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Photometric monitoring of three BL Lacertae objects in 1993-1998*

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Abstract. The results of optical photometric ($BVRI$) monitoring of three BL Lac objects over a time interval of about four years are presented. The sources are three classical radio-selected BL Lac objects, BL Lac, OJ 287 and PKS 0735+178. During our observation OJ 287 was in the stage of a large periodic outburst which consisted of at least two peaks. Almost all the observations obtained over consecutive nights detected intranight variations. In 1995 and 1996 BL Lac kept in faint states, with fewer and smaller rapid flares and fluctuations. On the contrary, in late 1997 BL Lac was at the stage of a large outburst, accompanied with much more large amplitude rapid flares and fluctuations. PKS 0735+178 was almost at its faint end from 1994 to early 1998. Over this time interval, the intraday variations and microvariations in PKS 0735+178 were rare and the amplitude was very small, except a rapid darkening of $\sim$0.4 mag on 24 January 1995. Previous work by Webb et al. (1988); Wagner et al. (1996); Pian et al. (1997) also showed the same behaviour of variability as BL Lac and PKS 0735+178 in BL Lac, S5 0716+714, PKS 2155 − 304, respectively. We propose that the motion of orientation of the relativistic jet in a BL Lac object be responsible for these variability behaviours.

Key words: BL Lacertae objects: general; BL Lac; OJ 287; PRS 0735+178 — galaxies: jets

1. Introduction

Variability has always been used to probe into central engine and physical processes of active galactic nuclei (AGNs). In recent years, considerable progress has been made in the studies of variability in blazars. For variability on short timescales, observations especially those performed simultaneously in several wave bands for several blazars have obtained a lot of interesting results (e.g. Urry et al. 1993, 1997 and reference therein, Wagner & Witzel 1995 and reference therein, Villata et al. 1997). These studies have introduced new strict constraints for models on the structure of the center engine and physical processes of blazar. When explaining these new observational results, shocks-in-jet model seems to be more reasonable than other models (Wager & Witzel 1995). On the other hand, studies for long term light curves have shown variability periodicity in several sources, such as OJ 287 (Sillanpää et al. 1988; Kidger et al. 1992), 3C 345 (Schramm et al. 1993), 3C 273 (Babadzhanyants & Belokon 1992), ON 231 (Liu et al. 1995). During the long term monitoring from 1993 to 1996, OJ 287 was found to burst almost exactly at the predicted time, and a large amount of observational data with a very good time resolution and a long time span were obtained (Kidger et al. 1995; Sillanpää et al. 1996a, 1996b; Takalo et al. 1996). The periodicity of long timescale variability in blazars and irregularity of rapid variability indicates that the origin for long timescale variability is probably different from that for the short timescale variability.

In this paper, some new CCD photometric results since late 1993 for three BL Lac objects, BL Lac, OJ 287 and PKS 0735+178 are presented. BL Lac is the prototype of BL Lac objects. OJ 287 is a classical radio selected BL Lac object. It shows variability at all wavelength from radio to γ-rays. Its range of variability in the B band is as large as 5.5 mag, $18.0 \geq B \geq 12.5$ mag (Takalo 1994). PKS 0735+178 is a highly variable BL Lac object. Historical light curves indicate that its range of variability in the B band is 13.90 – 17.72 mag (Bai & Xie et al. 1998). As a preliminary discussion of these data, we have compared the difference between variability behaviours in the high state and low state in BL Lac objects. We propose that the motion of orientation of the relativistic jet in a BL Lac object be responsible for these variability behaviours.

2. Observation and data reduction

The observations presented here were carried out with the 1.56 m telescope of Shanghai Observatory (SHO) and the

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* Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

one-meter telescope of Yunnan Observatory (YNO) from October 1993 to April 1998. The 1.56 telescope of SHO is equipped with a direct 1024×1024 pixels CCD camera at the Cassergrain focus. The one meter telescope of YNO was equipped with a direct 512×512 pixels CCD camera at the Cassergrain focus before 1996 November. Since 1996 November the telescope has been equipped with a 1024×1024 pixels CCD camera. The exposure time for B and V filters ranges from 300 to 400 s, and for R and I filters ranges from 100 to 300 s according to the brightness of the source. The bias was taken at the beginning and the end of the observation. Sky flat field frames were taken at dusk and dawn when possible. All images have been pre-reduced with the CCDRED package and then processed with the photometry tool, APPHOT, in IRAF software package. The calibration sequences in the field are taken from Smith et al. (1985). The magnitude is calculated with respect to the brightest standard star in the image frame containing the source, and the observing uncertainty is the rms error of differential magnitude between the calibration star (star 1) and the standard star that is not brighter than the source (star 2),

$$\sigma = \sqrt{\frac{\Sigma \delta_i^2}{N-1}}, \quad i = 1, 2, ... N, \tag{1}$$

where $\delta_i = (m2 - m1)_i - \overline{(m2 - m1)}$, $\overline{(m2 - m1)}$ is the mean differential magnitude, N is the number of repeat observations. In the case that the source was fainter than any standard star, the observing uncertainty was greater than the σ calculated above and was given according to the typical uncertainty of stars with brightness comparable with the source. The results are given in Table 1. In Table 1 the first column is the UT date, the second the Julian date, the third the magnitude, the fourth the rms error, and the last the filter used.

3. Observational results

3.1. BL Lac

On 12 October 1993, the source exhibited no convincing microvariability during the observation of one hour and 40 min. On the next night, 13 October, the source was about 0.1 mag brighter (see Table 1). On 22 October 1995 BL Lac was stable over the interval of our observation of about 2.5 hours. Six days later, 28 October, the source brightened by $\triangle V \sim 0.28$ mag. On 29 October 1995, the source was almost at the same brightness level as on the night before during our observation (see Table 1). Two month later, on 22 December 1995, the source became $\triangle V \sim 0.17$ mag brighter. On the next night, 23 December 1996, the source was a little fainter than on the night before (see Table 1). In August 1996, BL Lac undertook a small flare. From 14 to 24 August, the source brightened by ~ 0.3 mag and on 25 August it faded back by ~ 0.15 mag (see Table 1). On 14 August we also observed

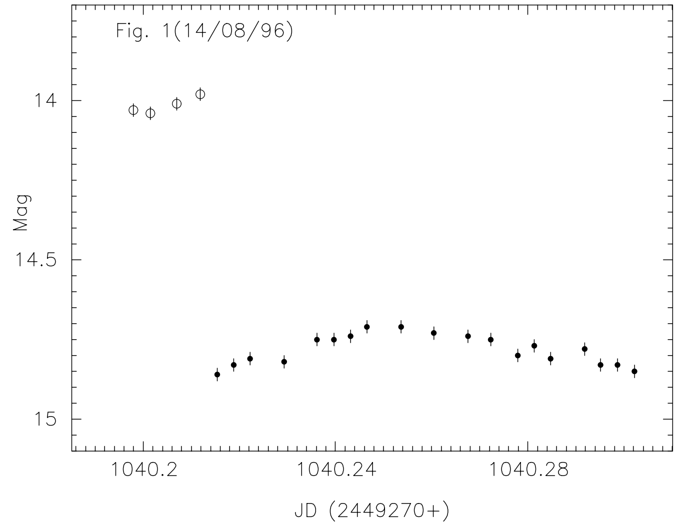

Fig. 1. Light curves of BL Lac on 14 August 1996. The open circles (○) are for I band data and filled circles (•) for R

a microvariation in the source. From JD = 2450310.1979 to 2450310.2153, the source brighten by $\triangle I = 0.05$ mag in 20 min, then by $\triangle R = 0.15$ mag in ~ 55 min (to 2450310.2635). On JD = 2450310.2635 it reached a maximum and then began to fade. The amplitude of this microvariability was ~ 0.20 mag (see Fig. 1 and Table 1). In early September 1996, the source was at the same brightness level as in August 1996, and the amplitude of variability was about 0.1 mag. During the observation of one hour and 40 min on 02 September, the source exhibited no evidence of microvariability (see Table 1). On 19 October 1996, the source was as bright as 14 September 1995, and showed no microvariability. On the next night, 20 October, the source was slightly fainter than on the night before (see Table 1). Over the interval of our observation from 7 to 11 November, the source gradually faded by ~ 0.25 mag (see Table 1). On 12 December 1996, BL Lac was ~ 0.43 mag brighter than on 11 November and gradually faded by $\triangle V \sim 0.23$ mag over the interval of the observation from 12 to 14 December 1996 (see Table 1).

Combining the historical light curves constructed by Shen & Usher (1970) and the long term monitoring results by Webb et al. (1988), we can see that the range of variation for BL Lac in the B band was 12.4 to 17.2 mag. The faintest magnitude ever recorded is $B = 17.99 \pm 0.11$ mag, $V = 16.73 \pm 0.08$ mag (Carini et al. 1992); nevertheless, during about 17 years (1973 to 1990) BL Lac reached this faintest state only once (on 1980.367), the usual fainter states for BL Lac were those states around $V = 15.7$ mag (see Fig. 13 of Carini et al. 1992). It is obvious that over the interval of 1995 and 1996 observing runs BL Lac kept at faint states, and was relatively stable. The amplitudes of intranight variation recorded in our observation were less than 0.3 mag (see Table 1). Better sampling

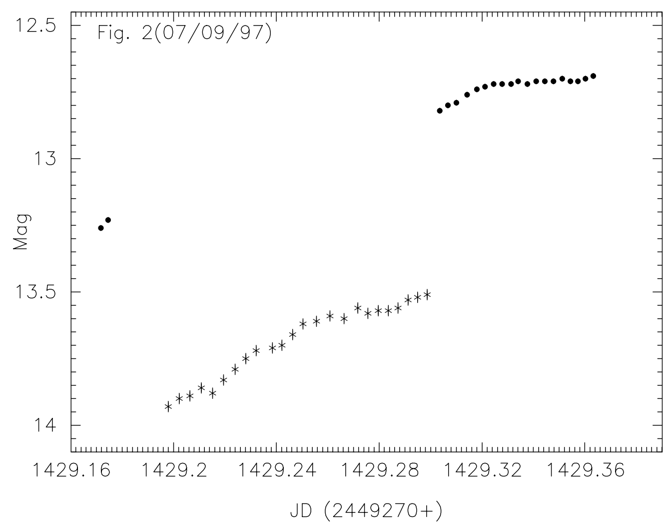

Fig. 2. Light curves of BL Lac on 07 September 1997. The stars ($*$) are for V band data, filled circles ($\bullet$) for R

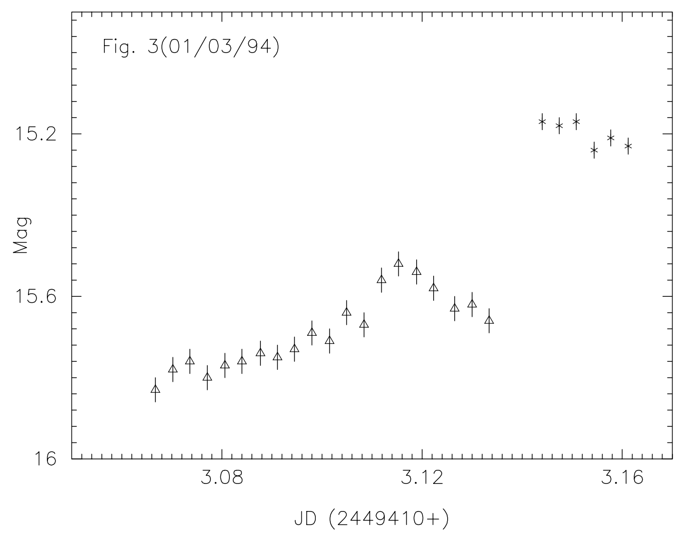

Fig. 3. The B and V band light curves of OJ 287 on 01 March 1994. The stars ($*$) are for V band data and triangles ($\triangle$) for B

observations for this source in 1995 by Maesano et al. (1997) also recorded no flares or fluctuation greater than half magnitude from the mean level.

During 1997 observing run, BL Lac became much brighter than it was in 1995 and 1996. On 7 September 1997, it was averagely 12.78 mag in the R band, about 1.9 mag brighter than it was on 14 December 1996 (see Table 1). During the observation on this night the source showed a steadily brightness increase of $\sim$0.55 mag (see Fig. 2 and Table 1), which was probably a part of an intranight variation. On 3 October 1997, the source became about 1.0 mag fainter in the R band. No significant variability was observed during the observation of about one hour on this night (see Table 1). The observations on 4 December recorded a microvariation. From the beginning of our observation to JD = 2450725.0053 the source brightened by $\triangle I = 0.11$ mag, then by $\triangle B = 0.13$ mag, and then faded back by about the same amount till JD = 2450725.0565. The amplitude of this microvariability was $\sim$0.24 mag (see Table 1). From 7 September to 4 December, it decreased $\triangle R \sim 1.4$ mag in its brightness. Nesci et al. (1998) monitored this source intensively in July 1997 for 9 nights (from 14 to 29 July) and found the source was never stable, but always showed a variability of at least 0.04 mag/hour, often with superimposed fast fluctuation on time scales of about an hour and with amplitudes of about 0.1 mag. The largest intraday variation had an amplitude of 0.7 mag. During their observation the source was at a bright state of about 14.0 mag in the V band. It was obvious that the source was at the stage of a large outburst during late 1997, accompanied with much more rapid flares and fluctuations than in 1995 to 1996 when the source was at faint states.

3.2. OJ 287

On 01 March 1994, the source was averagely 0.8 magnitude brighter than the mean level of B = 16.5 mag (Kidger et al. 1995). From the beginning of our observation to JD = 2449413.1153 the source brightened by $\triangle B \sim 0.31$ mag, then faded back by $\triangle B \sim 0.14$ mag and $\triangle V \sim 0.06$ mag (see Fig. 3 and Table 1). On 03 March 1994, the source showed a decline of $\triangle B \sim 0.19$ mag from the beginning of our observation to JD = 2449415.0844, then recovered about the same amount in the B band to JD = 2449415.1384, and then began another decline till the end of our observation. (see Fig. 4 and Table 1). On the average, the source was brighter on 03 March than on 01 march, and combining Figs. 3 and 4, we can see the variations on 1 and 3 March were probably parts of an intranight variation. On 04 December 1994, the source exhibited a microvariation of at least 0.23 mag. From the beginning of our observation (JD = 2449691.3398) to JD = 2449691.3757, the source first faded by $\triangle I$ = 0.05 mag, then by $\triangle V$ = 0.06 mag, and then by $\triangle B$ = 0.12 mag. On JD = 2449691.3757 it began to recover till the end of our observation (see Table 1). On 05 December, the source was a little brighter than on the night before. On 06 December the source was stable during the observation, but $\sim$ 0.2 mag brighter than on the night before. Forty-eight days later, on 23 January 1995, the source became averagely 0.5 mag fainter in the V band and exhibited a steady decline of $\triangle R = 0.17$ mag. On the next night the source showed a slow brightness increase of $\triangle R \sim 0.14$ mag which was superimposed by a microvariation of $\triangle R \sim 0.05$ mag (see Table 1). On 25 January 1995 the source brightened by $\triangle V \sim 0.13$ mag from the beginning of our observation to JD = 2449743.2431, then

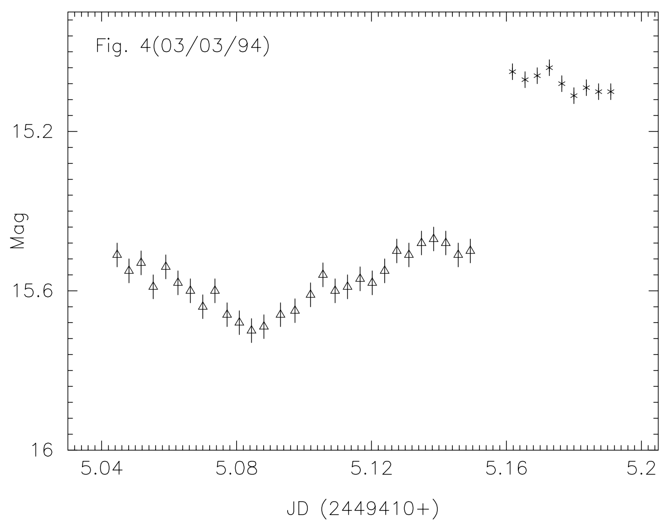

Fig. 4. The B and V band light curves of OJ 287 on 03 March 1994. The stars ($*$) are for V band data and triangles ($\triangle$) for B

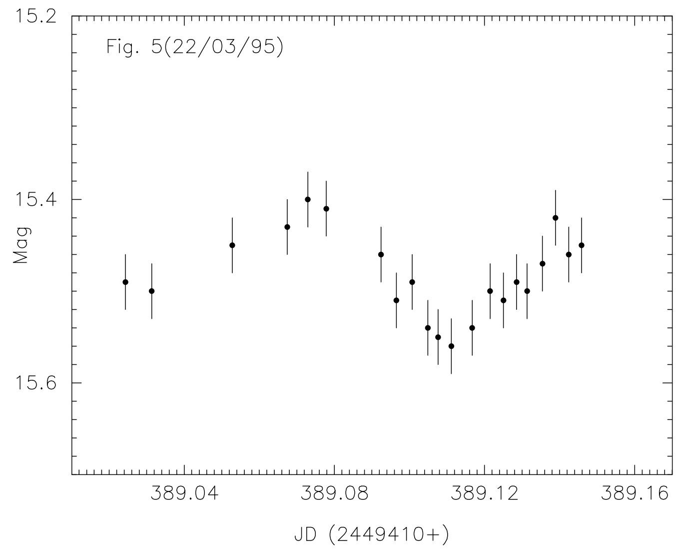

Fig. 5. The R band light curve of OJ 287 on 22 March 1995

slowly faded by $\triangle V \sim 0.15$ mag to the end of our observation. The observation on 26 January 1995 recorded a local brightness minimum of $V = 15.34$ mag which was brighter than the local maximum of $V = 15.41$ mag on the night before, implying that the source had undertaken a brightness oscillation over the interval between 25 and 26 January (see Table 1). On 27 January 1995 the source was a little fainter than on 26, but showed no convincing variation during our observation. On 28 January 1995 the source exhibited a slow darkening of $\triangle R = 0.12$ mag (see Table 1). The source was next observed on 22 March 1995 and ~ 0.5 mag fainter than on 28 January 1995. It exhibited a brightness oscillation with an amplitude of $\triangle R \sim 0.14$ mag (see Fig. 5 and Table 1). On the next night, 23 March, the source first faded by $\triangle R \sim 0.09$ mag and reached a local brightness minimum on JD = 2449800.125, then recovered 0.06 mag to JD = 2449800.1359, and then kept stable to the end of our observation (see Table 1). On 24 March 1995, the source was averagely 0.25 mag brighter than on the night before. The light curve on this night seems to show a brightness oscillation, but the amplitude is less than 3σ (see Table 1). Over the interval from December 1994 to March 1995 the source gradually faded by about one magnitude. This was consistent with the observation by Sillanpää et al. (1996a) who recorded an outburst in this source which peaked around 10 November 1994 and ended in April 1995.

On 24 January 1996 the source was about one magnitude brighter than it was in March 1995 (see Table 1). On 15 February 1996, the source was stable during our observation and ~ 0.09 mag fainter than on 24 January 1996 (see Table 1). On 15 April 1996, the source was about 0.27 mag brighter than on 15 February 1996. On the next night, 16 April, the source became a little fainter and kept stable during our observation (see Table 1). From 16 to 18 April 1996, the source gradually brightened by ~ 0.25 mag, but exhibited no convincing variation on each night. The source was next observed on 02 January 1997 and became ~ 0.6 mag fainter. Nearly one year later, on 04 December 1997, the source faded by another 0.2 mag. During the observation on this night it also exhibited a microvariation of ~ 0.1 mag (see Table 1). A month later, on 01 and 02 January 1998, the source became even fainter. On 01 January 1998, the source first faded by $\triangle B = 0.06$ mag, then brightened back by $\triangle B = 0.05$ mag, $\triangle V = 0.06$ mag and $\triangle R = 0.05$ mag to a local brightness maximum, and then began to fade to the end of our observation (see Table 1). The amplitude of this small flicker was at least 0.16 mag. During the observation of one hour and 45 min on 02 January 1998, the source showed no convincing variation (see Table 1). On 28 April 1998, the source was at the same brightness level as in January 1998 and showed no evidence of microvariability (see Table 1). Over the interval from January 1996 to April 1998 the source faded gradually by about one magnitude, back to the brightness level of March 1995. This is consistent with the observation by Sillanpää et al. (1996b) who detected a secondary outburst in this source which peaked just at Christmas 1995.

3.3. PKS 0735+178

The source was rather stable during 04-06 December 1994. Only a slightly brightness decrease of $\triangle V \sim 0.08$ mag was observed between 04 and 05 December (see Table 1). Forty-eight days later, 23 January 1995, the source brightened by $\triangle V \sim 0.65$ mag, and exhibited a small flicker of

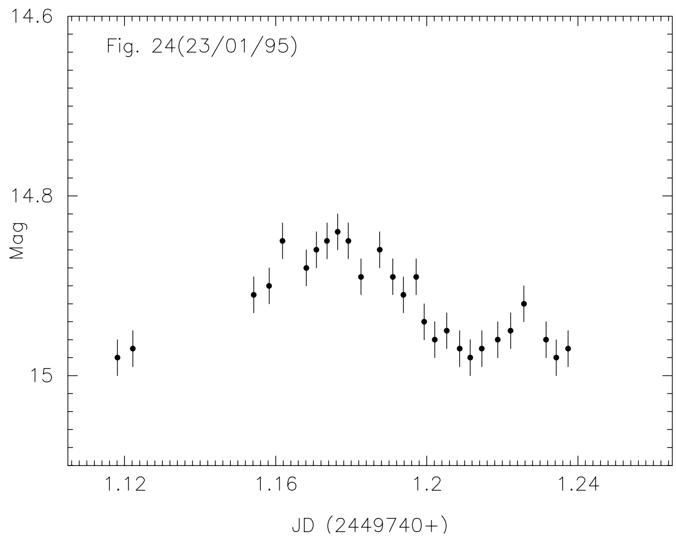

Fig. 6. The R band light curve of PKS 0735+178 on 23 January 1995

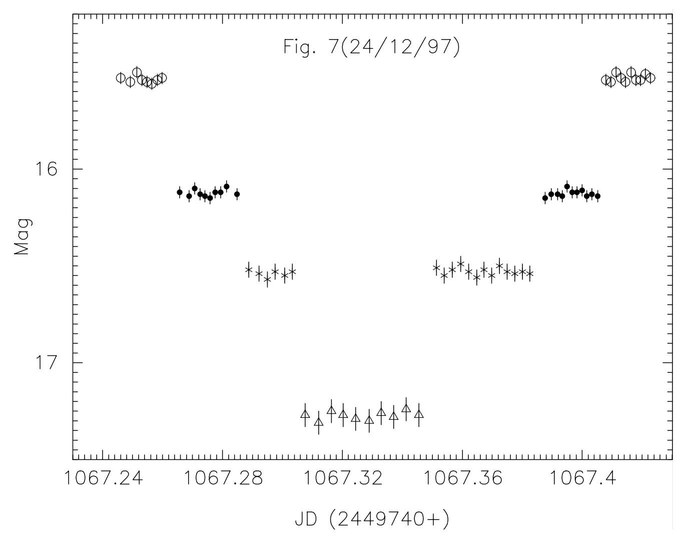

Fig. 7. Light curves of PKS 0735+178 on 24 Dec. 1997. The open circles (○) are for I band data, filled circles (•) for R, stars (∗) for V and triangles (△) for B

$\triangle R \sim 0.13$ mag from JD = 2449741.1222 to 2449741.2115, and a smaller flicker of 0.06 mag from JD = 2449741.2115 to 2449741.2343 (see Fig. 6 and Table 1). On the next night the source was $\triangle V \sim 0.4$ mag fainter than the night before, but showed no convincing microvariation. Then two days later, 26 January, it brightened back by $\triangle V \sim 0.15$ mag. From 26 to 29 January the source was stable, no significant intranight variation and microvariation being detected (see Table 1). The source was next observed a year later, on 24 January 1996, and was as bright as on 29 January 1995. No convincing microvariation was detected on this night (see Table 1). Twenty-two days later, 15 February 1996, the source faded by $\triangle V \sim 0.2$ mag. On 13 December 1996, the source became about one magnitude fainter in the V band. On 02 and 03 January 1997, it was a little fainter than in December 1996. On 04 December 1997, the source reached the minimum of our monitoring, with $B \sim 17.64$ mag, near the faintest magnitude ever recorded of $B = 17.72$ mag. During the observation of two hours and twenty minutes, the source showed no evidence of microvariability (see Table 1). Twenty days later, 24 December, the source brightened back by $\triangle V \sim 0.5$ mag. The observation on this night lasted over 4 hours, but detected no convincing microvariations (see Fig. 7 and Table 1). From 01 January to 24 February 1998 the source slowly faded by $\triangle V \sim 0.1$ mag. On 01 January 1998 the source was $\triangle V \sim 0.4$ mag brighter than on 24 December 1997 and exhibited a decline of ~ 0.16 mag from the beginning of the observation to JD = 2450815.2295. On 02 January during the observation of three hours and twenty minutes the source showed no convincing microvariation. On 22 February the source exhibited no evidence of microvariation during the observation of two and half hours. On 24 February, from the beginning of our observation to JD = 2450869.2220 the source was stable, but during last two hours of our observation the source showed a microvariation of ~ 0.3 mag (see Table 1).

4. Discussions

We have presented some new results of CCD photometry for three BL Lac objects in 1993-1998. During our observation OJ 287 was in the stage of a large periodic outburst which consisted of at least two peaks. Almost all the observations obtained over consecutive nights detected intranight variations. In 1995 and 1996 BL Lac kept in faint states, with fewer and smaller rapid flares and flickers. On the contrary, in late 1997 BL Lac was at the stage of a large outburst, accompanied with much more large amplitude rapid flares and fluctuations. Previous observation by Webb et al. (1988) also showed similar variability behaviour. Over the interval from 4 January 1981 to 15 December 1985, BL Lac was faint at $15.6 \leq B \leq 17.2$ mag and occurred with relatively little flaring activity, while in 1970-1981 when BL Lac was much brighter, $1 - 2$ mag flares occurred frequently (see Fig. 1 of Webb et al. 1988). PKS 0735+178 was almost at its faint end from 1994 to early 1998. Over this time interval, the intraday variations and microvariations in PKS 0735+178 were rare and the amplitude was very small, except a rapid darkening of ~ 0.4 mag on 24 January 1995. On the contrary, in 1970-1986 when the source was brighter than 16.5 mag in the B band at most time, Webb et al. observed many large rapid flares (see Fig. 1 and Table 3 of Webb et al. 1988). PKS $2155-304$ (see Fig. 8 of Pian et al. 1997) and S5 0716+714 (see Fig. 2 of Wagner et al. 1996) also exhibited similar variability behaviours as BL Lac and

PKS 0735+178, with more rapid flares in the bright state than in the faint state. Other BL Lac objects probably showed this variability behaviour too. But what causes this difference?

It is now widely believed that the continua emission of blazars mainly originates in the relativistic jet and is boosted by relativistic beaming,

$$S = S_0 D^4, \tag{2}$$

where S is the observed flux, S_0 the intrinsic flux, and D the Doppler factor,

$$D = \frac{1}{\gamma(1 - \beta \cos\theta)}, \tag{3}$$

θ is the angle of the jet orientated from the line of sight, $\beta = v/c$, c is the speed of light, v is the speed of the jet, $\gamma = (1 - \beta^2)^{-1/2}$. Suppose the orientation of the relativistic jet in a BL Lac object is not fixed in some cases and varies by a small amplitude with the time. According to Eqs. (3) and (2), this may cause the variation of Doppler factor D and hence the variation of observed flux S. That is to say, the observed variability in a BL Lac object can be divided into two components, one is the intrinsic flux variations of S_0 caused by randomly occurring, radiating decaying shocks or other motions in the relativistic jet and amplified by relativistic beaming, the other is the contributions from geometric variations of the orientation of the jet. As mentioned in the Introduction section, the difference between the periodicity in long timescale variability and the irregularity of short timescale variability suggests that the former have a different origin from the later. It is natural to deduce that the intrinsic flux variations of S_0 caused by randomly occurring shocks is just the irregular short time scale variations, the long time scale variability is thus caused by the variation of Doppler factor D, and the outburst states and low states, which provide the base-levels for small flares or flickers, are the states that θ varies to near the maximum and minimum, respectively. Therefore, when staying in low states, BL Lac objects have smallest Doppler factors, the intrinsic flares are least boosted, and the smaller ones will not be enhanced large enough to be observed. That is why BL Lac, PKS 0735+178, S5 0716+714 and PKS 2155 − 304 were less active and exhibit fewer small flares and flickers when they were in faint states.

The relativistic jet model above expanded can also explain the stable colour found during the periodic outburst in OJ 287 (Sillanpää et al. 1996b), since the motion of the orientation of a jet do not change the emission mechanism. Takalo et al. found that for both 3C 66A and OJ 287 the observed total amplitude of variations $\triangle f_\nu$ depends on the observing frequency approximately as ν^{-1} in the optical-infrared regime (Takalo et al. 1996), i.e.,

$$\triangle f_\nu \propto \nu^{-1}. \tag{4}$$

This phenomena can also be explained. The total amplitude of variations, according Eq. (2), is

$$\triangle f_\nu = S_0(D^4_{\max} - D^4_{\min}). \tag{5}$$

For blazars which are dominated by nonthermal emission, we have

$$S_0 \propto \nu^{-\alpha}, \tag{6}$$

where α is the spectra index. We thus have

$$\triangle f_\nu \propto S_0 \propto \nu^{-\alpha}. \tag{7}$$

For 3C 66A, the average spectra index in the optical-infrared regime is $\alpha = 1.0$ (Takalo et al. 1996), thus the total amplitude of variations is $\triangle f_\nu \propto \nu^{-1}$. For OJ 287, the average spectra index in the optical-infrared regime is $\alpha = 1.26$ (Kidger 1995) or $\alpha = 1.20 \pm 0.13$ (Cruz-Gonzalez & Huchra 1984), thus the total amplitude of variations approximately is $\triangle f_\nu \propto \nu^{-1}$.

If the motion of the orientation of a jet is precession and nutation (like the motion of the pole of the earth), that is to say the motion is periodic, the periodicity of long timescale is naturally an exhibition of this periodic motion. However, whether the variation of the orientation is possible needs further investigation to search for physical basis for it.

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