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Final Technical Report

NASA Grant NAG5-9162

Project Title: RXTE Observations of Selected Blazars

Institution: **Regents of the University of Michigan**

Institutional Principal Investigator: **Prof. Margo F. Aller**

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Period Covered by Report: March 15, 2000 to March 14, 2002

[redacted]

Final Technical Report

NASA Grant NAG5-9161

Project Title: RXTE Observations of Selected Blazars

Institution: **Trustees of Boston University**

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Total Funds Awarded: **$23,580**

Final Technical Report

NASA Grant NAG5-9162

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The work completed includes the analysis of observations obtained during Cycles 4 and 5 of the Rossi X-ray Timing Explorer (RXTE). The project is part of a longer-term, continuing program to study the X-ray emission process in blazars in collaboration with Dr. Ian McHardy (U. of Southampton, UK).

There were no inventions under this grant during the reporting period.

The goals of the program are to study the X-ray emission mechanism in blazars and the relation of the X-ray emission to changes in the relativistic jet. The program includes contemporaneous brightness and linear polarization monitoring at radio and optical wavelengths, total and polarized intensity imaging at at 43 GHz with a resolution of 0.1 milliarcseconds with the VLBA, and well-sampled X-ray light curves obtained from a series of approved RXTE programs.

The objects studied in this time period were 3C 120, 3C 279, PKS 1510−089, and BL Lac, all radio-bright with superluminal jets. Only the BL Lac data remain to be analyzed. This object was rather faint in the X-ray and therefore needs to have data from all available detectors in order to have sufficient signal-to-noise ratio to produce a useful light curve. Nearly all the data were obtained after the May 2000 propane leak from detector PCU0. The new calibration and background model files for this detector only became available in February 2002 and the software upgrade needed to use these new files has yet to be released by the NASA RXTE Guest Observer Facility. The BL Lac data will be analyzed shortly after the software update is distributed.

During RXTE cycle 4, the project was awarded RXTE time to monitor PKS 1510−089 and BL Lac weekly, and 3C 120 and 3C 279 bi-weekly. In cycle 5, based on the activity in the X-ray band, the sampling for BL Lac was increased to 3 times per week. Weekly observations of PKS 1510−089 continued, while observations of 3C 120 and 3C 279.

The X-ray data, including those from earlier cycles, were compared with radio measurements obtained 2–4 times per month in the centimeter-band with the Michigan radio telescope, bimonthly (monthly for 3C 120) imaging observations with the VLBA at 43 GHz, and optical observations obtained at several telescopes around the world (Lowell Observatory; TorinoU. Obs. and Perugia U. Obs., Italy; and Foggy Bottom Obs. of Colgate U.).

3C 120

The radio galaxy 3C 120 is a remarkable hybrid object. Of relevance to our project is its relativistic jet with apparent superluminal motion at $\sim 5c$, combined with Seyfert-like X-ray emission, complete with an iron line. Since the X-ray continuum of black-hole binary systems ("microquasars") in our Galaxy is similar to that of Seyferts, the investigators decided to determine whether 3C 120 shares the remarkable behavior of the microquasar GRS 1915+105: X-ray dips followed by ejections of superluminal knots. 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

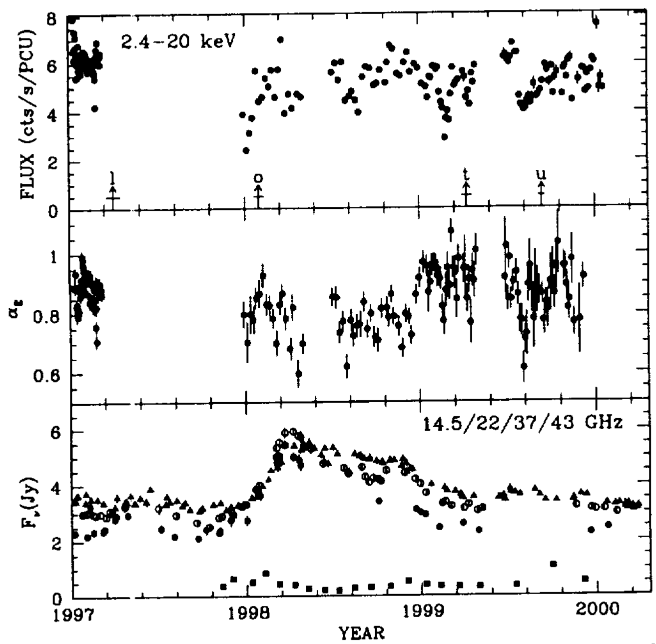

Figure 1. *X-ray light curve and variation of the X-ray spectral "energy" index of 3C 120. The times when a new, bright superluminal knot appeared at the radio core are marked by vertical arrows, with the uncertainties noted by horizontal bars.*

end of the radio jet) by $\sim$ 30 days.

The X-ray dips in GRS 1915+105 are thought to be caused by an instability breaking off a piece of the inner accretion disk, which then falls into the black hole, releasing a burst of energy down the jet (actually, jets, since there is a counterjet made invisible by relativistic beaming). When this disturbance travels past the radio core, a superluminal knot is seen. The observed delay 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 $3.1^{+2.0}_{-1.5} \times 10^7 M_\odot$ (Wandel et al. 1999). If everything were to scale as the Schwarzschild radius, then we would expect the time between X-ray dips to be 2–5$\times 10^6$ times longer in 3C 120 than the 25–100 s seen in GRS 1915+105 (Belloni 2001). Instead, it is 2.5–10$\times 10^5$ times longer. This modest yet definite discrepancy can be explained if the black hole in 3C 120 is maximally rotating (which decreases the size of its innermost stable orbit) while that of the microquasar is closer to (but not completely) static.

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, we find that the scaling $\sim$ 30-40 times smaller than if it were directly proportional to the Schwarzschild radius. This is 5–10 times smaller than can be explained by differences in the rotational state. Therefore, unless the core of the jet in 3C 120 is even farther than 0.3 pc from the black hole, the pressure of confinement of the jet (by either a magnetic field or an external medium) is different in the two types of object.

PKS 1510−089

The $z = 0.361$ quasar PKS 1510−089 is an extreme member of the extreme class of blazars. Its apparent speed is as fast as $\sim 40c$. Consistent with this, its radio variations show little or no frequency-dependent time delay much of the time. This implies that opacity effects are 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 0 to 0.5. The mm-wave spectrum has a similar slope, so the X-ray spectrum is consistent with inverse Compton models.

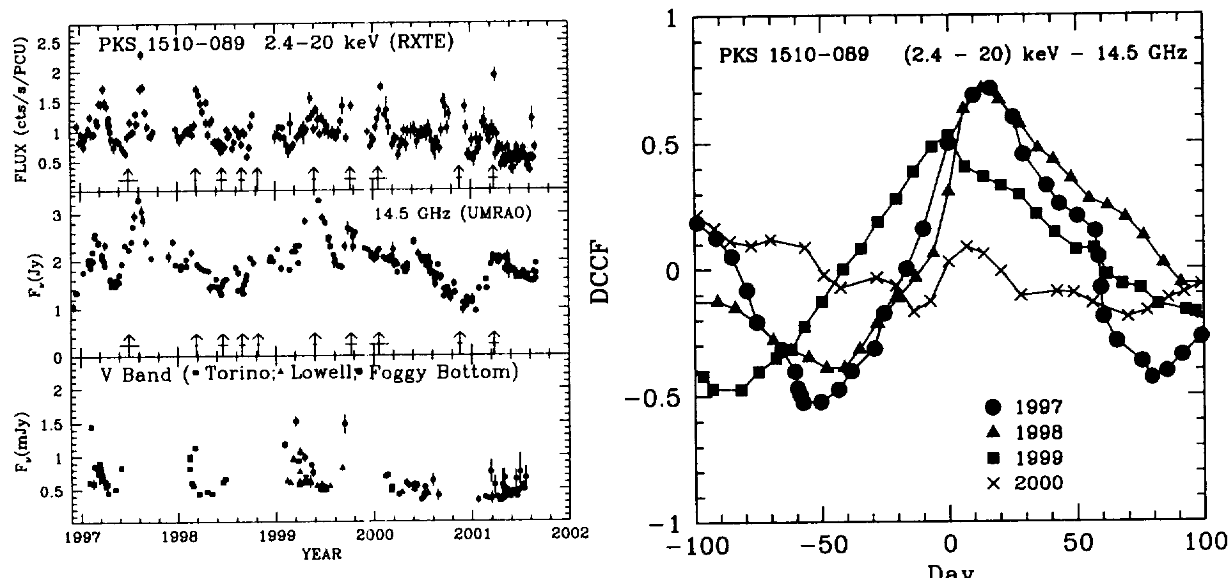

Figure 2. *Multifrequency light curves of PKS 1510−089. The vertical arrows have the same meaning as in Fig. 1. The single high X-ray points in 2001 require verification based on updated RXTE background models (software not yet available). Right panel: Discrete cross-correlation function for the radio and X-ray light curves. Positive time lag corresponds to radio leading the X-ray.*

Figure 2 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 of Ghisellini & Madau, but also occurs for synchrotron self-Compton emission (Marscher 2001). Such a reverse delay occurs only if the X-ray emitting region is *at or downstream of the radio core.* The investigators therefore conclude that the X-rays from PKS 1510−089 arise not from near the accretion disk, but from the radio-emitting part of the jet.

The X-ray–radio correlation became weaker in 1999, while the time delay vanished. In

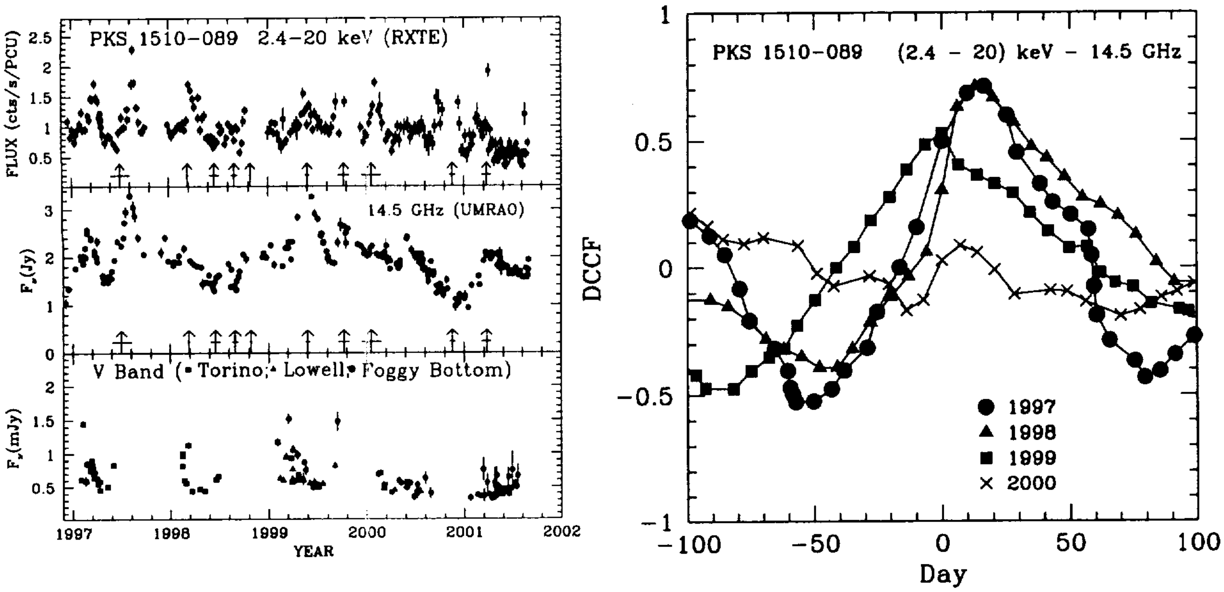

Figure 3. *Multifrequency light curves of 3C 279. The vertical arrows have the same meaning as in Fig. 1. Right panel: Discrete cross-correlation function for the optical and X-ray light curves. Positive time lag corresponds to optical leading the X-ray.*

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 between events at $>$ 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. The apparent speed of the superluminal knot ejected in early 2000 does appear 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). Furthermore, the direction of the jet within 0.5 mas of the core differed by $\sim 40°$ from that seen previously.

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 specify the beginning and end of a flare; this is exacerbated by the presence of 8-week annual sun-avoidance gaps. The investigators 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.

3C 279

Figure 3 shows the X-ray, optical, and radio light curves of the quasar 3C 279. 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 features in the jet downstream of the radio core. 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. 3, there is a sometimes and good 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. The close relationship between the X-ray and optical emission implies that nearly all the radiation observed in these blazars is relativistically beamed and produced in the jet.

The following publications resulted from this project:

Aller, M.F., Marscher, A.P., Marchenko-Jorstad, S.G., McHardy, I.M., and Aller, H.D. "Comparison of the X-Ray and Radio Light Curves of Quasar PKS 1510−089," 2000, *Bulletin of the American Astronomical Society*, **32**, 1611. Paper given at 197th American Astronomical Society Meeting, San Diego, CA, 7–11 Jan., 2001.

Marscher, A.P., Marchenko-Jorstad, S.G., Mattox, J.R., Wehrle, A.E., and Aller, M.F. "High-Frequency Observations of Blazars," 2000, in *Astrophysical Phenomena Revealed by Space VLBI*, ed. H. Hirabayashi, P.G. Edwards, and D.W. Murphy (Sagamihara, Japan: ISAS), 39-46.

Marscher, A.P., Jorstad, S.G., Gómez, J.L., and Aller, M.F., "Dips in X-Ray Flux Associated with Superluminal Ejections in the Radio Galaxy 3C 120", 2000, *Bulletin of the American Astronomical Society*, **32**, 1611. Paper given at 197th American Astronomical Society Meeting, San Diego, CA, 7–11 Jan., 2001.

Marscher, A.P. "Time Delays of Blazar Flares Observed at Different Wavebands," 2001, in *Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring*, ed. B.M. Peterson, R.S. Polidan, and R.W. Pogge, *Astronomical Soc. Pacific Conf. Ser.*, **224**, 23–34.

Marscher, A.P., Jorstad, S.G., Aller, M.F., McHardy, I.M., and Balonek, T.J. "RXTE, VLBA, Optical, and Radio Monitoring of the Quasars 3C 279, PKS 1510−089, and 3C 273", 2001, *Bulletin of the American Astronomical Society*, **33**, 1529. Paper given at 199th American Astronomical Society Meeting, Washington, DC, 6–10 Jan. 2002.

Marscher, A.P., Jorstad, S.G., Gómez, J.L., Aller, M.F., Teräsranta, H., Lister, M.L., and Stirling, A.M. "X-Ray Dips Followed by Superluminal Ejections as Evidence for an Accretion Disc Feeding the Jet in a Radio Galaxy," 2002, *Nature*, submitted.

Marscher, A.P., Jorstad, S.G., McHardy, I.M., Aller, M.F., Balonek, T.J., Villata, M., Raiteri, C.M., Ostorero, L., Tosti, G., and Teräsranta, H. "The Relationship between X-Rays and Relativistic Jets," 2002, in *Blazar Astrophysics with BeppoSAX and other Observatories*, ed. P. Giommi, E. Massaro, and G. Palumbo (Frascati, Italy: Agenzia Spaziale Italiana), in press.

Jorstad, S.G., Marscher, A.P., Aller, M.F., Balonek, Gómez, J.L., McHardy, I.M., Teräsranta, H., Raiteri, C.M., and Tosti, G. "Multifrequency Monitoring of 3C 120, 3C 279, and PKS 1510−089," 2002. in *Blazar Astrophysics with BeppoSAX and other Observatories*, ed. P. Giommi, E. Massaro, and G. Palumbo (Frascati, Italy: Agenzia Spaziale Italiana), in press.