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The 1997 Outburst of BL Lacertae and Detection of a 0.6-mag Rapid Variation

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Abstract

Photometric observations of BL Lac were carried out during the large optical and X-ray outburst in 1997. Time-resolved photometry on 1997 August 2 revealed a rapid increase of brightness by about 0.6 mag within 40 min. This large-amplitude, short-time variation is the most active one among known variability of blazars in the optical wavelength. By considering a model based on the "synchrotron self-Compton model" of the relativistic jets of blazars, the size of the variable source should be $R \sim 7.2 \times 10^{14}$ cm from the 40 min variation. The power-density spectrum of the light curve on the night yielded a dependence of the power to the frequency $f^{-1.0}$ for timescales of the variabilities and down to a possible minimum timescale of around 10 min. The clear difference between the observed $f^{-1.0}$ dependence from the canonical $f^{-1.5}$–$f^{-1.8}$ power indices observed in X-ray variations of radio-loud AGNs suggests that different mechanisms are responsible for short-term optical variability between BL Lacs and radio-loud AGNs.

Key words: Accretion, accretion disks — Black holes — Galaxies: individual (BL Lacertae)

1. Introduction

Blazars are a class of AGNs characterized by the most violent variation having several timescales and amplitudes. These objects sometimes exhibit extremely large variations with amplitudes of about a few mag, which is relatively well-known in radio (Aller et al. 1985; Stevens et al. 1994).

The existence of intraday variability at optical wavelengths is known for among many blazars and radio-loud AGNs (Xie et al. 1990; Wagner, Witzel 1995; Heidt, Wagner 1998). Even a shorter timescale variability, often called *microvariability*, is one of the main focuses of contemporary discussions on AGN variability (Miller et al. 1989; Carini et al. 1992; Jang, Miller 1995; Miller, Noble 1996). Microvariability has the shortest timescale of typically 1 hr and amplitudes of 0.1–0.2 mag at optical wavelengths, and is a rather common phenomenon in radio-selected BL Lacs (Miller, Noble 1996) and radio-loud AGNs (Jang, Miller 1995). The origin of the microvariability is still unsolved, though a relation to jets is suggested.

BL Lac, the prototype system of blazars, underwent an optical outburst in 1997 July–August (Noble et al. 1997; Maesano et al. 1997; Ma, Barry 1997); the last major one occurred at the first half of 1993 (Tornikoski et al. 1994). We subsequently started photometric observations, and report here on the detection of rapid, large-amplitude variability, which represents a 0.6 mag brightening within 40 min. It is the most active short-term variation among known variability of blazars at optical wavelengths.

2. Observations

CCD time-resolved photometric observations of BL Lac were made on eleven nights between 1997 July 31 and September 11 in order to clarify the existence of a short-term variation implied from the record of visual observations (Kato 1997). We used the 60-cm reflector at Ouda Station, Kyoto University, and a Thomson TH 7882 liquid-nitrogen cooled CCD camera having 576×384 pixels at the Cassegrain focus (focal length = 4.8 m), with a Johnson V-band interference filter (for details of the instruments, see Ohtani et al. 1992). The 2×2 binning mode was used throughout the observing period. The exposure times for the object frames were

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Table 1. Observing log of BL Lac between 1997 July 31 and September 11.

Date (1997)		Exposure time (s)	Number of frames	Time coverage (HJD−2450000)
July	31	40–60	13	661.104–661.116
August	1	30–40	56	662.223–662.312
	2	30–40	278	663.125–663.315
	11	30	4	672.291–672.294
	12	30	5	673.079–673.081
	13	30	10	673.991–673.993
	14	30	6	675.006–675.010
	15	30	9	676.020–676.282
	16	30	6	677.056–677.267
September	10	60	151	702.181–702.312
	11	60	103	703.168–703.256

typically set to 30–60 s, depending on the sky condition, which correspond to time resolutions of about 40–70 s. A log of the observations is presented in table 1.

Data reductions of the obtained frames were processed with a microcomputer-based automatic aperture photometry package developed by one of the authors (T. Kato). An updated comparison-sequence of the field summarized by Skiff (1997) was used, and the magnitudes of BL Lac are expressed as relative magnitudes to star **f** indicated in the finding chart of Bertaud et al. (1969). Stars **b** and **c** in the chart were used as check stars in order to estimate the accuracy of the photometry. A heliocentric correction was finally applied before the following analysis.

3. Results

Figure 1 is the overall light curve of BL Lac during the past three years, which was based on the data reported by a number of VSNET members (the present updated light curve is constantly available on URL: http://www.kusastro.kyoto-u.ac.jp/vsnet/LClast/index/lacbl.html). As indicated by figure 1, the object had usually been around 15 mag in visual or V-magnitudes, and the object had shown no particular activity before the current outburst.

The outburst was one of very active phenomena of this object, whose behavior was recorded in detail for the first time. Figure 2 is a magnified light curve of figure 1 for the period between HJD 2450634 and 2450716; this portion of the light curve illustrates the most active state during the outburst episode. The object frequently showed flares with a duration of about 1 d. Intervals of the repeating flares were 5–10 days in the first half of the outburst, and afterwards typically became shorter by 1–3 days in the latter half, though no conspicuous change was seen concerning the amplitudes of the variations. This behavior

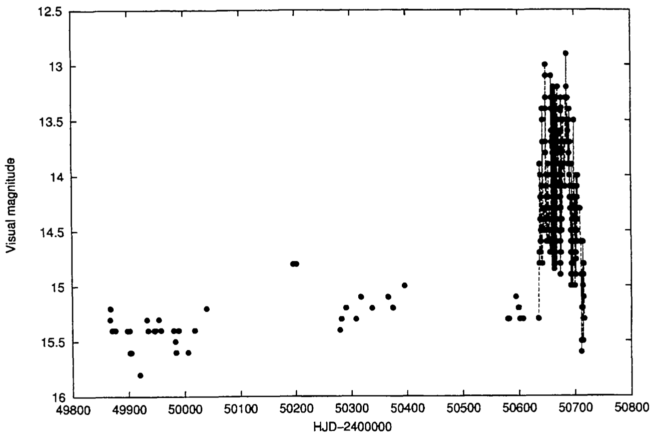

Fig. 1. Optical light curve of BL Lac past three years. The data-set is based on contributions reported by the VSNET members and the results obtained at Ouda station. The horizontal axis represents Heliocentric Julian date (HJD) minus 2400000 days, and the vertical axis represents the visual magnitude, except for the data-set taken at Ouda station with Johnson V-band interference filter. The rapid start of the current outburst of the object was detected on HJD 2450636.

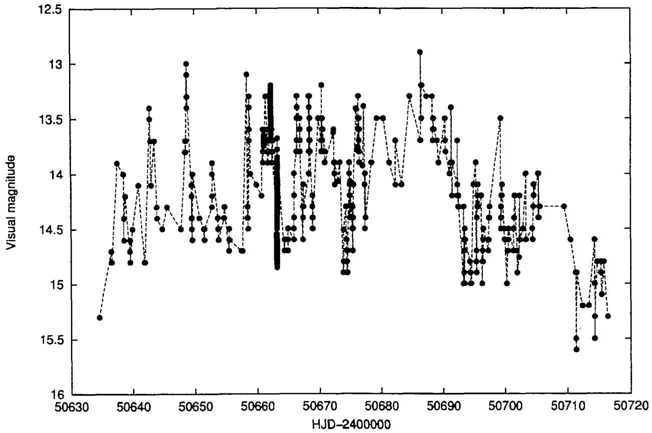

Fig. 2. Magnified light curve of figure 1 for the period between HJD 2450634 and 2450716. Frequent flares with durations of about 1 d appeared during the outburst.

of the flares suggests that the activity of the outburst increased near the end of 1997 July. According to Nesci et al. (1998), in fact, the object showed a small amplitude intraday variability in the latter half of July with timescales of about one hour.

During our observing period, we obtained the longest dense data-sequence on 1997 August 2 (figure 3). The object was observed continuously for about 4.6 hr with observational errors of around 0.025 mag based on com-

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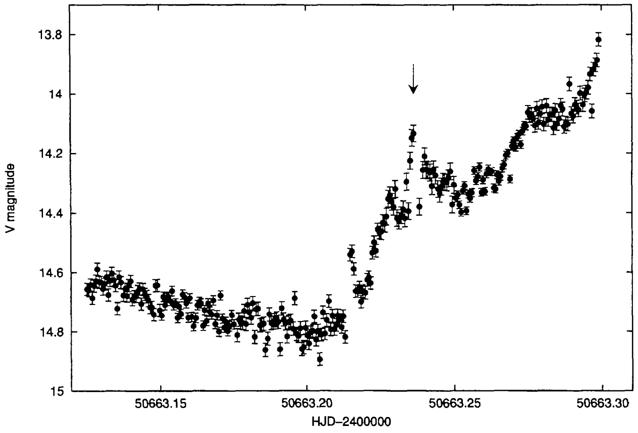

Fig. 3. V-band light curve of BL Lac on 1997 August 2 taken by the time-resolved CCD photometry at Ouda station. The horizontal axis represents Heliocentric Julian date (HJD) minus 2400000 days, and the vertical axis represents the V-magnitude. The light curve indicated the most dramatic variability of the object. A rapid large variation was detected with an amplitude of 0.6 mag (a downward arrow), but the duration of the variation was only about 40 min.

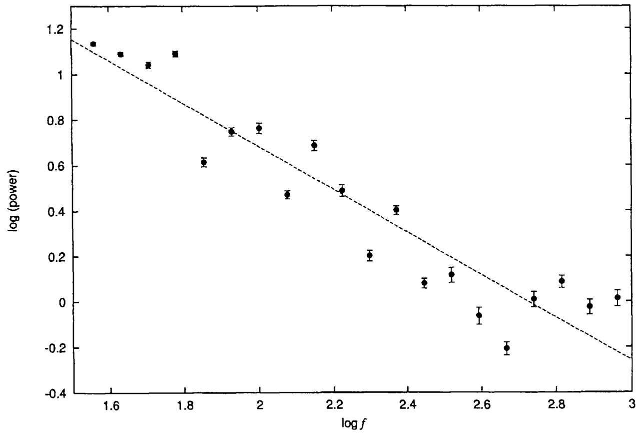

Fig. 4. Power-density spectrum of the light curve on 1997 August 2 (figure 3), plotted with a range of $\log(f) = 0.005$–0.03. The horizontal axis represents the logarithm of the frequency (d^{-1}), and the vertical axis represents the logarithm of the power. The power-density spectrum has an $f^{-1.0}$ trend, and the slope is constant to $\log(f) \sim 2.7$. The noise level suggests the existence of variations with a minimum timescale of about 10 min.

parisons between the comparison star (star **f**) and one of check stars (star **c**).

As can be seen from figure 3, the object gradually declined by 0.2 mag from HJD 2450663.125 to 2450663.20 in the first half of the light curve, and no definite short-term variation was detected during this period. The brightness of the object, however, changed to rise rapidly from HJD 2450663.20; this trend continued to the end of the night. The object thus finally increased its brightness by 1 mag in 2.4 hr. The light curve also indicated small modulations with very short durations of about 40 min; the typical amplitudes of the modulations were about 0.1 mag.

In addition, we found the most conspicuous feature on HJD 2450663.23 at the onset of the brightening state (marked by a downward arrow in figure 3). Although the clearly detected variation had an amplitude of 0.6 mag at maximum, the duration was only about 40 min, which is quite short for such a relatively large amplitude. The duration is comparable to the typical timescales of the microvariability characterized by the shortest timescale of a variation detected at optical wavelengths among AGNs, while the 0.6 mag amplitude is exceptionally large for that of the microvariability, which is typically around 0.1 mag. The unprecedented rapid variation corresponds to an approximately 70% change of the optical brightness within 40 min. We additionally detected spike-like small variations with amplitudes of 0.2–0.3 mag and durations of obviously less than 10 min on HJD 2450663.215 and 50663.228.

It is commented that no apparent variation was detected on the other ten nights, though the object indicated the most dramatic variability on August 2.

4. Discussion

The observation on August 2 indicated that BL Lac showed the most active intraday variability at optical wavelengths. As for the outburst of the object, Massaro et al. (1998) also presented V-band photometry and one of their observations corresponded to just following our observing period on that night. BVI simultaneous photometry during the same period of Massaro et al. (1998) appeared to Speziali and Natali (1998). A combination of the results obtained in Japan and Europe took a continuous $\sim$ 11 hr coverage of the object on that night. The combined light curve revealed a whole feature of the $\sim$ 1 mag hump with a duration of 7 hr, which demonstrated an active intraday variability of the object during the outburst.

While, the observations by the VSNET members revealed a detailed behavior of the object throughout the outburst. The light curve is characterized by quasi-periodic repeated variations with intervals of a few days and typical amplitudes of 1 mag; thus, the variations are connected to the intraday variability of the object during the outburst, which were reported by the other observations referred to above and in this paper.

As for the emissions of blazars, the most acceptable

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picture is synchrotron radiation and inverse Compton scattering of synchrotron photons within relativistic jets aligned to the line of sight (so-called synchrotron self-Compton model), which is suggested by the observed broad-band (radio–γ-rays) featureless spectra and the violent variabilities. The variabilities of blazars are considered to be caused by collisions between knotty regions (blobs) in the relativistic jet and their environments. Mastichiadis and Kirk (1997) revealed that the observed short-term spectral variability of a blazar Mkn 421 is the consequence of a sudden increase in the maximum energy of ejected non-thermal electrons, which could be due to such collisions.

We estimated an order of magnitudes of the size of a blob as the major flux source, based on the extreme short-term flux variation of 0.6 mag ($\approx$ factor of 1.7) detected on August 2. The timescale of 40 min of the rapid optical flare ($t_{\rm var}$) puts some constraints upon the size, adopting $t_{\rm var} = R/(c\delta)$,

$$R \sim 7.2 \times 10^{14} \left(\frac{t_{\rm var}}{40\ \rm min}\right)\left(\frac{\delta}{10}\right)\ \rm cm, \qquad (1)$$

where c and δ are the speed of light and Doppler boosting factor of the source, respectively. The value of δ which we used is typical for BL Lac objects (e.g., Sambruna et al. 1996).

We calculated the power-density spectrum of the light curve on August 2 in order to search for a minimum timescale of short-term variations (figure 4), because the $\sim$1 min time resolution is useful for resolving variabilities in shorter timescale on the blazar phenomena. The power-density spectrum reveals the best-fit power index of -0.94, i.e. $f^{-0.94} \approx f^{-1.0}$, and the slope is constant to around $\log(f) = 2.7$. The range of $\log(f) = 2.7$–3.0 represents the level of photon noise. We then subtracted this level from the power-density spectrum and fitted it again, and its result re-confirmed the trend of $f^{-1.0}$. The power above the noise level suggests the existence of variations with a minimum timescale of around 10 min in the optical-light curve.

It should be noted that since the spectrum was based on a single-night sequence, following tests will therefore be significant. The $f^{-1.0}$ frequency dependency of the power-density spectrum for optical variations is, however, clearly different from the canonical $f^{-1.5}$–$f^{-1.8}$ power-density spectrum observed in X-ray variations of usual AGNs (Lawrence, Papadakis 1993; Green et al. 1993; Hayashida et al. 1998), and this discrepancy suggests something essentially different mechanisms of short-term variability between BL Lacs and usual AGNs.

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