High Energy Blazar Astronomy
ASP Conference Series, Vol. 299, 2003
L.O. Takalo and E. Valtaoja

The Connection between X-Ray and Radio-Optical Emission in Blazars

Alan P. Marscher and Svetlana G. Jorstad[1]

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

[1] *also Sobolev Astronomical Institute of St. Petersburg State University, Universitetskij pr. 28, 198504 St. Petersburg, Russia*

Ian M. McHardy

Department of Physics and Astronomy, University of Southampton, Highfield, Southampton, S017 1BJ, UK

Margo F. Aller

Department of Astronomy, University of Michigan, 830 Dennison, Ann Arbor, MI 48109-1090, USA

Thomas J. Balonek

Department of Physics and Astronomy, Colgate University, 13 Oak Dr., Hamilton, NY 13346-1398

Massimo Villata, Claudia M. Raiteri, and Luisa Ostorero

Osservatorio Astronomico di Torino Pino, Torinese (TO), Italy

Gino Tosti

Perugia University Observatory, Perugia, Italy

Harri Teräsranta

Metsähovi Radio Observatory, Metsähovintie 114, Kylmala, FI-02015, Finland

Abstract. We have been carrying out multiwaveband observations in support of X-ray monitoring of blazars and the radio galaxy 3C 120 with the RXTE satellite. In 3C 120, we have observed four X-ray dips, each followed about 4 weeks later by ejections of superluminal radio knots down the jet. This behavior, of similar nature to that of the microquasar GRS 1915+105, is interpreted as infall of a section of the inner accretion disk causing energy to be ejected down the relativistic jet. The X-ray emission from the quasars PKS 1510−089, 3C 279, and 3C 273 shows pronounced variations on timescales as short as ~ 1 day. Over a two-year period, X-ray flares in PKS 1510−089 peaked about 2 weeks after the maxima of radio outbursts. This "reverse" time lag can be explained by light-travel delays within the source. In 3C 279 the X-ray and optical variations were generally well correlated, with very small (perhaps zero) time delay. We conclude that the X-ray and optical emission from these quasars occurs near the radio core rather than close to the black hole.

1. Introduction

The prolonged operation of the *Rossi* X-ray Timing Explorer (RXTE) provides a unique opportunity to explore the X-ray light curves of blazars and other active galactic nuclei (AGN). Although only a relatively small number of blazars are bright enough to detect with RXTE, for those that are we can obtain detailed, long-term light curves of a number of the most interesting objects. Our program, started in 1996, focuses on several of these.

In order to probe the relationship between the relativistic jet and the X-ray emission, we support the RXTE observations with monitoring of (1) the structure and polarization of the radio jet at a resolution of about 0.1 milliarcseconds (mas) with the VLBA, (2) the total radio–mm flux density at various frequencies, and (3) the optical and/or infrared (IR) brightness. From these data, we have determined that the X-ray variations in blazars correspond to changes in the jet. This is in contrast to lower-luminosity AGN (including 3C 120), in which the X-rays appear to be emitted from the central engine.

Here we summarize some preliminary results on the radio galaxy 3C 120 and the quasars 3C 273, PKS 1510−089, and 3C 279. Each object exhibits a distinct pattern of behavior, although for some the pattern changes with time. The sequences of VLBA images and light curves (which will be updated as more data become available) can be viewed on the web site of the Boston University blazar research group (http://www.bu.edu/blazars). (The reader is warned that the details of the light curves will probably change when the newly released RXTE instrumental response functions and X-ray background models are applied to the data in late 2002. Updates will be posted on the web site.)

2. The Radio Galaxy 3C 120: Evidence that the Accretion Disk Feeds the Jet

The AGN 3C 120 is a schizofrenic object with three personalities: radio galaxy, Seyfert galaxy, and blazar. It sports a prominent relativistic radio jet with apparent superluminal motion at $\sim 5c$ (Gómez et al. 2000, 2001). In the X-ray, however, it has Seyfert-like characteristics, complete with an iron line (e.g., Grandi et al. 1997) and a continuum spectrum that is flatter at lower flux levels. Since the X-ray emission of black-hole binary systems ("microquasars") in our Galaxy also possesses these properties, the lead author and collaborators set out to determine whether 3C 120 shares the remarkable behavior of the microquasar GRS 1915+105: X-ray dips followed by ejections of superluminal knots (Mirabel & Rodríguez 1998). As shown in Figure 1 and reported in Marscher et al. (2002), this is indeed the case: There are four significant X-ray dips that precede the "time of ejection" (coincidence of the moving feature with the core at the narrow end of the radio jet) by ~ 30 days.

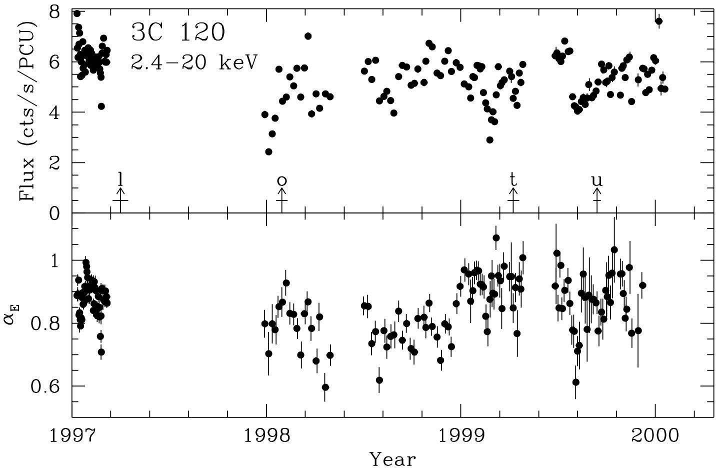

Figure 1. X-ray light curve and variation of the X-ray spectral "energy" index of 3C 120. The times when a new, bright superluminal knot appeared at the radio core are marked by vertical arrows, with the uncertainties noted by horizontal bars.

The X-ray dips in GRS 1915+105 are thought to be caused by an instability in the inner accretion disk sending chunks of the disk toward and then into the black hole. This releases a burst of energy down the jet (and, presumably, an anti-beamed counterjet). The loss of the piece of inner accretion disk causes a momentary drop in the soft X-ray flux, with the hard X-ray flux from the corona not as affected. When this disturbance travels past the radio core, a superluminal knot is seen. (See Mirabel & Rodríguex 1998, Belloni 2001, and Zdziarski & Grandi 2001 for discussions of the theoretical models.) The observed time lag between the minimum in the X-ray light curve and the appearance of the moving knot at the site of the radio core implies that the radio core is at least 0.3 pc downstream of the black hole. On a radio image, the angular distance between the two $\sim$ 0.15 milliarcsec, projected on the plane of the sky.

The black hole in GRS 1915+105 has a mass of 10–14 $M_\odot$ (Greiner, Cuby, & McCaughrean 2001), while that in 3C 120 is $\sim 3 \times 10^7 M_\odot$ (Wandel et al. 1999). If the dimensions of a source were proportional to the Schwarzschild radius, then we would expect the time scales to be $2–3\times10^6$ times longer in 3C 120 than in GRS 1915+105. If we compare the time delay between the X-ray dip and the appearance of the superluminal knot at the core in 3C 120 with that of GRS 1915+105 (Fender et al. 1999), we find that the scaling $\sim$ 40 times smaller than that predicted by such a scaling law. Unless the core of the jet in 3C 120 is even farther than 0.3 pc from the black hole, we can conclude from these considerations that the pressure of confinement of the AGN jet (by either a magnetic field or an external medium) is different from that of the microquasar. The ratio of the time between events (5×10^5: 0.5–1.2 yr for 3C 120 vs. 25–100 s for GRS 1915+105; Belloni 2001) $\sim$ 5 times smaller than that expected from linear scaling with black-hole mass. This could be explained by differences in the rotational state (the innermost stable orbit varies from 0.5 to 3 Schwarzschild radii as one goes from a static to a maximally rotating black hole), with the

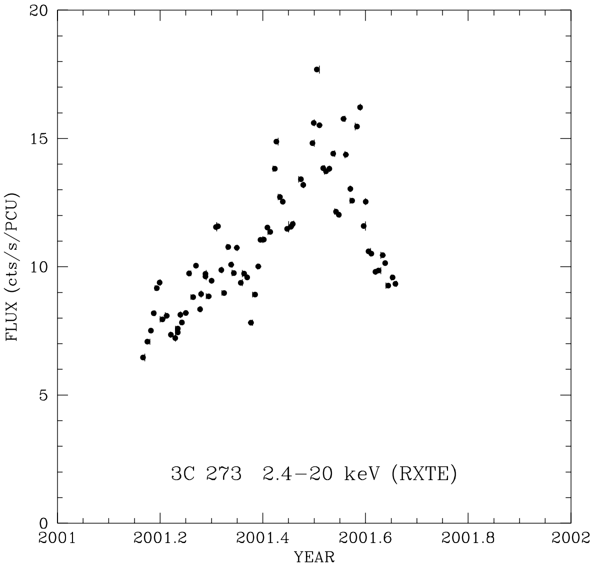

Figure 2. X-ray light curve of 3C 273 in 2001.

black hole in 3C 120 rotating maximally and that in the microquasar closer to static. However, with only one object of each class available for comparison, we do not yet know how much the time delays vary in systems of similar mass and size.

It is rather interesting that the Lorentz factor inferred for the jet of the microquasar GRS 1915+105 (Fender et al. 1999) is essentially the same (~ 5) as that for the AGN 3C 120 (Gómez et al. 2000). This is as expected if the kinematics are related to the scale-invariant escape velocity near the black hole.

We resumed monitoring 3C 120 with RXTE and the VLBA in March 2002, with denser coverage (4 times per week and once per month, respectively). We hope to determine whether there is a relationship between the decrease in luminosity integrated over time and either the brightness or the apparent speed of the associated superluminal knot.

3. The Quasar 3C 273

Although 3C 273 is the brightest X-ray quasar, long-term X-ray monitoring of this object with frequent sampling was not undertaken prior to the availability of RXTE. An unevenly but sometimes densely sampled RXTE light curve is presented by Kataoka et al. (2003). Continuous, dense (3–4 times per week) sampling started with our program in March 2001. Intensive but relatively brief (daily for 50 and 20 days) campaigns by McHardy et al. (1999 and 2003) demonstrated that there is a strong correlation between near-IR (probably synchrotron) and X-ray variability in this object.

We show the early results of our RXTE monitoring of 3C 273 in Figure 2. The X-ray flux varies on all sampled time scales, from ~ 2 days to months. We have not yet correlated this with other wavebands. One problem is the need for IR monitoring, which is difficult to arrange on a consistent basis. Yet it is important because the optical emission from 3C 273 is dominated by the "big blue bump," so that detecting variability in the nonthermal emission of the jet is a struggle at optical bands.

4. The Quasar PKS 1510−089

The $z = 0.361$ quasar PKS 1510−089 is an extreme member of the already extreme class of blazars. Jorstad et al. (2003) have clocked its apparent speed at $40c$. Consistent with this, its radio variations show little or no frequency-dependent time delay much of the time. This implies that opacity effects are often relatively unimportant, as one might expect if knots move out of the core region so rapidly. The X-ray spectrum is flatter than most blazars, with the energy index α_E (where $F_\nu \propto \nu^{-\alpha_E}$) varying within the range of 0 to 0.5. The mm-wave spectrum has a similar slope, so the X-ray spectrum is consistent with inverse Compton models.

Figure 3 displays the X-ray, radio, and optical light curves, with the dates of superluminal ejections marked, as well as the discrete cross-correlation function each year (through 2000) of the X-ray and radio variations. The correlation was very good during the first two years, with a *reverse* (radio leads the X-ray) time lag of about 15 days. The only way to understand such a reverse delay is for light-travel effects to be important. This is explicitly the case for the mirror Compton model (Ghisellini & Madau 1996), but those who have investigated this hypothesis have found that it produces flares that are too weak or too strongly time-delayed (Böttcher & Dermer 1998; Bednarek 1998). The time delay also results naturally if the X-rays are synchrotron self-Compton (SSC) emission (Marscher 2001; Sokolov & Marscher, these proceedings). Such a reverse delay occurs only if the X-ray emitting region is *at or downstream of the radio core.* We therefore conclude that the X-rays from PKS 1510−089 arise not from near the accretion disk, but from the SSC process in the radio-emitting part of the jet. This is similar to the conclusion drawn by Lähteenmäki & Valtaoja (2002) and Jorstad et al. (2001) from comparison of γ-ray with either radio variability of times of ejection of superluminal radio knots.

The X-ray–radio correlation became weaker in 1999, at which point the time delay vanished. In 2000, the correlation went away altogether, although so did the connection between radio outbursts at 14.5 GHz and superluminal ejections at 43 GHz. We conclude that the opacity of the jet increased by late 1999, causing time delays of variations at 14.5 GHz relative to > 40 GHz and 14.5 GHz. This could have been caused by a slight change in the direction of the jet or a decrease in the bulk Lorentz factor. Indeed, the direction of the jet within 0.5 mas of the core differed by $\sim 40°$ from that seen previously. Furthermore, the apparent speed of the superluminal knot ejected in early 2000 appears to be more than a factor of 2 slower than those ejected in 1999, although there are considerable uncertainties given the time coverage and image quality (there was bad weather during our VLBA observations in December 2000 and January 2001).

Ejections of superluminal knots tend to occur near the epochs of X-ray flares. However, the X-ray light curve is so complex that it is difficult to spec-

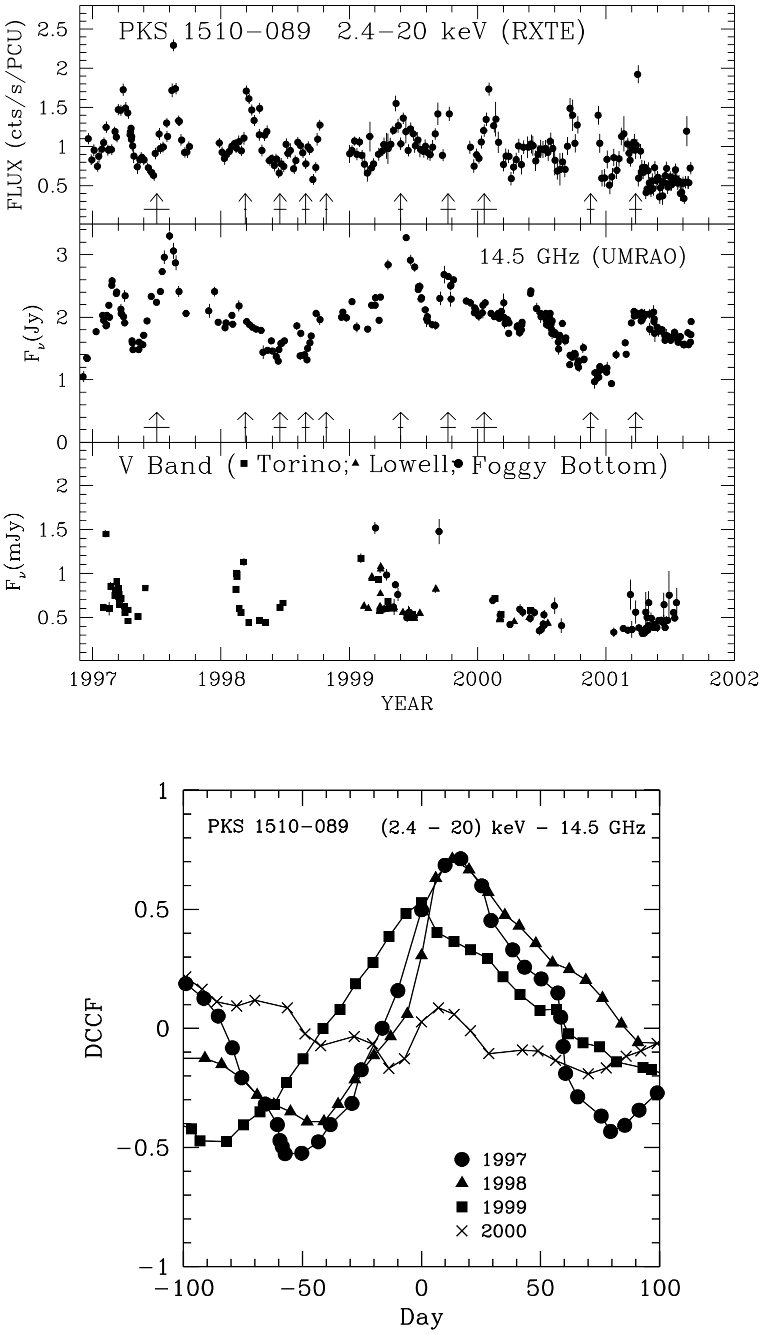

Figure 3. *Left panel:* Multifrequency light curves of PKS 1510−089. The vertical arrows denoting dates of ejection of superluminal radio knots have the same meaning as in Fig. 1. The single high X-ray points in 2001 require verification based on updated response functions and RXTE background models. *Right panel:* Discrete cross-correlation function for the radio and X-ray light curves. Positive time lag corresponds to radio leading the X-ray.

ify the beginning and end of a flare; this is exacerbated by the presence of 8-week annual sun-avoidance gaps. We are working on statistical methods for evaluating the significance of the apparent connection between X-ray flares and superluminal ejections.

The time coverage at optical wavelengths is insufficient to determine whether optical outbursts are associated with X-ray flares in PKS 1510−089. We expect an improvement on this in 2002-03 because of both better communication with other observers and the completion of the Liverpool Telescope on La Palma that we intend to use.

5. The Quasar 3C 279

Figure 4 shows our X-ray, optical, and radio light curves of the quasar 3C 279, which is on almost every blazar lover's list of favorite objects. While there is little correspondence between the X-ray and radio total flux variations, this is expected owing to opacity effects and the presence of numerous strong components in the jet. As with PKS 1510−089, there appears to be a correspondence between X-ray flares and superluminal ejections, but this requires verification with a statistical analysis.

As is demonstrated in Fig. 4, there is a sometimes good and sometimes excellent correlation between the X-ray and optical variations. The discrete cross-correlation function is sharply peaked at 0–3 days (X-ray leading the optical) in 1997, 1999, and 2001. In 1996 and 1998 the maximum is lower and poorly defined, which indicates similar optical and X-ray activity but not detailed correspondence between the two wavebands.

6. Theoretical Considerations

The close relationship between the X-ray and radio (PKS 1510−089) or optical (3C 279) emission implies that nearly all the radiation observed in these blazars is relativistically beamed and produced in the jet. The site of activity is at or near the radio core, not near the black hole. (This conclusion is more secure in PKS 1510−089 than in 3C 279.) We still need to determine the physical processes that cause the jet to light up at the core. If the core is a system of standing shocks (Daly & Marscher 1988), what causes the change in pressure at the boundary to sustain the shock? If it is the position where the jet energy density becomes rest-mass dominated and the Lorentz factor of the flow reaches its asymptotic value (Marscher 1980), are the most energetic disturbances ever seen upstream of this point?

The relationship between synchrotron self-Compton (SSC) X-ray emission and the radio–optical synchrotron radiation in blazars is not as obvious as we had naïvely thought. As mentioned above with regard to the reverse time lag in PKS 1510−089, internal light-travel delays can cause the X-ray changes to lag behind the radio–optical variations. Furthermore, as shown by McHardy et al. (1999), several decades of synchrotron seed photon frequencies are scattered up to a given X-ray energy if the electron energy distribution is a power law. Finally, gradients in the magnetic field and/or density and maximum energy of relativistic electrons can cause different synchrotron frequencies to be emitted

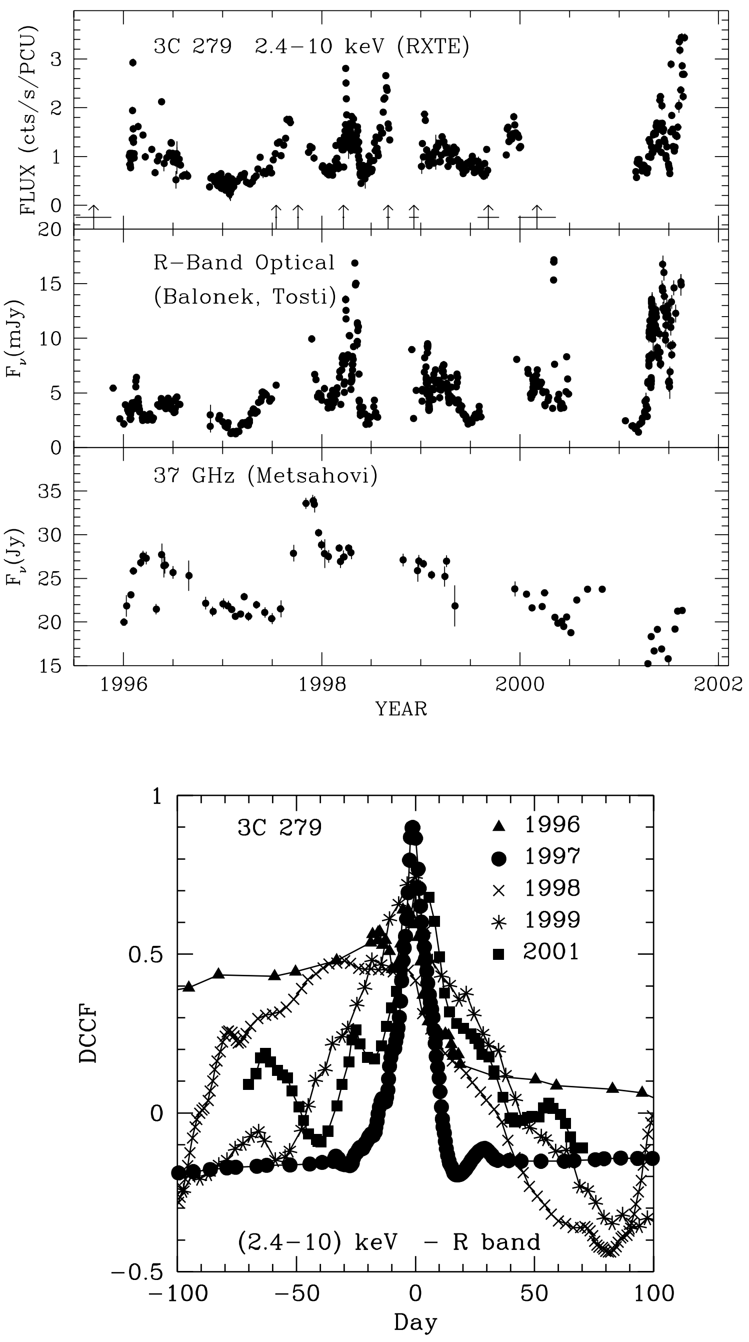

Figure 4. *Left panel:* Multifrequency light curves of 3C 279. The vertical arrows have the same meaning as in Fig. 1. *Right panel:* Discrete cross-correlation function for the optical and X-ray light curves. Positive time lag corresponds to optical leading the X-ray.

from different volumes (e.g., Marscher 1980; Marscher & Gear 1985; Ghisellini et al. 1985; Georganopoulos & Marscher 1998). All this complicates the expected multifrequency behavior of flares.

Given this, it is clear that current models are inadequate for analyzing the observations to learn about the physics of jets. More sophisticated models are needed that include the factors listed above as well as other effects that might be important. We hope that current efforts will soon produce a more precise theoretical framework for interpreting the results of detailed multifrequency monitoring (see Sokolov & Marscher, these proceedings).

7. Conclusions

It appears that nonthermal emission from the jet dominates the radiative output at all wavebands — except the blue-ultraviolet in some cases — from blazars. In less extreme objects such as 3C 120, the X-ray emission probably comes primarily from the accretion disk (and/or corona), with synchrotron radiation from the jet dominating at radio to far-IR wavelengths (with thermal emission from dust possible as well in the mid- and near-IR). The connection between X-ray dips and superluminal ejections in the radio demonstrates the link between events in the accretion disk and disturbances in the jets in active galactic nuclei. It is not clear in how many other objects this could be observed, since there are relatively few superluminal radio sources whose X-ray emission arises from the region close to the black hole.

Blazar enthusiasts have always maintained that multiwavelength monitoring is the key to unraveling the complex physics of nonthermal emission from blazars and other AGNs. Finally, it appears that this potential is being realized. However, the intensity of the monitoring required is higher than we had imagined because the timescales of variability are shorter and the modes of variability are more numerous than we had expected. Fortunately, with RXTE and the future AGILE and GLAST γ-ray missions (plus, if approved, the KRONOS X-ray monitoring satellite), we finally have or will have telescopes that can provide dense monitoring at high frequencies. We need to be ready to match this capability with ground-based radio, infrared, and optical observations with equally good time coverage. It is now clear that this will provide us with effective resolution that is even finer than that of the exquisite images made possible by the VLBA. The combination of timing and interferometric techniques serves as a powerful probe of the exciting and exotic activity from the core of the jet down to the neighborhood of the supermassive black hole.

Acknowledgments. This research was supported in part by NASA grants NAG5-9161 and NAG5-11811 (to Boston U.) and NAG5-9162 (to U. Michigan), U.S. National Science Foundation grants AST-0098579 (Boston U.) and AST-9421979 and AST-9900723 (U. Michigan). The University of Michigan Radio Astronomy Observatory was funded in part by the NSF and by the U. Michigan Department of Astronomy. The VLBA is an instrument of the National Radio Astronomy Observatory, a facility of the NSF operated under cooperative agreement by Associated Universities Inc.

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