). (Simulations are being carried out to ensure that the correlation is statistically significant given the power spectra of the variations at each waveband.) Note that the X-ray peaks in the two major 1997 flares occur when the radio flux density has fallen to $\sim$ 80% of its maximum value; this is consistent with the SSC explanation (see below). The radio variability of this object occurs almost completely in the core region; the superluminal components are quite weak by the time they can be resolved from the core.

The radio and X-ray variations after early 1998 are not as well correlated, however (see Fig. 2), with suggestions of a $\sim$ 6 day "forward" time lag. This implies a change in the site where the primary emission occurs, with the radio originating downstream of the higher frequency emission site. We are in the process of interpreting the VLBA images to determine whether there was a change in the structure of the radio jet that might explain this.

The X-ray flares often have symmetric profiles but in at least one case (early 1998) an abrupt rise is followed by a gradual decay. Some flares are "clean," while others are characterized by rapid fluctuations superposed on a longer-

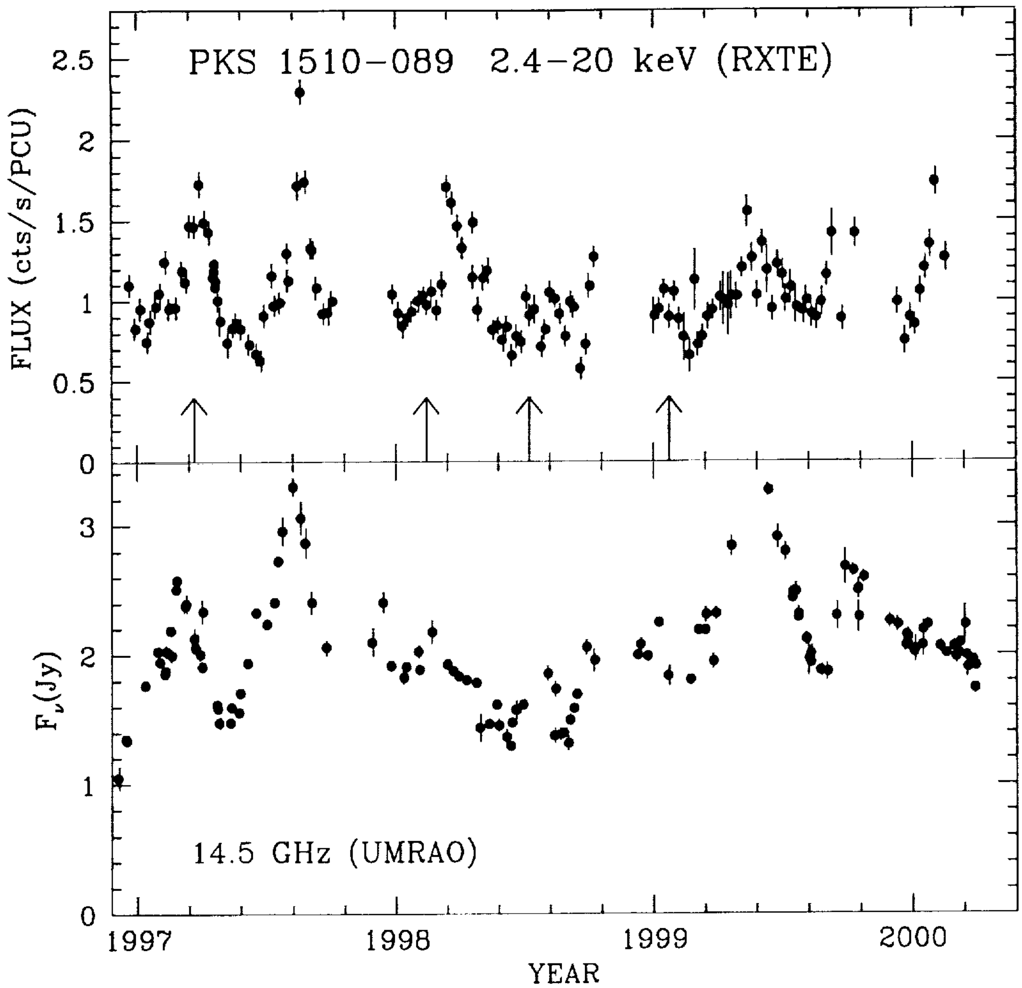

Figure 1. RXTE 2.4–20 keV and UMRAO 14.5 GHz light curves (observations by the PI and collaborators) of PKS 1510−089 from the end of 1997 to early 2000. The data show a high degree of variability that is well-correlated with the radio variability in 1997 but becomes less well correlated at later epochs. Arrows show times of known ejections of superluminal radio knots; some ejections were probably missed owing to the very rapid motions and inadequate time coverage of the observations, so we cannot form any conclusions with regard to correlations of X-ray flares with superluminal ejections.

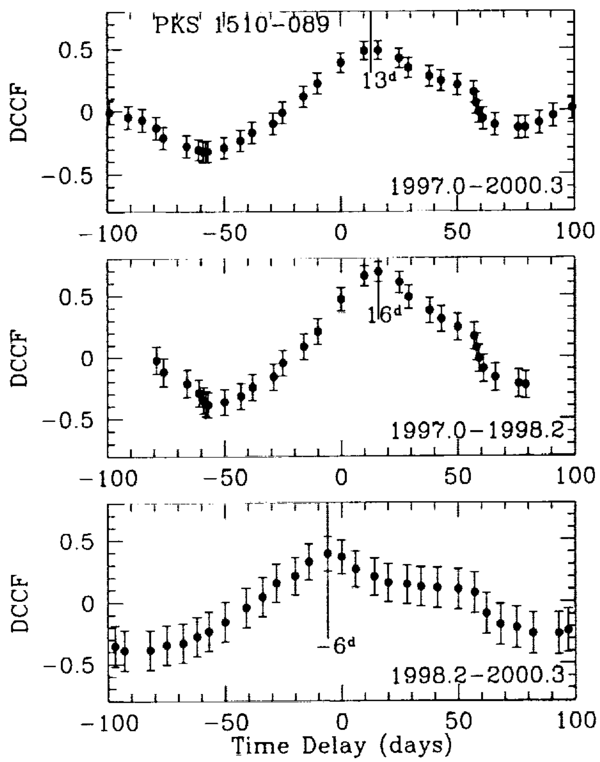

Figure 2. Discrete cross-correlation function of the 14.5 GHz and X-ray light curves of PKS 1510−089. A negative time delay corresponds to the X-ray variations leading the radio.

term trend. We are investigating whether these characteristics are correlated with other properties such as spectral index.

2.2. 3C 279

This $z = 0.538$ quasar has been the target of a number of multiwavelength campaigns. The infamous 1996 February flare (ironically, nearly all the potential optical observers were at a conference on variability in Miami!) was well monitored at γ-ray energies (0.1–3 GeV) by EGRET and in medium-energy (2.4–10 keV) X-rays by RXTE (Wehrle et al. 1998 and Lawson, McHardy, & Marscher 1999). The flares were essentially simultaneous, although the errors on the γ-ray fluxes are large because of the short time bins. This requires that the emitting regions be co-spatial, which in turn provides independent evidence for relativistic beaming in order to avoid high pair-production opacities for the γ rays (see Wehrle et al. 1998). The beaming required is of the same order as that needed to explain the apparent superluminal motion of radio knots in 3C 279 (Wehrle et al. 2000). The flare profile was symmetric and well-fit by an exponential rise to a sharp peak, followed by an exponential decline.

There have been indications that optical flares are related to γ-ray flares in 3C 279, but the spotty time coverage in the γ-ray part of the spectrum renders correlations difficult to establish. Unlike PKS 1510−089, we (same collaboration) find no detailed correspondence between the X-ray and radio variations. In general, however, the overall nonthermal flux across all wavebands tends to rise and fall together on long time scales ($\sim$ 1 yr) (Makino et al. 1989; Maraschi et al. 1994).

2.3. 3C 273

It is surprising that 3C 273, the brightest quasar at X-ray as well as optical and, at many epochs, radio frequencies, has not been the subject of a long-term, well-sampled monitoring campaign with RXTE to date. McHardy et al. (1999) carried out an intensive study in 1997 over a time span of 50 days, finding that the 2.4–20 keV flux fluctuates by about 50% on time scales of order one week. Rather poorly time-sampled K-band measurements suggest that the near-IR leads the X-ray variations by 0.75 ± 0.25 days.

2.4. PKS 1406−076

Wagner et al. (1995) tentatively identified an optical flare with a 2-day γ-ray flare in 1993 January. If the correspondence is real, then there is a reverse time lag, with the optical leading the γ-ray by about a day. Although the peak of the γ-ray flare is not well-defined, it appears that the optical brightness had fallen to $\sim$ 60% of its peak when the high-energy flare reached maximum flux.

2.5. BL Lac

A detailed study of variability in BL Lac by Bregman et al. (1990) and Hufnagel & Bregman (1992) at radio, IR, and optical wavelengths shows that the source exhibits flickering behavior that is more pronounced and more rapid at the shorter wavelengths. In general, the light curves of blazars tend to contain major flares and quenchings, upon which are superposed more rapid, apparently stochastic variations. Yet, the mm-wave, infrared, and optical spectra of blazars such as BL Lac connect smoothly, which indicates that the emission regions connect smoothly and probably overlap.

3. Theoretical Predictions of Forward Time Delays

Because the physics of relativistic jets is rather complex, there is not yet a comprehensive model for the multiwaveband variability of blazars. Rather, theorists tend to concentrate on models in which one or two mechanisms dominate. This at least has the virtue of being simple enough to interpret. In this section I present some of the results of these theoretical analyses as they apply to frequency dependent time delays.

Frequency dependent lags in the radio can be explained as the effects of opacity: the longer wavelength emission becomes optically thin farther down the jet, hence a disturbance propagating down the jet becomes evident first at the shorter wavelengths. At higher frequencies, it is unlikely that opacity plays a role in the observed time lags.

Frequency-stratified emission leading to forward time lags (low-frequency following high-frequency flares) occurs naturally when relativistic electrons are accelerated along a thin front and then advect away from the front. Marscher (1980) proposed that this occurs at the base of an accelerating jet. Georganopoulos & Marscher (1998) applied this model to the BL Lac object PKS 2155−304. Marscher and Gear (1985) showed that it is also possible to obtain frequency-stratified emission from shock waves in relativistic jets. In either case, the highest frequency emission can arise only in a thin sheet behind the acceleration front before the high-energy particles lose energy and can no longer radiate at these frequencies. Similarly, the lower frequency emission occurs over a larger volume since the radiative losses are less severe for the electrons emitting at these frequencies. The basic picture is sketched in Fig. 3, in which the frequencies are arbitrarily scaled such that $\nu = 1$ corresponds to the regime where radiative energy losses dominate over adiabatic and other losses.

The above jet and shock models are, in their simplest forms, capable of explaining the properties of certain strong synchrotron outbursts in blazars characterized by the ejection of bright superluminal knots that are associated with the shocks. However, it is now clear (Jorstad et al. 2001) that most mm-wave flares in γ-ray blazars are accompanied by ejections of quite weak superluminal features and that essentially all the interesting stages of the events take place in or very close to the radio core. (Note that Marchenko et al. 2000 found that γ-ray flares are well correlated with the epochs of superluminal ejections.) It should then be very revealing to investigate and model the structure of the core in order to develop models for multiwaveband variability.

Unfortunately, until we can do 43 and 86 GHz VLBI that includes one or more space-based antennas — as in the proposed Japanese VSOP 2 and NASA ARISE missions — we cannot directly image the radio cores: The resolution of an Earth-based interferometer is just too low. However, if the suggestion of Daly & Marscher (1988) is right, then the core is a system of standing conical shocks. These have been simulated with 2D+ relativistic hydrodynamical codes by Gómez et al. (1997). Immediately downstream of the conical shocks is a thin

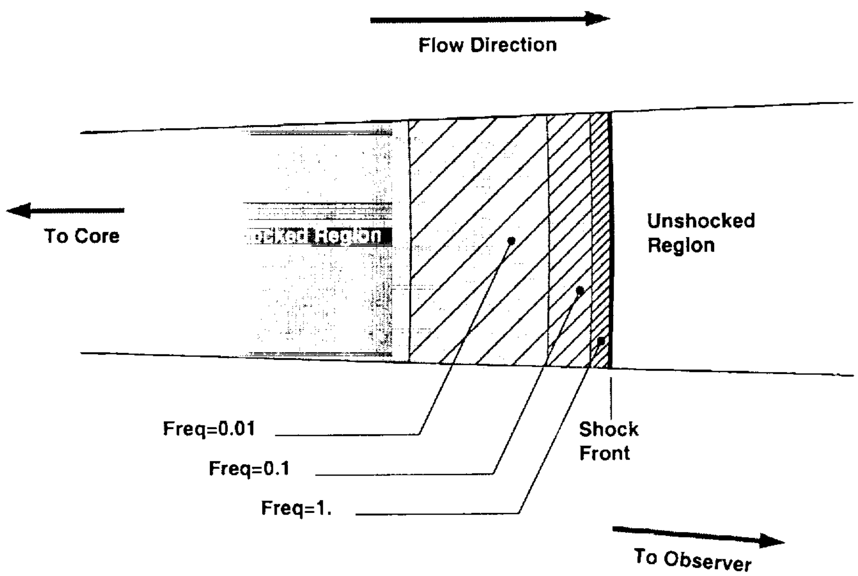

Figure 3. Sketch of the dependence of the primary site of emission on frequency in the shocked jet model. The arrows indicate the amplitude of the Lorentz factor. In order to make the sketch legible, the x-ray to optical (thinnest) portions are expanded greatly such that the scale is not accurate.

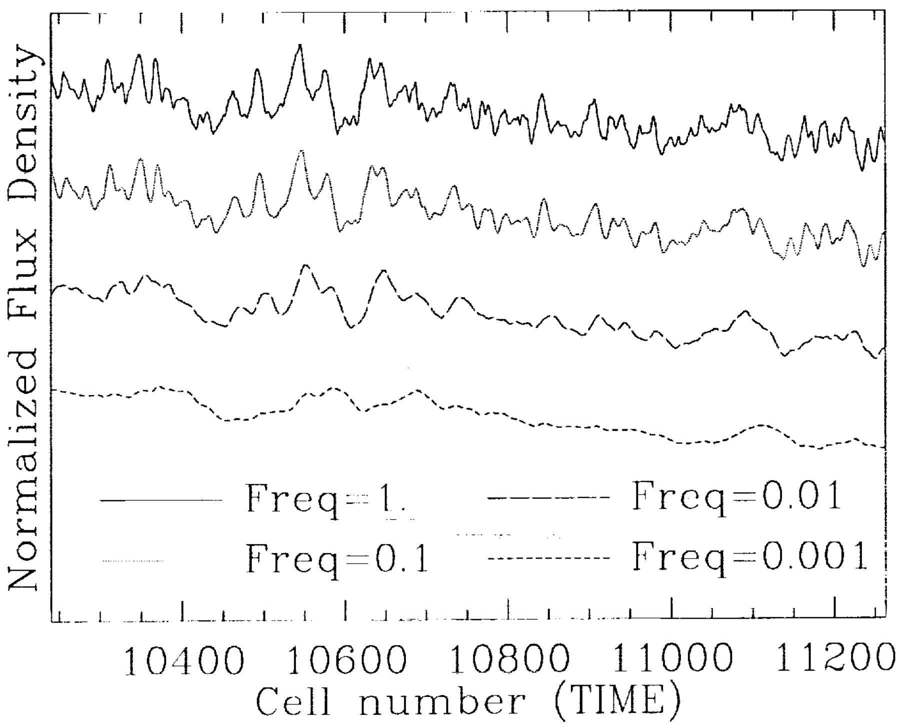

Figure 4. Flickering in the light curve of a blazar as a shock propagates down a hydromagnetically turbulent jet. The frequencies are scaled such that a value of 1.0 is a high frequency where radiative losses are important. The slow decline of the flux density is caused by the evolution of the overall emission from the shock, while the rapid variations result from turbulent cells passing into and out of the emission region at that given frequency. From Marscher (1996).

but rather long rarefaction, also in the shape of a cone. Perhaps a disturbance propagating down the jet becomes brightest when it interacts with the standing shocks and then fades quickly as it passes through the rarefaction. However, light-crossing time delays (from front to back) spread out the emission region in the observer's frame, so it is not clear whether the observer will ever view the entire disturbance contained within the rarefied region. If flares are both excited and quenched by disturbances propagating into standing shocks and then rarefactions, it could explain one of the puzzles of blazar variability: The decay timescales at radio-IR frequencies are often much shorted than expected for either radiative or adiabatic losses.

Light curves — especially at frequencies above the radio regime — are not usually smooth (see, e.g., Fig. 1). In order to explain the flickering and other details of the light curves, one must add some complexity to the models. Fortunately, this process can be guided by the observations. For example, the modest linear polarizations observed in most blazars indicate that the magnetic field contains a substantial component that is randomly oriented. The configuration usually adopted involves a superposition of an axially aligned magnetic field and a random component. The implication of the random component is that the fluid in the jet is hydromagnetically turbulent. This should have little impact on the lower frequency radiation that is emitted over a large volume, since effects of the density and magnetic field fluctuations are essentially averaged out. However, at the high frequencies where the emission is confined to a thin sheet, the turbulent "cells" affect a larger fraction of the radiation, causing rapid flickering and minor flares. Simulated synchrotron light curves are shown in Fig. 4.

Another complication is that the parsec-scale radio jets imaged by VLBI appear to be bent (e.g., Jorstad et al. 2001, who show that this is the case for EGRET-detected blazars), with some studies suggesting that their axes follow helical paths. Marscher, Gear, & Travis (1992) have shown that the consequent gradient in Doppler beaming factor can explain some otherwise puzzling features of multiwavelength light curves of some blazars, such as the self-absorption turnover frequency decreasing as the flux increases and simultaneous variations at optically thick as well as optically thin wavelengths. In keeping with this last point, if the variations at optically thin frequencies are not simultaneous, then bending is not the source of the changes.

However, the effects of bending on the IR to γ-ray variations remain essentially unexplored. Still other jets show changes in the direction of ejection (which presumably corresponds to the direction of the inner jet), with the superluminal components following straight, ballistic paths. Although the actual change in nozzle direction is probably quite small (less than a few degrees), this can make a major difference in the emission from these highly beamed blazars. The result should be an increase in the overall nonthermal emission across the entire electromagnetic spectrum between $\sim 10^{10}$ and 10^{24} Hz, similar to what occurs in 3C 279 (see above).

4. Reverse Time Delays

How can a source produce a flare that peaks at radio to optical frequencies before it reaches the X-ray or γ-ray maximum? One clever model that does so is the Mirror Compton idea of Ghisellini & Madau (1996). A cloud composed either of neutral gas or nonrelativistic electrons that happens to lie next to the jet will receive blueshifted synchrotron photons from a flare upstream in the jet. The cloud then scatters some of the photons back upstream, where the relativistic electrons in the jet will see them blueshifted yet again. The electrons will then Compton scatter these photons toward the observer, who will measure a highly beamed but time-delayed X-ray and γ-ray flare. The intensity of the high-energy flare is expected to have a strong inverse dependence on the duration of the time delay, since the loss of photons from the process increases strongly with the distance between the site of the flare and the cloud.

Another possible way to get a reverse time delay might operate in an external Compton radiation (so named because the seed photons originate outside the jet) model. If an increase and then decrease in the magnetic field occurs prior to an increase and decrease in the number of relativistic electrons, then the synchrotron flare will peak before the inverse Compton flare. This seems not to be very reasonable physically, but perhaps there is a way to make it work.

A third process by which a reverse time delay could occur is in a synchrotron self-Compton flare whose observed time scale is limited by light-travel time across the emitting region (see Lawson et al. 1999 for a brief discussion). There is a delay for the seed photons from the flare to arrive at the site of any particular electron; the synchrotron radiation, on the other hand, is emitted promptly when the magnetic field and number of electrons is increased. The result is a time-delayed inverse Compton flare. As yet unpublished calculations by A. Sokolov (a Boston University graduate student) show that the time delay is most pronounced for the case of an excitation front (e.g., a shock front) approaching the observer within a small angle θ' to the line of sight *in the frame of the region being excited.* The maximum time lag occurs when $\theta' = 0$ (e.g., a forward shock wave propagating through a high-density turbulent cell in a jet) and the decay time of the excited electrons roughly matches the light-crossing time. In this case, the X-ray/γ-ray peak can occur as late as when the synchrotron flux has dropped to $\sim 60\%$ of its maximum value. Interestingly, this number is $\sim 90\%$ if $\theta' = 180°$ (e.g., if a cloud moves through a standing shock). All of the negative time lags observed thus far are consistent with this model, although the case of PKS 1406−067 pushes it to its limit.

The shapes of the light curves of individual flares might allow us to discriminate among these possibilities. The symmetric exponential rises and falls observed for many flares can be produced by light-travel limited flares only when the light-crossing time is roughly equal to the decay time of the energized electrons. Although this would result in a roughly symmetric light curve, there is no obvious reason for light-travel limited flares to have exponential profiles. Part of the problem might simply be our tendency to model triangular shapes that curve at the bottom as exponentials. Indeed, if we look at Fig. 1 it is apparent that the data become noisy at fluxes within about 30% of the quiescent level. Furthermore, some of the flares in Fig. 1 are decidedly *not* shaped like expontials; e.g., the very sharp rise and more gradual drop-off of the early-1998 flare is reminiscent of the theoretical profiles of light-travel limited flares.

5. Polarization

Since the magnetic field plays a very important role in synchrotron radiation and probably also in collimating the jet (e.g., Meier & Koide 2000), polarization observations are potentially very important. In an ongoing study, a large collaboration in which I am involved has found that while the degree of polarization of a number of blazars increases toward higher frequencies (from mm-wave to optical), the position angles are very similar. This suggests that either the magnetic field direction is the same (it tends to be nearly transverse to the jet in such sources) from the radio core to the optical emission site or the radio core *is* the optical emission site. Polarization monitoring has been neglected despite the fact that it is easier to get the required telescope time now that a number of 2-meter class telescopes are no longer under high demand to perform projects other than monitoring. Furthermore, an X-ray polarization mission should be possible (and has been proposed to NASA). Besides information on the direction and uniformity (or lack thereof) of the magnetic field, polarization also allows one to determine whether a flare at one waveband is intimately related to that at another waveband: the position angles should be roughly the same in this case.

6. Conclusion

Theoretical models abound but need to be developed further so that when we have multiwaveband light curves with good time coverage we can "listen" to what the variations are telling us. My impression is that they are screaming out information on the geometry and physics of the flares and jets, but that we are not good listeners. In order to improve the situation, we need to maintain observatories in orbit that are capable of (and will be used for!) providing well-sampled light curves. GLAST will certainly help in this regard, although I wish that it were possible to equip every satellite with an IR–uv telescope. We blazar enthusiasts need to shout loud and clear: Keep RXTE alive! Launch KRONOS! Launch VSOP-2 and ARISE! Launch an X-ray polarization mission! Tell those observatory directors and time allocation committees that there is no better glory for their precious telescopes than to spend all their time monitoring active galactic nuclei!

Acknowledgments. This work was supported in part by NASA Astrophysical Theory grant NAG5-3839, by NASA Rossi X-Ray Timing Explorer Guest Investigator grants NAG5-4245, NAG5-7338, and NAG5-7323, and by NASA Astrophysical Data Program grant NAG5-9161. The VLBA is an instrument of the National Radio Astronomy Observatory (NRAO), which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universties, Inc. UMRAO is supported by funds from the University of Michigan and the National Science Foundation.

References

Hartman, R.C. et al. 1999, ApJS, 123, 79

Bregman, J.N., et al. 1990, ApJ, 352, 574

Daly, R.D., & Marscher, A.P. 1988, ApJ, 334, 539

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

Ghisellini, G., & Madau, P. 1996, MNRAS, 280, 67

Gómez, J.L., Martí, J.M., Marscher, A.P., & Ibáñez, J.M., & Alberdi, A. 1997, ApJ, 482, L33

Hufnagel, B.R., & Bregman, J.N. 1992, ApJ, 386, 473

Jorstad, S.G., Marscher, A.P., Mattox, J.P. Wehrle, A.E., & Bloom, S.D. 2001, ApJ, submitted

Lawson, A.J., McHardy, I.M., & Marscher, A.P. 1999, MNRAS, 306, 247

Makino, F., et al. 1989, ApJ, 347, L9

Maraschi, L., et al. 1994, ApJ, 435, L91

Marchenko, S.G., Marscher, A.P., Mattox, J.R., Hallum, J., Wehrle, A.E., and Bloom, S.D. 2000, in Proceedings of the 5th Compton Symposium, ed. M.L. McConnell and J.M. Ryan, AIP Conf. Proc., 510, 357.

Marscher, A.P. 1980, ApJ, 235, 386

Marscher, A.P. 1996, in Blazar Continuum Variability, ed. H.R. Miller, J.R. Webb, and J.C. Noble, ASP Conf. Ser., 110, 248

Marscher, A.P., & Gear, W.K. 1985, ApJ, 298, 114

Marscher, A.P., Gear, W.K., & Travis, J.P. 1992, in Variability of Blazars, ed. E. Valtaoja & M. Valtonen (Cambridge Univ. Press), 85

McHardy, I., Lawson, A., Newsam, A., Marscher, A., Robson, I, & Stevens, J. 1999, MNRAS, 310, 571

Meier, D.L., & Koide, S. 2000, in Astrophysical Phenomena Revealed by Space VLBI, ed. H. Hirabayashi, P.G. Edwards, & D.W. Murphy (Sagamihara, Japan: ISAS), 31

Wagner, S.J., et al. 1995, ApJ, 454, L97

Wehrle, A.E., et al. 1998, ApJ, 497, 178

Wehrle, A.E., et al. 2000, ApJ, in press