Microvariability in the southern gamma-ray blazar PKS 0537-441

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Abstract.
The southern blazar PKS 0537-441 is one of the most variable active galactic nuclei. It has displayed extreme forms of variability in its emission from radio to gamma-ray wavelengths. Here we present results of new optical microvariability observations of this blazar in the V and R bands, obtained with high-quality CCD photometry made with a 2.15-m telescope at CASLEO, Argentina. We have found variability with amplitudes of more than 100% over timescales of $\sim$ 2 days, similar to what has been observed in gamma-rays by EGRET. The spectral index, contrarily to what is expected from microlensing, showed changes of $\sim$ 27% during the observing period, with a trend to steepen with decreasing flux. This seems to reflect an intrinsic mechanism behind the variability and, consequently, suggests that optical and gamma-ray emitting regions in this source can be co-extensive. If the most extreme manifestations of radio variability are also intrinsic, they might involve coherent emission processes. We have used our observations, along with EGRET and ROSAT data, to constrain the central black hole mass, which seems to be $\sim 8 \times 10^7\ M_\odot$. For such a mass the γ-ray variability is originated at $\sim$ 290 gravitational radii from the central source.

I INTRODUCTION

The southern blazar PKS 0537-441 (at a redshift $z = 0.894$) is an extremely variable source across the entire electromagnetic spectrum. There are reports of strong and rapid variations in its flux density at radio [8,9], optical [5,11], and gamma-ray wavelengths [13,4]. The source has been claimed to have a foreground galaxy and microlensing-based variability [12,10], although this has been recently disputed by some authors [2,6]. In 1993 this blazar displayed one of the most extreme episodes of variability ever detected with changes up to 40% of the radio emission over timescales $\sim 10^4$ s [8]. Such variability, if produced in a synchrotron source, would imply brightness temperatures $T_{\rm b} \sim 10^{21}$ K, which are 9 orders of magnitude above the inverse Compton limit. The origin of this phenomenon, later observed in other sources, is unknown at present.

Here we present results of an optical monitoring campaign of this peculiar blazar

TABLE 1. Microvariability optical observations of PKS 0537-441

Band	Date	σ (mag)	$t_{\rm v}$ (hours)	Variable?	$C = \sigma_{\rm s}/\sigma$	Y (%)
V	12/15-20/1998	0.0034	42.4	Yes	31.4	109.2
R	12/15-20/1998	0.0034	42.4	Yes	33.1	96.4

aimed to detect rapid variability in the R and V bands over timescales from minutes to several days, and we discuss the implications for the *gamma*-ray emission.

II OBSERVATIONS

The observations were carried out in December 1998 with the 2.15-m CASLEO telescope at San Juan, Argentina. The instrument was equipped with a cryogenically-cooled CCD camera with a Tek-1024 chip. Each field frame contained the blazar and several stars, six of which were used for calibration and control purposes following the procedures described in detail in Ref. [11].

The microvariability observations were made using Johnson's V and R filters with integration times of ~ 1 min. Calibration frames (bias and flat field images) were taken each night according to standard procedures. The data reduction was performed through the IRAF software package running in a UNIX workstation.

III RESULTS

The results are summarized in Table 1. Observational errors, determined from the scatter of the control lightcurves, are of ~ 0.003 mag. Blazar lightcurves are variable at both observing frequencies at a confidence level of more than 30 σ. In the V band, the variability amplitude, defined as

$$Y = \frac{100}{< D >}\sqrt{(D_{\rm max} - D_{\rm min})^2 - 2\sigma^2}, \tag{1}$$

where $D_{\rm max}$ and $D_{\rm min}$ are the maximum and the minimum in the differential lightcurve, reaches 109.24 %, whereas it results of 96.37 % in the R band. There is no time lag between the brightness changes at the different frequencies. The timescale of the major outburst is $t_{\rm v} \sim \Delta F/(dF/dt) \approx 1.5 \times 10^5$ s. Within a single night, variations of about 30 % are observed in both bands.

The average spectral index is $\alpha_{RV} = -1.6$ ($S_\nu \propto \nu^\alpha$). Variability amplitudes of 27.44 % are present with a similar timescale to that observed in brightness. The index changes in the sense that it becomes steeper with decreasing flux density.

IV DISCUSSION

The observed variability in the spectral index at two close frequencies implies that gravitational microlensing (basically an acromatic phenomenon) cannot be the source of the optical variability in PKS 0537-441. Models involving changes in the viewing angle of superluminal components are also discarded by the same reason. Other extrinsic effects that could be effective in the radio band, as interstellar scintillation, are not present at optical frequencies. We conclude, then, that the variability is intrinsic to the source. The correlation between the flux level and the continuum slope in the sense that the continuum is steeper when the source is fainter agrees with the picture of synchrotron radiation originated in a shocked jet [7].

If no beaming is introduced in the source, our data provides an upper limit to the central black hole mass, which is constrained by a gravitational radius not larger than 2.4×10^{15} cm to be $< 2.7 \times 10^9\ M_\odot$. A more accurate determination can be obtained from the γ-ray variability data combined with the ROSAT X-ray information.

Since PKS 0537-441 is a strong γ-ray emitter, the optical depth to pair production for a γ-ray of energy E created at a height x above the center of the X-ray emitting accretion disk that surrounds the central black hole and that is propagating outward along the x-axis (i.e. towards the observer) should be $\tau_{\gamma\gamma} \sim 1$.

The optical depth is

$$\tau_{\gamma\gamma} = \int_x^\infty \alpha_{\gamma\gamma}(E, X)\, dX, \tag{2}$$

where $\alpha_{\gamma\gamma}$ is the $\gamma - \gamma$ absorption coefficient. Following Ref. [1] we compute $\tau_{\gamma\gamma}$ for a two-temperature accretion disk model with an intensity distribution given by $I(E, R) \propto E^{-\alpha} R^{-w}$, with R being the radial distance over the disk ($R_{\min} \leq R \leq R_{\max}$). For a 2-T disk model with $R_{\min} = 6R_{\rm g}$ (Schwarzschild geometry), $R_{\max} = 100R_{\rm g}$, and $w = 3$, we get, using the reported ROSAT flux $F_{\rm 1KeV} = 0.79$ μJy, the index $\alpha_{\rm X} = 2.1$ [14], and cosmological parameters $q_0 = 1/2$ and $h = 0.7$,

$$\tau_{\gamma\gamma} \approx 2 \times 10^{28} \left(\frac{M}{M_\odot}\right)^{-1} \left(\frac{x}{R_{\rm g}}\right)^{-7.2}, \tag{3}$$

where we have considered 1-GeV photons.

The variability observed by EGRET in the γ-ray emission [4] imposes a constraint to the size of the γ-spheres at $E > 100$ MeV:

$$x_\gamma \leq c t_{\gamma,\rm v} \frac{\delta}{1+z} \quad \text{cm}, \tag{4}$$

where δ is the Doppler factor and $t_{\gamma,\rm v}$ is the timescale of the γ-ray variability. Adopting the Doppler factor $\delta \sim 3.8$ estimated by Fan et al. in Ref. [3], we obtain $x_\gamma \leq 3.5 \times 10^{15}$ cm, and then, demanding that $\tau_{\gamma\gamma} \sim 1$, we get:

$$M_{\rm Schw} \approx 3 \times 10^7 \quad M_\odot. \tag{5}$$

In a similar way, if we consider a Kerr black hole in our disk model, the mass results:

$$M_{\rm Kerr} \approx 8.3 \times 10^7 \quad M_\odot. \tag{6}$$

These estimates are consistent with the value derived by Fan et al., which is insensitive to the kind of black hole involved (they obtain 5.8×10^7 $M_\odot$). For a mass of $\sim 8 \times 10^7$ $M_\odot$ the observed γ-ray variability must be produced at a distance of ~ 290 gravitational radii from the central source.

Two points are noteworthy. First, the mass of the hole seems to be relatively small compared to those determined in other not-so-variable objects like M87 and 3C273. This could be a generic feature of extremely variable AGNs, as it is also suggested by the estimates of Fan et al. [3] for several strongly variable γ-ray blazars. And secondly, the size scales of the optical and γ-ray regions are similar, indicating that they are possibly generated by the same population of particles. Future simultaneous optical and γ-ray observations of PKS 0537-441 could be used to set this question.

Finally, we notice that if the ultra-rapid radio variability observed by Romero et al. in 1993 [8] is also intrinsic to the source, then coherent emission processes should be occurring in the innermost region of this object, otherwise violations of the inverse Compton limit seems to be unavoidable.

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