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# X-ray, Optical, and Radio Monitoring of Gamma-Ray Blazars

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**Abstract.** We have performed multi-frequency monitoring of the quasars 3C 279 and PKS 1510−089 plus BL Lac over several years. We investigate the light curves to define characteristic time scales of variability and search for correlation between high energy and lower frequency events. We find a meaningful correlation between X-ray and optical variations for 3C 279 and BL Lac and between X-ray and radio light curves for PKS 1510−089. In all cases the correlation occurs for variations with time scales from a few weeks to 2-3 months. For the quasars the X-ray variations follow those at lower frequencies by 6-16 days while in BL Lac the correlation coefficient peaks at zero lag. The structure function for the X-ray light curves of the quasars shows a similar slope $\sim 0.7-0.8$ on time scales where a connection with low energy events is detected.

## 1. Introduction

The quasars 3C 279 and PKS 1510−089 and BL Lac belong to the extreme subclass of active galactic nuclei known as *blazars*, characterized by violent variabilty (Mattox et al. 1997), high optical and radio polarization (Mead et al. 1990; Aller et al. 2003), highly relativistic radio jets (Jorstad et al. 2001), and high $\gamma$-ray luminosity (Hartman et al. 2001). The fast variability and high linear polarization imply a synchrotron nature for the radio to optical emission. Comparison of the polarization associates the radio and optical emission (Lister & Smith 2001) and places the latter inside the radio jet. The nature and location of the X-ray emission has been unclear. The most popular models for the high energy production involve inverse-Compton scattering of low energy seed photons by the relativistic electrons of the radio jets. The seed photons can come from a variety of sources such as the radio jet itself (synchrotron self-Compton, SSC), a molecular torus (Blażejowski et al. 2000), an accretion disk (Dermer & Schlickeiser 1993), or emission line clouds (Sikora et al. 1994). Monitoring of the flux variability at different frequencies is a prime method for separating the

different models. A number of campaigns have produced very important results (e.g. McHardy et al. 1999; Böttcher et al. 2003). However, their duration has usually been limited to a few weeks while the variability on longer time scales has significantly larger amplitude. Here we present a time series analysis of the long-term light curves of three blazars at different frequencies.

## 2. Observations

We have been carrying out X-ray observations of 3C 279 and PKS 1510−089 with the Rossi X-ray Timing Explorer (RXTE) from 1996 until the present. The majority of observations are performed 2-3 times per week with 1-2 ks duration each. The RXTE observations for BL Lac cover the period from 1999 to 2001, first weekly, then semi-weekly. The observations provide fluxes and spectral indices over the energy range of 2.4-10 keV (2.4-20 keV for PKS 1510−089).

The most intensive monitoring at longer wavelengths contemporaneous with the X-ray light curves are in the optical $R$-band for 3C 279 and BL Lac and at 14.5 GHz for PKS 1510−089. The majority of the 3C 279 measurements have been obtained at Foggy Bottom Observatory of Colgate University. These data are supplemented by observations at Lowell Observatory, Torino Observatory, Crimean Astrophysical Observatory, and Abastumani Observatory. The optical data for BL Lac include the intensive monitoring of the WEBT campaing 2000-2001 (Villata et al. 2002) plus observations from Lowell and Foggy Bottom Observatories. The data from different telescopes were checked for consistency and corrected if necessary. The radio observations are from the University of Michigan Radio Astronomy Observatory. Figure 1 shows the light curves normalized by their maxima and binned into 1-day intervals.

## 3. Time Series Analysis

To compare the timescale of variability at different wavelengths and to determine correlations between X-ray and radio/optical flux variations, we construct the structure function (SF, Simonetti et al. 1985) in each band, and the discrete cross-correlation function (DCCF, Edelson & Krolik 1988) between X-ray and low frequency light curves. Figure 2 (left panel) displays the calculated SF and the best power-law approximation according to the $\chi^2$ test for 3C 279. For all three sources the time scales of variability can be separated into three types: short, medium, and long. The parameters of the SFs at different time scales are given in Table 1. Figure 2 (right panel) shows the discrete cross-correlation functions between the X-ray and low-energy light curves. For 3C 279 and PKS 1510−089 the DCCF peaks at 16 and 6 day delays of the X-ray emission, respectively, while the DCCF for BL Lac has a maximum (0.70±0.19) at zero lag.

## 4. Discussion

The positive time lag of X-ray relative optical/radio variations for the quasars can be explained by frequency stratification or, in the case of SSC emission, by

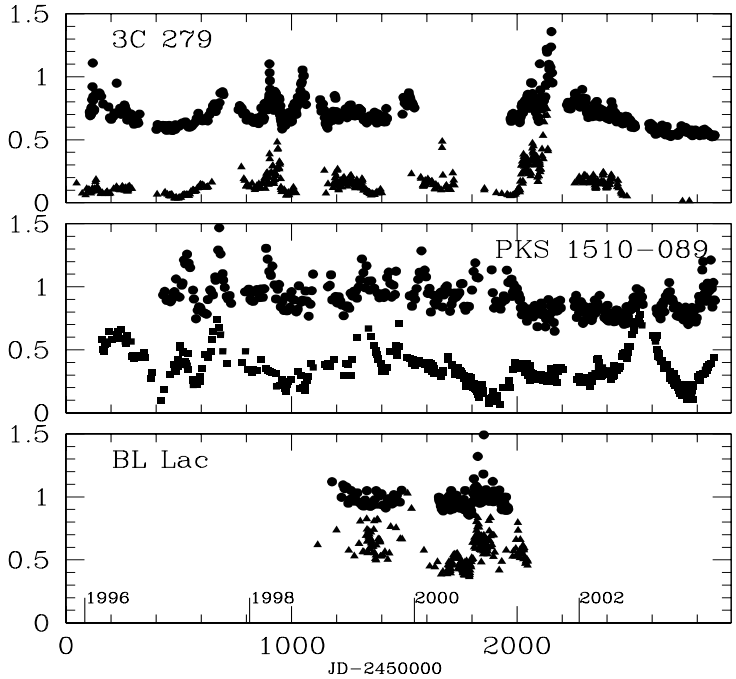


Figure 1. Normalized X-ray (circles), $R$-band (triangles), and 14.5 GHz (squares) light curves of 3C 279, PKS 1510−089, and BL Lac. The X-ray light curves are shifted by 0.5 relative to those at lower frequencies.

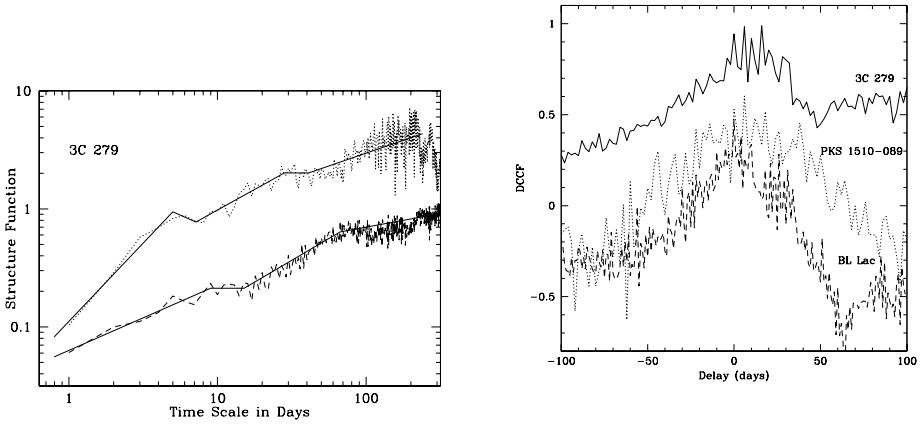


Figure 2. *Left panel:* Structure functions for the X-ray (dashed) and optical (dotted) light curves of 3C 279, the thick solid lines show the best power-law approximation. *Right panel:* Discrete cross-correlation functions between the X-ray and R-band light curves for 3C 279 (solid), X-ray and radio light curves for PKS 1510−089(dotted), and X-ray and R-band light curves for BL Lac (dashed). The DCCF for 3C 279 is shifted by +0.2, the DCCF for BL Lac is shifted by −0.2. A negative delay corresponds to X-rays leading.

Table 1. Parameters of Structure Functions

| 3C 279 | Short (day) | Medium (day) | Long (day) |
|---|---|---|---|
| X-rays | 1-10; 0.55±0.05 | 11-67; 0.78±0.04 | >67; 0.32±0.02 |
| R-band | 1-5; 1.33±0.11 | 8-30; 0.70±0.07 | >30; 0.43±0.05 |
| PKS1510−089 | Short (day) | Medium (day) | Long (day) |
| X-rays | 1-5; 1.58±0.25 | 9-53; 0.69±0.07 | >60; 0.45±0.03 |
| 15 GHz | 1-5; 0.22±0.09 | 8-210; 1.11±0.02 | >210; 0.06±0.04 |
| BL Lac | Short (day) | Medium (day) | Long (day) |
| X-rays | <2; ∼1.5 | 2-120; 0.22±0.03 | |
| R-band | 0.5-12; 0.25±0.03 | 13-42; 1.11±0.06 | >45; 0.16±0.06 |

the extra time required for the synchrotron seed photons to cross the source to reach the relativistic electrons that scatter them (Sokolov et al. 2004). Both quasars show a similar slope of the structure function $\alpha \sim 0.7$ for the X-ray variations on time scales from ∼10 to ∼60 days; in the case of 3C 279 the optical variations exhibit the same slope. For PKS 1510−089 the slope of the SF for the radio light curve is steeper, which suggests a contribution to the X-ray emission from the infrared seed photons of the jet. BL Lac shows a lag $< 1$ day between the X-ray and optical variations and a flat SF slope for optical variations shorter than 2 weeks and for X-ray variability on time scales from days to 3-4 months. Böttcher et al. (2003) discuss a possible 4-5 hr delay of intraday optical variations relative to X-rays. In this context, much of the X-ray emission from BL Lac might be synchrotron radiation.

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