Abstract. This paper has been withdrawn by the author(s), due crucial errors in 'Introduction' and "Discussion and Conclusion". We present the optical light curve for the $\gamma$-ray blazar PKS 1510$-$089 with a significant variability of 2.0 mag within about 41 minutes in the R band which is the most violently rapid variability detected in our optical monitoring campaign operating since 1982. In the framework of the relativistic beaming model, the central supermassive black hole mass of PKS 1510$-$089 is of $(1.16 - 1.98) \times 10^8 M_\odot$. This is larger than some previous estimates for the central mass in blazars that have been based on models for nonthermal emission, but is consistent with the estimated result of the $M_\bullet - \sigma_*$ correlation. Some other physical parameters, including the emission region size, Doppler factor $\delta$, the efficiency $\eta$ for conversion of accreted matter into energy and luminosity are calculated. The value of $\eta = 62.2$ strongly implies that the relativistic beaming is responsible for the rapid variability of the $\gamma$-ray loud blazar PKS 1510$-$089.

Key words: galaxies: active — galaxies: fundamental parameters — quasars: individual (PKS 1510$-$089)—radiation mechanisms: non-thermal
The Supermassive Black Hole in the Gamma-ray Loud Blazar PKS 1510–089

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1. Introduction

One of the most important quantities in theoretical models of active galactic nuclei (AGNs) is the black hole mass (M\textsubscript{\bullet}) that, together with the total luminosity, defines the fraction of the Eddington luminosity at which the AGN is emitting. Since the earliest days of research on quasars and AGNs, supermassive black holes (SMBHs) have been considered to be the most likely driving power of the activity in these sources (Richstone et al. 1998; Kormendy & Gebhardt 2001; Merritt & Ferrarese 2001). Indeed, compact dark masses, probably SMBHs, have been detected in the cores of many normal galaxies using stellar dynamics (Kormendy & Richstone 1995). In the case of AGNs, however, direct detection of nuclear SMBHs through stellar-dynamical methods has not been achieved on account of technical difficulties arising from the large surface brightness contrast between the stellar component of the galaxy and the AGN itself on arcsecond and smaller angular scales. The strongest evidence to date has been the detection of Keplerian motions of megamaser sources in the Seyfert galaxy NGC 4258 (Miyoshi et al. 1995).

Variability is one of the important properties of AGNs and a powerful constraint on models of these sources. Observations show that AGNs are characterized by rapid and large amplitude continuum variations over the entire electromagnetic spectrum. CCD-based differential photometric observations of rapid variability over timescales of significantly less than a day in the optical emission of AGNs are powerful tools for probing the innermost regions of these objects. The original models based on a central black hole surrounded by an accretion disk (Rees 1984) were based on the constraints on the source size and energy density provided by the early single-band variability studies. PKS 1510–089 is one of the γ-ray loud blazars (a subclass of AGNs) which characterized

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by their powerful featureless continuum radiation spanning from radio to gamma-ray bands. It is generally believed that synchrotron self-Compton (SSC) emission of high energy electrons in a relativistic jet is responsible for the multiwaveband continuum of the BL Lacs (Urry & Padovani 1995). The emission is highly beamed. The featureless continuum of the blazars permits us to use timescale of variability to estimate black hole mass. It has been pointed out that the masses of black holes in all the radio-loud quasars of low redshift PG sample should exceed $10^9 M_\odot$ (Laor 2000). This suggests the black hole mass controls the radio-loudness $R$, defined as the ratio of radio to optical fluxes. The relativistic jet is generally thought to originate from the innermost vicinity of black hole (Blandford 2001). The emission from the jet may reflect the black hole parameters in a more direct way. In addition, the black hole model and accretion disk theory suggest that the observed minimal timescale of variation and the bolometric luminosity should obey the Abramowicz – Nobili relation.

In this paper, we present the optical light of the γ-ray loud blazar PKS 1510−089 with the 1-m telescope at the Yunnan Astronomical Observatory in 2000. Using this result, we derive an estimate of the center black hole mass in PKS 1510−089. Throughout this paper, the $q_0 = 0.5$, and $H_0 = 75 \text{km s}^{-1} \text{Mpc}^{-1}$ are adopted.

2. The observational light curve and central SMBH’s mass

The optical observations were carried out at the Yunnan Astronomical Observatory, with the 1-m telescope equipped with a direct CCD ($1024 \times 1024$ pixels) camera at the Cassegrain focus. The data reduction and observational errors are discussed in detail in previous works (Dai et al. 2001).

This quasar presents a pronounced UV excess, a very flat X-ray spectrum, and a steep γ-ray spectrum. Up to now, the maximum brightness variation of 5.4 mag in the B band has been obtained by Liller et al. (1975). A bright state in 1987 was followed by a rapid dimming (Villata et al., 1997 and references therein). Small amplitude oscillations on short time scales have also been observed by Villata et al. (1997), who found a variation of 0.63 mags in the R and B bands. This object has been included in our monitoring program since 1999. In our previous observations in 1999, it exhibited a high level of activity each night. It brightened from 17.21 mag to 16.65 mag in 40 minutes in the B band. A rapid decline of 0.55 mag in 22 minutes, and a flare of 0.51 mag in 26 minutes were observed on May 15, on June 15, 1999 in the R band respectively (Xie et al. 2001). Our recent observations on May 29, 2000 are displayed in Fig. 1. The source was still in a very active state during our observation period. An apparent variation of about 2 mag in the R band within 41 minutes was observed. The source faded from 16.02 to 17.74 in 27 minutes and then brightened to 15.74 in about 13 minutes. This is the
most extremely rapid variability in our optical monitoring program since 1982. Fig. (1a) shows that the differential magnitudes of two comparison stars are less than 0.02 mag during the night and Fig (1b) shows the light curve about this maximum variation of PKS 1510−089. According to the definition of the variability parameter (Romero et al. 1999, Fan et al. 2001), the value of this dramatic variability is C=59.6. We examine the contribution of the host galaxy to the variability and find there is no correlation between intranight brightness variations and seeing conditions, which means that seeing in no way has affected the computed magnitudes of PKS 1510−089. So, we conclude that the observed apparent variation of PKS 1510−089 is intrinsic to the source, as determined by a rigorous check for correlations between variability and seeing conditions.

If we view the dramatic variability as a single event, the observed variability by 2.0 mag within 41 minutes in PKS 1510−089 can be used to compute the efficiency ($\eta$) for conversion of accreted matter into energy. If $\Delta L$ is the change in luminosity within the variability time scale $\Delta t_{\text{obs}}$ (defined as $\Delta t_{\text{obs}} = F |\Delta F/\Delta t|$, Wagner & Witzel 1995), then $\eta$ can be written as (Cavallo & Rees, 1978; Xie et al. 1989)

$$\eta \geq 5.0 \times 10^{-43} \frac{\Delta L}{\Delta t_{\text{obs}}}$$  \hspace{1cm} (1)

where $\Delta L$ is in erg s$^{-1}$ and $\Delta t_{\text{obs}}$ in seconds. The value of $\Delta L$ of the variability in our observation is $7.3 \times 10^{47}$ erg s$^{-1}$. Using equation (2), the value of $\Delta L$, and $\Delta t_{\text{obs}}$ which is equal to 2700 s, we find $\eta \geq 62.2$. This value of $\eta$ strongly suggests the presence of relativistic beaming in PKS 1510−089 (Guilbert et al. 1983; relativistic beaming is inferred if $\eta > 0.1$). In our previous paper (Xie et al. 1991), we have obtained a formula to estimate the Doppler factor $\delta$,

$$\delta \geq \left(\frac{\eta_{\text{obs}}}{\eta_{\text{in}}}\right)^{1/(4+\alpha)} \hspace{1cm} (2)$$

where $\eta_{\text{obs}}$ and $\eta_{\text{in}}$ are the conversion efficiency of the observed and intrinsic values respectively, and $\alpha$ is the spectral index in the form $f_\nu \propto \nu^{-\alpha}$. In the optical band, we assume $\alpha = 1.0$ (Stocke et al. 1991). It is known that the efficiency of conversion for nuclei reactions is $\eta_{\text{in}}=0.007$, and that for pure accretion is $\eta_{\text{in}} < 0.1$. The median value of 0.05 is almost equal to the value 0.057 in the thick accretion disk theory for the Schwarzschild metric (Paczynski & Witta, 1980). Thus we obtained the value of $\delta$ in the range of 3.62–6.16. This value of the Doppler factor, $\delta$, can be used to compute the size of the emission region, $R$, using the light travel time argument, namely

$$R \leq \frac{c \delta \Delta t_{\text{obs}}}{1 + z} \hspace{1cm} (3)$$

where $c$ is the light velocity, $z$ is the cosmological redshift, $\delta$ is the Doppler factor. The resulting value of $R$ from equation (3) is $(2.15 - 3.67) \times 10^{14}$ cm. Note that $R$ need not be the linear dimension of a massive black hole, it could be the thickness of a thin plane shock at some distance out along a jet or the thickness of the optically thin boundary of an optical-thick emission region (Marsher & Gear 1985).
If the blazar’s luminosity is produced from accretion of its central black hole, the luminosity $L$ should be significantly correlated with the mass of the central black hole, $M_\bullet$

$$L \sim \frac{GM_\bullet \dot{M}}{r}$$

where $\dot{M}$ is mass accretion rate, and $r$ is the radius of the marginally bound orbit. The luminosity $L$ is expressed as $\nu L_\nu$ (Peterson 1997). The $M_\bullet$ and the minimal timescale of AGN variability, $\Delta t_{\text{min}}$, are related with

$$\Delta t_{\text{min}} = \frac{\tau r_s}{c} = 0.98 \times 10^{-5} \tau \left(\frac{M_\bullet}{M_\odot}\right)s$$

where $r_s = \frac{2GM_\bullet}{c^2}$ is the radius of the black-hole event horizon (i.e., the boundary at which the escape velocity equals the speed of light), $G$ is the gravitational constant, $M_\bullet$ is the mass of the black hole, and $c$ is the speed of light, $\tau$ is the dimensionless parameter $\tau = \pi r_s^{3/2} + a$ and it must obey $\tau > \tau_{\text{min}} = 2\pi$ for $a=1$; the hole rotates at the maximum possible rate. If $\tau_{\text{max}} < 2\pi$, observations exclude the possibility of the black hole model (Abramowicz & Nobili 1982). Adopting $\tau = \tau_{\text{min}} = 2\pi$ and considering the relativistic beaming effect, the intrinsic minimal timescale of AGN variability is

$$\Delta t_{\text{min}}(\text{in}) = \frac{\delta}{1+z} \Delta t_{\text{min}}(\text{obs}),$$

$$M_\bullet \leq 1.62 \times 10^4 \delta \frac{\Delta t_{\text{min}}(\text{obs})(M_\odot)}{1+z}$$

A similar formula was obtained by Miller et al. 1989. We obtain the central supermassive black hole of $(1.16-1.98) \times 10^8 M_\odot$ in PKS 1510−089. Baganoff et al. (2001) also obtained consistent results with the X-ray variability of a few hundred second rise/fall timescales and the 10-ks duration which provide compelling evidence that the X-ray emission is coming from accretion onto a supermassive black hole of $2.6 \times 10^6 M_\odot$ at the Galactic Centre. Barth et al. (2002) assume the blazar Mrk 501 follows the $M_\bullet - \sigma_*$ relation defined for nearby galaxies (Ferrarese, & Merritt, D. 2000; Gebhardt et al. 2000), and found the center supermassive black hole mass of $(0.9 - 3.4) \times 10^9 (M_\odot)$.

### 3. Conclusions and discussions

In the framework of the EC models, Tavecchio et al. (2000) suggested that the quasar-like blazar environment is rich in soft photons, produced by the accretion disk and/or by the broad line region (BLR). They estimated the physical quantities in the jet emitting region and shed light on the energy transport mechanisms in jets using the BeppoSAX X-ray observation results. They found that the central black hole masses of three quasar-like balzars, 0836+710, 1510-089, 2230+114, are in the range of $10^7 - 10^9 M_\odot$.

To explain the observed rapid variability, there are some mechanisms, like eclipsing of hot spots by the accretion disk or microflares in the accretion disk (Wiita, 1996). It has been suggested that the turbulent magnetic field with a relativistic jet may produce the rapidly oscillating variation seen in some blazars (Massaro et al. 1998; Nesci et al.
Among these models, the relativistic model appears to be the most promising to explain the observed rapid variability in \(\gamma\)-ray loud blazars. The nature of the variations provides strong constraints on the astrophysical processes near the event horizon of the black hole. This makes PKS 1510–089 a valuable source for testing the theory of accretion onto supermassive black holes in \(\gamma\)-ray loud balzars.

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