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Optical monitoring of PKS 1510−089: a binary black hole system?

J. Wu,★ X. Zhou, B. Peng, J. Ma, Z. Jiang and J. Chen

National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China

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ABSTRACT

Three deep flux minima with nearly the same time-scales and intervals have been observed for the blazar PKS 1510−089 in the past few years. It has been proposed that there is a binary black hole system at the nucleus of this object, and a new minimum was predicted to occur in 2002 March. We monitored this source with a 60/90 cm Schmidt telescope from 2002 February to April. In combination with the data obtained by Xie et al. in the same period, for the 2002 minimum we present a nearly symmetric light curve, which would be required by an eclipsing model of a binary black hole system. We also constrain the time-scale of the minimum to be 35 min, which is more consistent with the time-scales (∼42 min) of the three previous minima than is the 89 min time-scale given by Xie et al. The wiggling milliarcsecond radio jet observed in this object is taken as further evidence for the binary black hole system. The 'coupling' of the periodicity in the light curve and the helicity in the radio jet is discussed for blazars in the framework of a binary black hole system.

Key words: galaxies: active – galaxies: jets – galaxies: photometry – quasars: individual: PKS 1510−089.

1 INTRODUCTION

Blazars, as a subset of active galactic nuclei (AGN), are characterized by rapid and strong variability in multiple wavebands. This behaviour gives us much important information on their central physics. Variability studies of blazars have been essential in understanding their inner structures, radiation mechanism and other physical processes.

PKS 1510−089 has been the target of many monitoring programmes (e.g. Villata et al. 1997; Xie et al. 2002). It is a flat-spectrum radio quasar at redshift 0.361 and has a parsec-scale jet within just 3° of our line of sight according to Homan et al. (2002). A pronounced ultraviolet excess, a very flat X-ray spectrum and a steep γ-ray spectrum are found in this object. Its light curve is quite different from those of other blazars. Besides fast and small-amplitude variations and irregular outbursts, some brightness minima have also been observed (see Xie et al. 2002, and references therein). In particular, three deep minima were reported by Xie et al. (2001), Dai et al. (2001) and Xie et al. (2002) with variations of 0.65 mag/41 min on 1999 June 14, 2.00 mag/41 min on 2000 May 29, and 0.85 mag/44 min on 2001 April 16, respectively. These minima have nearly the same time-scales (∼42 min) and intervals (336 ± 14 d). Based on these results, Xie et al. (2002) argued that the minimum was a periodic phenomenon, and proposed that there was a binary black hole (BBH) system at the centre of PKS 1510−089. The minimum occurs when the primary black hole (PBH) is eclipsed by the secondary black hole (SBH). They also predicted that a new minimum would occur in 2002 March, and they confirmed this with new observations (Xie et al. 2004).

However, the time-scale of the new minimum reported by Xie et al. (2004) is 89 min, which is more than twice the time-scales of the three previous minima. In fact, the authors had no observation for about 55 min before the minimum point (see figs 8 and 9 in Xie et al. 2004), making their recorded fading phase (73 min) much longer than the brightening phase (16 min). This highly asymmetric light curve would be rejected by an eclipsing model of a binary system.

We also monitored this object from 2002 February to April. In combination with the data in Xie et al. (2004), we provide new constraints on the optical variations of PKS 1510−089 in this period. Section 2 describes our observation and data reduction procedures. The results are presented in Section 3. Section 4 discusses the evidence for BBH from periodic light curves and wiggling jets, and Section 5 gives a summary.

2 OBSERVATION AND DATA REDUCTION

Our optical observation was performed on a 60/90 cm Schmidt telescope located at the Xinglong Station of the National Astronomical Observatories of China (NAOC). A Ford Aerospace 2048 × 2048 charge-coupled device (CCD) camera is mounted at its main focus. The CCD has a pixel size of 15 μm and a field of view of 58 × 58 arcmin^2, resulting in a resolution of 1.7 arcsec pixel^{-1}. The telescope is equipped with a 15-colour intermediate-band photometric system, which covers the wavelength range from 3000 to 10 000 Å.

★E-mail: jhwu@bao.ac.cn

Table 1. Observational log and results.

Observation date (UT)	Observation time (UT)	Julian date	Exposure time (s)	R (mag)	R_{err} (mag)
2002 02 23	20:26:23	245 2329.352	300	16.83	0.04
2002 02 23	20:33:58	245 2329.357	300	16.81	0.04
2002 02 23	20:41:36	245 2329.362	300	16.83	0.04
2002 03 05	20:47:40	245 2339.366	600	16.80	0.05
2002 03 05	21:00:20	245 2339.375	600	16.77	0.05
2002 03 06	20:34:59	245 2340.358	300	16.71	0.05
2002 03 06	20:42:28	245 2340.363	300	16.75	0.05
2002 03 06	20:50:17	245 2340.368	300	16.70	0.05
2002 03 07	20:28:16	245 2341.353	300	16.69	0.05
2002 03 07	20:35:48	245 2341.358	300	16.62	0.05
2002 03 07	20:43:40	245 2341.364	300	16.66	0.05
2002 03 07	20:51:08	245 2341.369	300	16.78	0.06
2002 03 08	20:33:04	245 2342.356	300	16.47	0.12
2002 03 08	20:40:47	245 2342.362	300	16.60	0.09
2002 03 08	20:48:20	245 2342.367	300	16.62	0.12
2002 03 09	20:45:13	245 2343.365	300	16.75	0.03
2002 03 09	21:01:52	245 2343.376	300	16.71	0.03
2002 03 09	21:09:24	245 2343.382	300	16.65	0.03
2002 03 10	20:35:07	245 2344.358	300	16.69	0.04
2002 03 10	20:42:37	245 2344.363	300	16.68	0.04
2002 03 10	20:50:09	245 2344.368	300	16.67	0.04
2002 03 10	20:57:50	245 2344.373	300	16.69	0.04
2002 03 12	20:07:37	245 2346.339	600	16.66	0.05
2002 03 12	20:20:17	245 2346.347	600	16.65	0.04
2002 03 14	19:56:06	245 2348.331	600	16.61	0.02
2002 03 14	20:08:45	245 2348.339	600	16.67	0.02
2002 03 14	20:21:29	245 2348.348	600	16.62	0.02
2002 03 23	19:30:26	245 2357.313	600	16.69	0.03
2002 03 23	19:43:47	245 2357.322	600	16.72	0.03
2002 03 23	19:56:18	245 2357.331	600	16.66	0.03
2002 03 24	20:32:04	245 2358.356	300	16.70	0.05
2002 03 24	20:40:39	245 2358.362	300	16.58	0.05
2002 03 24	20:48:24	245 2358.367	300	16.59	0.05
2002 03 26	20:31:41	245 2360.355	600	16.74	0.06
2002 03 26	20:44:20	245 2360.364	600	16.76	0.09
2002 03 26	20:56:59	245 2360.373	600	16.68	0.07
2002 04 09	19:38:24	245 2374.318	600	16.78	0.02
2002 04 09	19:50:52	245 2374.327	600	16.77	0.02
2002 04 09	20:03:30	245 2374.336	600	16.83	0.03
2002 04 10	19:46:14	245 2375.324	600	16.70	0.05
2002 04 10	19:58:51	245 2375.333	600	16.81	0.03
2002 04 10	20:11:27	245 2375.341	600	16.86	0.03

The telescope and photometric system are mainly used to carry out the Beijing–Arizona–Taiwan–Connecticut (BATC) survey, and have shown their efficiency in detecting fast variability in blazars (e.g. Peng, Wu & Zhou 2003; Wu et al. 2005).

Our monitoring programme covered the period from 2002 February 23 to April 10. Three or four photometric measurements were made in each night. However, as a result of the weather condition, only 14 nights' data are useful. We used the most sensitive *i* filter of the BATC photometric system, which has a central wavelength of 6711 Å and a passband of 497 Å, and is close to the Cousins *R* band. An exposure time of 300–600 s, depending on the weather and seeing conditions, was able to produce a CCD image with a good signal-to-noise ratio. The observational parameters are summarized in Table 1. Fig. 1 illustrates the finding chart of PKS 1510−089 and the four comparison stars used by us. The four comparison stars were also used in other monitoring programmes (e.g. Villata et al. 1997; Xie et al. 2002) and have *R* magnitudes of 13.95 ± 0.03, 14.22 ± 0.03, 14.35 ± 0.05 and 14.61 ± 0.02, respectively.

Two automatic procedures have been developed for data reduction of the BATC images. 'Pipeline I' includes bias subtraction and flat-fielding of the CCD images, and 'Pipeline II' measures the instrumental magnitudes of point sources in the BATC images. The latter is based on Stetson's standard procedure of DAOPHOT (Stetson 1987). The extinction coefficients and zero-points of the instrumental magnitudes were obtained by observing the four Oke & Gunn (1983) standard stars, and were used to calibrate the instrumental

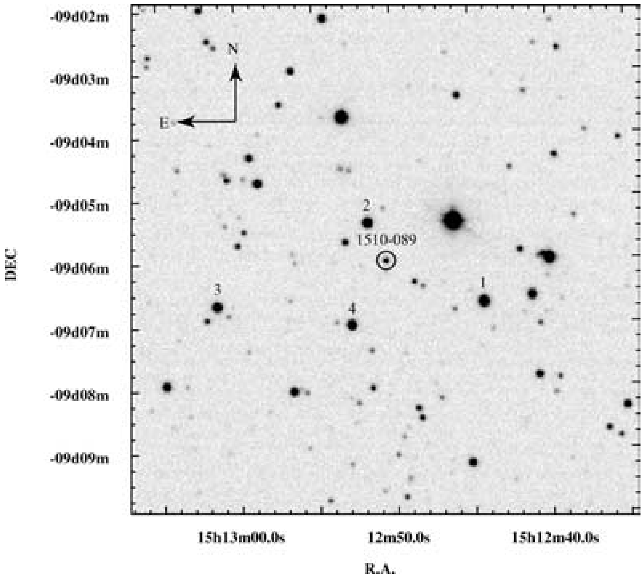

Figure 1. Finding chart of PKS 1510−089 and the four comparison stars used by us. The image was taken with our Schmidt telescope in the BATC *i* band on JD 245 2344 with size 8×8 arcmin^2 (cut from a 58×58 arcmin^2 image).

magnitudes into the BATC AB magnitudes. For details of the data reduction procedures, see Zhou et al. (2003).

The light curves of PKS 1510−089 were given in the *R* band in Xie et al. (2004). For comparison, we calibrated our *i* magnitudes into *R* magnitudes, which was done by using the perfect linear relationship between the BATC *i* magnitude and the Cousins *R* magnitude found by Zhou et al. (2003), i.e. $R = i + 0.1$. Our light curves in the *R* band were then obtained.

3 LIGHT CURVES AND TIME-SCALE OF THE MINIMUM

The observational results are given in Table 1, with the columns being the observation date and time (UT), the Julian date, the exposure time, and the *R* magnitude and its error. The overall light curve in the *R* band is plotted in Fig. 2, in which data in Xie et al. (2004) are also plotted. The two data sets are basically consistent with each other, except that our amplitudes of variation within each night are much smaller than those of Xie et al., which is possibly due to our much shorter monitoring durations within each night.

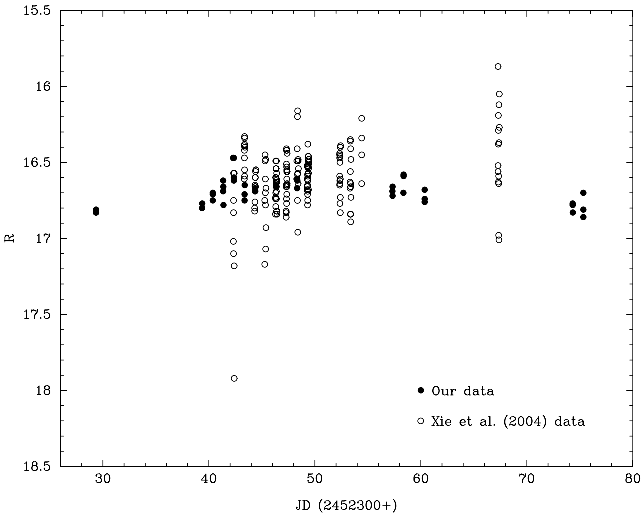

Figure 2. Light curve of PKS 1510−089 in the *R* band from 2002 February 23 to April 10.

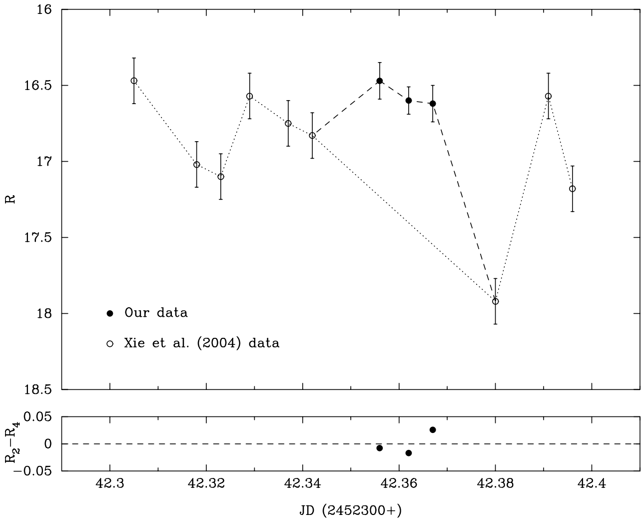

Figure 3. Light curve of PKS 1510−089 in the *R* band on 2002 March 8. The open circles and dotted line are data in Xie et al. (2004), while the filled circles and dashed line are our observations. The lower panel gives the differential magnitudes between the second and fourth comparison stars.

The predicted 2002 minimum occurred on March 8 (JD 245 2342) according to Xie et al. (2004). The light curve in that night is given in Fig. 3, which combines our and Xie et al.'s data. The upper panel illustrates the light curve of the target quasar, while the lower panel shows the differential magnitude (average set to 0.0) between the second and fourth comparison stars. From Fig. 3 we can see that our observations just filled the large gap in Xie et al.'s observations. After a short time of fading phase beginning at JD 245 2342.329, the source underwent a brief brightening phase, as observed by us but missed by Xie et al. Then its brightness in the *R* band dropped from 16.62 ± 0.12 to 17.92 ± 0.15 mag within 19 min, and rose back to 16.57 ± 0.15 mag in 16 min. Therefore, the actual time-scale of the minimum is 35 min, rather than 89 min reported by Xie et al. (2004). The light curve of the minimum becomes basically symmetric, in contrast to the result of Xie et al.

As mentioned in Section 1, Dai et al. (2001) and Xie et al. (2001), Xie et al. (2002) reported three minima with time-scales of 41, 41 and 44 min, respectively. Xie et al. (2002) argued that the minimum is a periodic phenomenon and that there is a BBH system at the centre of PKS 1510−089. They used the measured time-scales to estimate the black hole masses. In this sense, the new 35 min time-scale of the 2002 minimum, as constrained by a combination of our data and those of Xie et al. (2004), is more consistent with the time-scales of the three previous minima than is the 89 min time-scale measured by Xie et al. (2004). Moreover, the basically symmetric light curve is more reasonable for an eclipsing model.

4 DISCUSSION

4.1 BBH model from periodic light curves

Periodicities in light curves are often attributed to the presence of BBHs (see the review by Komossa 2003, and references therein). A prominent example is the BL Lac object OJ 287, which in the optical bands shows quite a strict period of 11.86 yr (Sillanpää et al. 1988, 1996; Valtaoja et al. 2000; Pursimo et al. 2000). Most explanations of the periodicity are based on the assumption that there is a BBH system in the nucleus of OJ 287 (e.g. Sillanpää et al. 1988; Villata et al. 1998; Valtaoja et al. 2000; Liu & Wu 2002). The periodicity is linked to the orbital motion of the BBH system.

For PKS 1510−089, the situation is much different. Its light curves show periodic minima rather than periodic outbursts. The best model to explain the minima in such short time-scales is the eclipsing model, as described by Xie et al. (2002). Other possibilities can hardly result in minima with such short time-scales. In fact, the four minima with nearly the same time-scales and intervals and the basically symmetric light curves would argue strongly for an eclipsing model and a BBH system.

4.2 Evidence for BBH from radio observations

Evidence for BBH in PKS 1510−089 comes also from radio observations. PKS 1510−089 is a radio-loud source with high polarizations. Early radio observations detected an arcsecond jet in this object (O'Dea, Barvainis & Challis 1988) and classified it as a source with a well-aligned jet (Tingay, Murphy & Edwards 1998; Cao 2000). More recently, more sensitive VLBA and VLBI observations detected a milliarcsecond (mas) jet in the opposite direction to its arcsecond jet (Fey & Charlot 1997; Kellermann et al. 1998; Jorstad et al. 2001; Homan et al. 2001), and thus the object shows perhaps the most highly misaligned jet ever observed (Homan et al. 2002).

In order to connect the highly misaligned milliarcsecond and arcsecond jets, Homan et al. (2002) argued that the jet in PKS 1510−089 bends at a deprojected distance of ∼30 kpc from the nucleus, near the probable boundary of the host galaxy. The bend is caused either by ram pressure from winds in the intracluster medium or by the density gradient in the transition to the intergalactic medium.

In fact, the jet shows bends on all scales on the 1.7- and 5-GHz VLBA maps, from milliarcsecond to arcsecond. The smaller the scale, the more significant the bend (see fig. 2 in Homan et al. 2002). Homan et al. also noted that the jet ridge-line 'wiggles in the plane of the sky after the first 10 mas'. Similarly, the 15-GHz image of Kellermann et al. (1998) reveals a short jet extending to the north and then bending to the north-west within 2 mas of the core. Furthermore, multi-epoch VLBA observations have detected several components moving away from the nucleus with different speeds and position angles (see fig. 26 in Jorstad et al. 2001). This pattern of ejection naturally leads to a wiggling or precessing inner jet.

The wiggling or precessing jet can best be explained in terms of a BBH system. BBHs were first proposed to be in AGNs by Begelman, Blandford & Rees (1980) and have since been used frequently to explain the observed curved or misaligned jets (e.g. Roos, Kaastra & Hummel 1993; Conway & Wrobel 1995). BBH systems are formed mainly via galaxy mergers. In most cases, the SBH is in an orbit non-coplanar with the accretion disc of the PBH, inducing torques in the inner parts of the disc and resulting in precession of the disc and its jet.

Therefore, the VLBA and VLBI observations of the distorted jets in PKS 1510−089 provide further evidence for the presence of the BBH in its nucleus. However, the situation in PKS 1510−089 is much different. Its light curves show periodic minima rather than periodic outbursts. Correspondingly, the interpretation of the periodic minima is also different: they are linked to the periodic eclipse of the PBH by the naked SBH according to Xie et al. (2002). In their scenario, the orbit of the SBH passes our line of sight to the PBH. This configuration represents an extreme case of BBH systems, for which a schema is given in Fig. 4. The circle represents the orbit of the SBH around the PBH, and the Earth is in the orbital plane. The thick lines denote two extreme positions of the inner part of the primary accretion disc. When the SBH moves to position B1, the inner part of the primary accretion disc tends to move to position D1 under the gravity of the SBH, and its jet is directed to J1. When the SBH moves to position B2, the inner part of the primary disc tends to move to position D2 under the gravity of the SBH, and its jet is directed to J2. Therefore, as the SBH moves along the circle, its gravity makes the inner part of the primary disc vibrate between D1 and D2 and the jet oscillate between J1 and J2. Consequently, an apparently wiggling jet is formed. When the SBH moves to B3, the point on our line of sight to the PBH, the PBH is eclipsed and a flux minimum occurs. The minimum is a periodic phenomenon, and the periodicity is caused by the orbital motion of the BBH system.

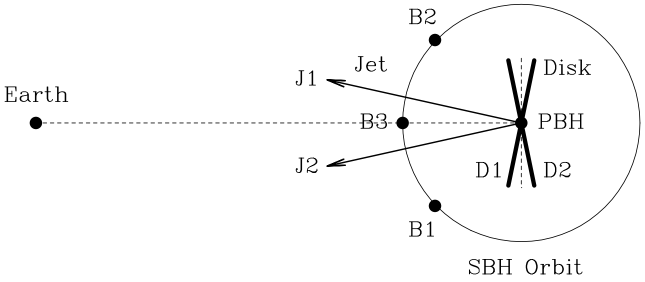

Figure 4. Schema of the configuration of the BBH system in PKS 1510−089. The Earth is in the orbital plane of the SBH. When the SBH moves along the orbit, the inner part of the primary accretion disc will vibrate between positions D1 and D2, and the jet will oscillate between J1 and J2, resulting in a wiggling pattern. (The jet is not in the orbital plane and actually follows a highly eccentric precession when the SBH moves along its orbit. See text for details.) The angles are enlarged for clarity. The minimum occurs when the SBH moves to position B3.

For simplicity, Fig. 4 gives only a 2D diagram. In 3D reality, the jet will have a small angle to the orbital plane of the SBH, and the primary accretion disc will be slightly tilted relative to the normal of the plane. When the SBH moves along its orbit, the jet and the primary accretion disc will follow a highly eccentric precession, with J1 and J2 being the two extreme directions of the jet. The angles in Fig. 4 are enlarged for clarity. The jet actually stays in roughly the same direction from the point of view of the observer, with only a small wiggling in the plane of the sky. During the orbital motion of the BBH system, the SBH could eclipse the PBH but it does not pass through the jet, and the jet does not cross the line of sight when precessing.

4.3 The 'coupling' of periodicity and helicity in blazars

It is interesting to note that a (quasi-)helical jet and a periodic light curve usually coexist in blazars. OJ 287 itself shows evidence for a helical jet in its 8.4-GHz VLBI map (Vicente, Charlot & Sol 1996). Other examples that present both helical jets and periodic light curves include 3C 120 (Webb 1990; Gómez, Marscher & Alberdi 1999b), 3C 345 (Webb et al. 1988; Zensus, Cohen & Unwin 1995), AO 0235+16 (Jorstad et al. 2001; Raiteri et al. 2001), BL Lac (Tateyama et al. 1998; Fan et al. 1998), Mrk 501 (Xu et al. 1995; Hayashida et al. 1998) and PKS 0735+17 (Fan et al. 1997; Gómez et al. 1999a), and it has been proposed that most of these objects harbour a BBH system in their nuclei (Villata & Raiteri 1999; Caproni & Abraham 2004a,b; Ostorero, Villata & Raiteri 2004). In other words, the periodicity in the light curve and the helicity in the jet usually 'couple' in blazars and are interpreted within the scenario of a BBH system. In fact, the 'coupling' of the periodicity and helicity can easily be explained in that the periodicity in helical jets will result in periodicity in relativistic boosting in jets and hence the periodicity in brightness.

Similarly, the periodic minima and wiggling jet observed in PKS 1510−089 can both be taken as evidence for a BBH system. The SBH orbits around the PBH and exerts tidal torques on its accretion disc, resulting in disc vibration and jet wiggling. The eclipse of the PBH by the SBH leads to the periodic flux minima.

5 SUMMARY

The blazar PKS 1510−089 was monitored from 2002 February to April. Based on a combination of our data and those of Xie et al. (2004), we constrained a new time-scale of 35 min and a nearly symmetric light curve for the 2002 minimum reported by Xie et al. The new results are more consistent with the three previous minima observed by Dai et al. (2001) and Xie et al. (2001, 2002) and are more reasonable for an eclipsing model of a BBH system suggested by Xie et al. (2002). Radio observations have revealed wiggling jets in PKS 1510−089 and provided further evidence for the BBH system. The 'coupling' of the periodicity in the light curve and the helicity in the radio jet is discussed for blazars within the framework of BBH systems.

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