

## The WEBT BL Lacertae Campaign 2000

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**Abstract.** We present *UBVRI* light curves of BL Lacertae from May 2000 to January 2001, obtained by 24 telescopes in 11 countries. More than 15 000 observations were performed in that period, which was the extension of the Whole Earth Blazar Telescope (WEBT) campaign originally planned for July–August 2000. The exceptional sampling reached allows one to follow the flux behaviour in fine detail. Two different phases can be distinguished in the light curves: a first, relatively low-brightness phase is followed by an outburst phase, after a more than 1 mag brightening in a few weeks. Both the time duration (about 100 d) and the variation amplitude (roughly 0.9 mag) are similar in the two phases. Rapid flux oscillations are present all the time, involving variations up to a few tenths of mag on hour time scales, and witnessing an intense intraday activity of this source. In particular, a half-mag brightness decrease in about 7 h was detected on August 8–9, 2000, immediately followed by a  $\sim 0.4$  mag brightening in 1.7 h. Colour indexes have been derived by coupling the highest precision *B* and *R* data taken by the same instrument within 20 min and after subtracting the host galaxy contribution from the fluxes. The 620 indexes obtained show that the optical spectrum is weakly sensitive to the long-term trend, while it strictly follows the short-term flux behaviour, becoming bluer when the brightness increases. Thus, spectral changes are not related to the host galaxy contribution, but they are an intrinsic feature of fast flares. We suggest that the achromatic mechanism causing the long-term flux base-level modulation can be envisaged in a variation of the relativistic Doppler beaming factor, and that this variation is likely due to a change of the viewing angle. Discrete correlation function (DCF) analysis reveals the existence of a characteristic time scale of variability of  $\sim 7$  h in the light curve of the core WEBT campaign, while no measurable time delay between variations in the *B* and *R* bands is found.

**Key words.** galaxies: active – galaxies: BL Lacertae objects: general – galaxies: BL Lacertae objects: individual: BL Lacertae – galaxies: jets – quasars: general

## 1. Introduction

BL Lacertae is a well-known source that has been observed in the optical band for more than a century. It has been used to define a whole class of active galactic nuclei (AGNs), which are characterized by absence or extreme weakness of the emission lines, intense variability at all wavelengths, high polarization, and superluminal motion of radio components. The BL Lacertae objects, together with the flat-spectrum radio quasars, are known as “blazars”.

Although the details of blazar emission are under debate, the commonly accepted general scenario foresees a central black hole fed by an accretion disc, and a plasma jet which is responsible for the non-thermal continuum. In order to explain several observational pieces of evidence, the emitted radiation is assumed to be relativistically beamed towards us. The low-energy emission, from the radio band to the UV–X-ray region, is likely synchrotron radiation produced by ultra-relativistic electrons in the jet. The origin of the higher-energy radiation, up to  $\gamma$ -rays, is less clearly established: it is reasonable to suppose that the soft radiation produced by the synchrotron process can be inversely comptonized up to the  $\gamma$ -ray energies (SSC models), but it is also possible that the photons to be comptonized come from out of the jet, either directly from the accretion disc or from the broad line region (EC models). Recent observations seem to indicate that a mixture of SSC and EC processes may be at work in the blazar jets (see e.g. Madejski et al. 1999 and Böttcher & Bloom 2000 for the case of BL Lacertae). Another possibility is that the high-energy emission is produced by pair cascades coming from the interaction between soft photons and highly relativistic protons (proton models).

The violent flux variations observed in blazars have been explained in a variety of ways: shocks travelling down the jet (e.g. Marscher 1996), changes of the Doppler factor due to geometrical reasons (e.g. Dreissigacker & Camenzind 1996; Villata & Raiteri 1999), accretion disc instabilities (e.g. Wiita 1996), gravitational microlensing (e.g. Schneider & Weiss 1987). The observation of microvariability, that is of flux changes on time scales of less than a day, raises the question of what is the smallest time scale of variability in blazars and,

if the variations are of intrinsic nature, of how small the size of the emitting region can be.

Variability studies are thus a powerful tool to investigate blazar emission and to discriminate among the various theoretical interpretations, in particular when observations are done in a continuous way and simultaneously at different wavelengths. This is why in the last years optical observers have set up collaborations to make the observational effort more efficient.

The Whole Earth Blazar Telescope (WEBT; <http://www.to.astro.it/blazars/webt/>) is an international organization that includes about 30 observatories located all around the world. Its aim is to obtain accurate and continuous monitoring of a source during a time-limited campaign (from few days to several weeks), which is often organized in concert with satellite observations in the X- and  $\gamma$ -rays, and ground-based observations in the radio band and at TeV energies. The location at different longitudes of its members allows them to optimize observations during the 24 hours of the day, gaps due to daylight being, in theory, extremely small. In practice, limitations due to bad weather conditions, telescope overscheduling, technical problems are present, but in any case this monitoring strategy has already demonstrated that it can provide unprecedentedly dense sampling (see Villata et al. 2000 about the WEBT campaign on S5 0716+71 of February 1999, and Raiteri et al. 2001 about the first-light WEBT campaign on AO 0235+16 of November 1997), and even better results are expected by the robotization of at least some of the telescopes participating in the WEBT.

In this paper we report on *UBVRI* photometric monitoring of BL Lacertae during the summer 2000 WEBT campaign and its extension (May 2000–January 2001). The core optical campaign took place simultaneously with the planned high-energy campaign coordinated by M. Böttcher, involving X-ray and TeV observatories such as BeppoSAX, RXTE, CAT, and HEGRA (Böttcher et al. 2002). Previous WEBT campaigns on BL Lacertae had been organized in June 1999, in conjunction with observations by the BeppoSAX and ASCA satellites (Mattox 1999). The results of these campaigns are presented in Ravasio et al. (2002) and Villata et al. (2002).

The present paper is organized as follows: in Sect. 2 we review optical studies on BL Lacertae; the observing strategy and data reduction/assembling procedures are described in Sect. 3. *UBVRI* light curves are presented in Sect. 4, colour indexes are discussed in Sect. 5, and the autocorrelation study can be found in Sect. 6. Discussion and conclusions are drawn in Sect. 7.

## 2. BL Lacertae

The AGN BL Lacertae lies within an elliptical galaxy (Miller et al. 1978), at a distance  $z = 0.0688 \pm 0.0002$  (Miller & Hawley 1977). Ejection and evolution of four highly-polarized superluminal radio components moving on curved trajectories have been observed by Denn et al. (2000) with the VLBA.

One puzzling feature is that, although BL Lacertae stands as the prototype of a whole class of objects in which emission lines are absent or extremely weak, on some occasions broad  $H\alpha$  and  $H\beta$  emission lines were found in its spectrum, raising the issue of its membership to the class named after it (Vermeulen et al. 1995). Corbett et al. (2000) analysed eight spectra taken over a period of 30 months, from June 1995 to December 1997, and found that the equivalent width of the  $H\alpha$  line varies approximately inversely with the optical continuum flux: this suggests that the broad-line region is likely not photoionized by the beamed synchrotron radiation of the jet (which nevertheless cannot be ruled out), but by radiation coming from the hot accretion disc.

BL Lacertae has been observed for more than a century in the optical band, and it is well known for its intense variability on both long (months, years) and short (days or less) time scales. Since the early work by Racine (1970), microvariability was detected in optical observations of this source. Miller et al. (1989) observed a 0.12 mag variation in 1.5 h.

Carini et al. (1992) reported on 17 years of optical monitoring, in which the source exhibited “erratic” behaviour, its  $V$  magnitude varying between 14.0 and 16.0. From their  $B - V$  versus  $V$  plot no well-defined correlation between brightness and colour appeared, but a “bluer when brighter” trend is recognizable. The authors searched for microvariability, and found several episodes of variations as fast as  $0.1 \text{ mag h}^{-1}$ , the most rapid rate of change observed being  $0.19 \text{ mag h}^{-1}$ .

*BVRI* photometry of BL Lacertae in 1993–1995 was presented by Maesano et al. (1997), confirming the spectral flattening for a flux increase.

A big observing effort was undertaken during the summer 1997 broad optical outburst, announced by Noble et al. (1997). Subsequent circulars reported on high flux levels also in the  $\gamma$ - and X-rays (Hartman et al. 1997; Grove & Johnson 1997; Madejski et al. 1997; Makino et al. 1997).

Webb et al. (1998) carried out *BVRI* observations during the outburst, and found that variations were simultaneous in all bands, but of higher amplitude at the higher frequencies, and that there was a marginal evidence of a spectral flattening when the source brightens. These two latter features were recognized also in the microvariability events detected by Nesci et al. (1998) and Speziali & Natali (1998), presenting variations up to  $0.4 \text{ mag h}^{-1}$ . *VR* observations on 11 nights in July 1997 were performed by Clements & Carini (2001), who detected

nightly variations from 0.1 to 0.6 mag. They also found that BL Lac became bluer when brighter and commented that it is not clear whether the colour changes can be ascribed to the AGN or are rather due to a greater contribution from the underlying galaxy when the AGN is fainter. An extremely fast brightening of 0.6 mag in 40 min was detected by Matsumoto et al. (1999) on August 2, 1997, inside a larger flux increase of more than 1 mag between 17 and 19 UT, confirmed by Ghosh et al. (2000). In the same night, the decreasing phase of the flare was observed by Massaro et al. (1998) and Speziali & Natali (1998) as a variation of more than half a mag in about 2 h (see also Ghosh et al. 2000). Rapid and large-amplitude flux variations were also observed by Sobrito et al. (1999) and Tosti et al. (1999). These papers also contain extended light curves during the 1997 outburst.

During the optical outburst, the EGRET instrument on the Compton Gamma Ray Observatory revealed a  $\gamma$ -ray flux more than 4 times the previous detection, and a harder spectrum than before (Bloom et al. 1997). Moreover, a noticeable  $\gamma$ -ray flux increase observed on July 18–19 apparently preceded by several hours a brief optical flare. The RXTE and ASCA satellites detected an X-ray flux respectively 2–3.5 times and more than 3 times higher than measured by ASCA in 1995 (Madejski et al. 1999; Tanihata et al. 2000). The multiwavelength spectrum of BL Lac during the July 1997 outburst was examined by Böttcher & Bloom (2000) in terms of a homogeneous jet model.

Intraday variability was found also the next year, in summer 1998, when the source was in a fainter state (Massaro et al. 1999; Nikolashvili et al. 1999).

*VRI* photometry of BL Lacertae in 1997–1999 was presented by Fan et al. (2001): they detected microvariations with amplitude decreasing with increasing wavelength. They also analysed the correlation among bands, finding no time delay longer than 0.2 d.

An analysis of colour variability of BL Lac during the 1997 and 1999 outbursts was performed by Hagen-Thorn et al. (2002). They showed that in both cases the spectral energy distribution remained unchanged during the outburst, and that the spectrum was flatter in the more powerful outburst of 1997.

Since BL Lacertae is one of the few blazars for which time-extensive light curves exist, a number of investigations have been devoted to the search for periodicities in its flux variations.

Recurrent variations every 0.31, 0.60, and 0.88 yr were recognized by Webb et al. (1988) by means of a discrete Fourier transform (DFT) analysis of their light curves, extending from June 1971 to January 1985. No evidence of periodicity was found instead by Carini et al. (1992).

“Whitening” of time series was the method used by Marchenko et al. (1996; see also Hagen-Thorn et al. 1997) to search for periodicities in a 20-year long light curve of BL Lac: they found that only a long-term component of  $P = 7.8 \pm 0.2 \text{ yr}$  is statistically significant.

In their study of the long-term optical base-level fluctuations in AGNs, Smith & Nair (1995) identified a best-fit, well-defined cycle of 7.2 yr for the baseline meanderings shown by the 20-year BL Lac light curve of the Rosemary Hill Observatory. It is interesting to notice that the mere

**Table 1.** List of participating observatories by longitude.

Observatory	Tel. size (cm)	$N_{\text{obs}}$	$N_U$	$N_B$	$N_V$	$N_R$	$N_I$
Kyoto, Japan	25	607	0	0	0	77	0
Osaka Kyoiku, Japan	51	1209	0	0	56	463	53
Mt. Maidanak (AZT-22), Uzbekistan	150	447	59	100	59	131	57
Mt. Maidanak (T60-K), Uzbekistan	60	743	99	128	133	0	0
Abastumani, Georgia (FSU)	70	2743	0	0	0	1253	0
Crimean, Ukraine	20	2470	0	38	67	159	78
Nyrölä, Finland	40	40	0	0	0	40	0
Skinakas, Crete	130	630	0	313	0	314	0
Catania, Italy	91	1071	132	132	132	0	0
Vallinfreda, Italy	50	92	0	24	5	34	26
Monte Porzio, Italy	70	112	0	25	30	28	29
Perugia, Italy	40	673	0	0	76	527	63
Torino, Italy	105	900	0	83	57	578	54
Guadarrama, Spain	20	18	0	0	0	9	0
Roque de los Muchachos (KVA), La Palma	60	2018	0	148	1	401	0
Roque de los Muchachos (NOT), La Palma	256	74	0	7	0	58	9
Bell Farm, Kentucky	60	1	0	0	0	1	0
St. Louis, Missouri	35	176	0	69	17	72	17
Sommers-Bauch, Colorado	60	8	0	0	3	3	0
Lowell, Arizona	180	323	0	119	8	185	8
San Pedro Martir, Mexico	150	25	0	6	9	7	3
Palomar, California	150	108	0	54	0	54	0
Clarke and Coyote, California	28	248	0	0	0	91	0
University of Victoria, Canada	50	889	0	0	0	363	0
Total		15 625	290	1246	653	4848	397

$N_{\text{obs}}$  is the total number of observations done, i.e. the number of unbinned data;  $N_U$ ,  $N_B$ ,  $N_V$ ,  $N_R$ , and  $N_I$  are the numbers of data points in *UBVRI* remained after discarding and binning some of the original data

application of the Fourier analysis led the authors to derive a period of 7.7 yr, in fair agreement with the results obtained by Marchenko et al. (1996).

Fan et al. (1998) analysed the historical optical light curve of BL Lacertae with the Jurkevich method and derived a long-term period of  $\sim 14$  yr.

### 3. Observations during the WEBT campaign

Originally, the WEBT campaign was planned for the period July 17–August 11, 2000, that is from one week before to one week after the planned high-energy campaign (Böttcher et al. 2002). Simultaneous observations were also performed in the radio band from the University of Michigan Radio Astronomy Observatory (UMRAO) and from the Metsähovi Radio Observatory, in Finland.

At the campaign start, BL Lacertae was in a relatively faint phase. A subsequent, considerable brightening of the source in late September 2000 caused a campaign extension up to January 2001.

Data were finally collected from May 2000 to January 2001.

Table 1 shows the list of observatories which participated in the WEBT campaign. The name and country of the observatory (Col. 1) is followed by the telescope diameter (Col. 2), by the total number of observations done ( $N_{\text{obs}}$ , Col. 3), and by the number of data points in *UBVRI* derived, sometimes after binning (Cols. 4–8).

#### 3.1. Observing strategy

The participating observers were suggested to perform optical observations alternately in two bands (Johnson's *B* and Cousins' *R*, but other *R* filters were also accepted) in order to obtain a *BR* sequence of frames throughout each observing night. Exposure times were chosen in view of a good compromise between high precision and high temporal density. In those cases where high precision would have required gaps of 15–20 min in each light curve, it was suggested that observations be obtained in the *R* band only. As a matter of fact, intensive *B* monitoring was considered to be appropriate only for telescopes larger than 1 m. Moreover, at the beginning and end of the *BR* (or *R*-only) sequence, a complete set of filters (*U*)*BVRI* (Johnson-Cousins when possible) was suggested in

**Table 2.** Offsets given to the datasets in order to remove systematic differences; when a range is given, it means that different values were used in different nights; the accuracy of the offsets is similar to that of the corresponding datasets, ranging from less than 0.01 to about 0.05 mag; in few cases no comparison was possible and no offset was given.

Observatory	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>
Kyoto	–	–	–	0	–
Osaka Kyoiku	–	–	–0.05	–0.04–0	0
Mt. Maidanak (AZT-22; SITE)	0	0	0	0	0
Mt. Maidanak (AZT-22; ST-7)	–	–0.27––0.25	–0.10	–0.21––0.11	–0.10
Mt. Maidanak (T60-K)	–0.15	+0.10	+0.10	–	–
Abastumani	–	–	–	–0.04–+0.06	–
Crimean	–	–0.20	–0.05	–0.07––0.04	–0.05
Nyrölä	–	–	–	+0.01	–
Skinakas	–	0	–	+0.02	–
Catania	0	+0.05–+0.15	+0.05	–	–
Vallinfreda	–	+0.10	–0.05	0	–0.05
Monte Porzio	–	+0.10	–0.05	–0.07	–0.05
Perugia	–	–	0	0	0
Torino	–	–0.13––0.04	–0.10	–0.13––0.01	–0.10
Guadarrama	–	–	–	0	–
Roque de los Muchachos (KVA)	–	0	0	+0.02	–
Roque de los Muchachos (NOT)	–	+0.05	–	–0.01	–0.05
Bell Farm	–	–	–	0	–
St. Louis	–	0	0	+0.01–+0.02	0
Sommers-Bauch	–	–	0	+0.04	–
Lowell	–	+0.06	0	0	0
San Pedro Martir	–	–0.10	–0.10	–0.10	–0.10
Palomar	–	–0.05	–	–0.125	–
Clarke and Coyote	–	–	–	–0.04	–
University of Victoria	–	–	–	+0.04–+0.11	–

order to follow the whole optical spectrum behaviour of the source.

### 3.2. Data reduction and assembling

Data were collected as instrumental magnitudes of the source and reference stars, in order to apply the same analysis and calibration procedures to all datasets. Frame pre-reduction, i.e. bias/dark correction and flat-fielding, was performed by the observers. Instrumental magnitudes were obtained by either standard aperture photometry procedures or Gaussian fitting, in most cases by the observers themselves.

A minority of data came from photometer observations: these data were provided directly as standard magnitudes

A careful data assembling was required, since the whole dataset consisted of more than 15 000 observations coming from 22 different observatories, 24 different telescopes, and 25 different detectors.

The analysis was performed through the following steps:

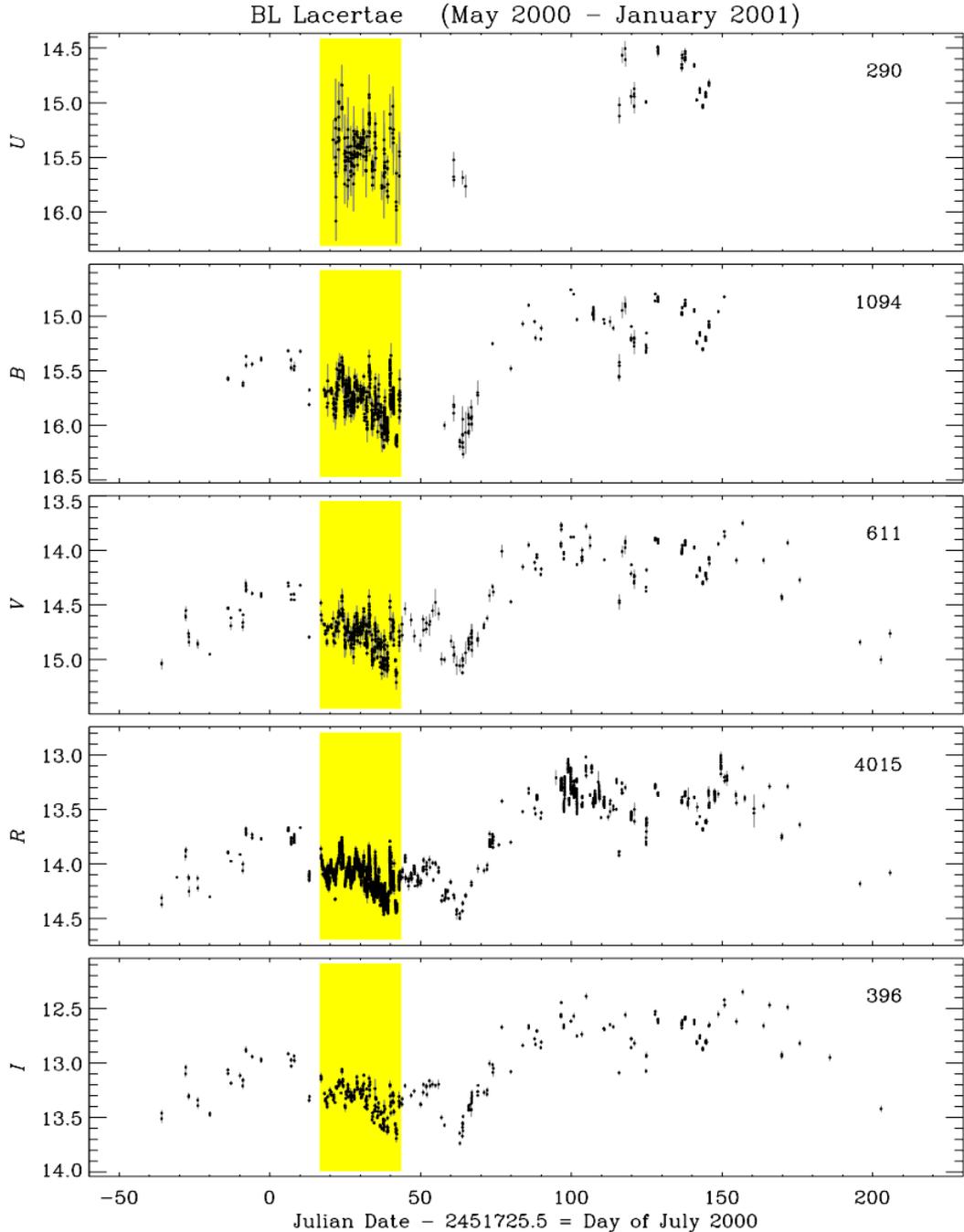
- Obtaining standard magnitudes of BL Lac from instrumental ones. Stars B C H K originally identified by Bertaud et al. (1969; their b c h k) were used as reference stars for

the magnitude calibration of the source. The photometry adopted was that published by Bertaud et al. (1969) for the *U* and *B* bands, and the one from Fiorucci & Tosti (1996) for the *VRI* bands<sup>1</sup>.

- Discarding bad and unreliable points.
- Binning the data when needed.
- Check of the final light curves for each observatory (see Table 1 for the relevant data numbers).
- Putting together different datasets, night by night.
- Estimating the offsets existing among different datasets (see Table 2) from overlapping data, and correcting them, night by night.
- Discarding less precise data in favour of higher-precision simultaneous data.

Table 3 shows the number of data points remained in the various bands at the end of the data assembling procedure (to be compared with the totals of Table 1, where the last step of the assembling procedure is not considered), and the minimum and maximum magnitudes reached.

<sup>1</sup> In the error calculation, calibration errors were not taken into account, since the main goal was to analyse flux variations, rather than to obtain a precise evaluation of the magnitude.



**Fig. 1.** *UBVRI* light curves of BL Lacertae from May 2000 to January 2001; the numbers on the right are the numbers of data points in each light curve; the grey (yellow in the electronic version) strip corresponds to the period of the core WEBT campaign.

**Table 3.** Number of points plotted in the *UBVRI* light curves; minimum and maximum magnitudes reached.

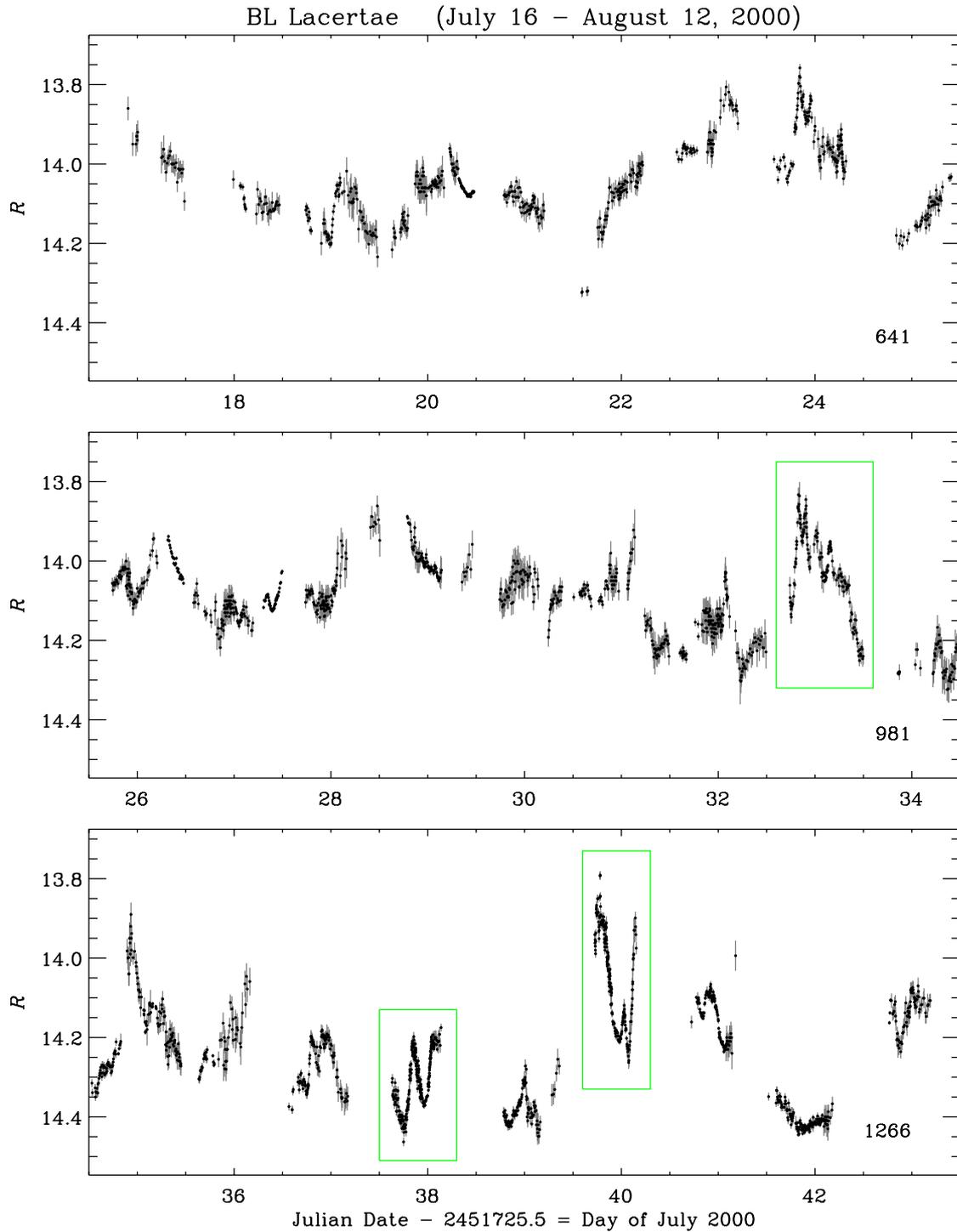
	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>
$N_{\text{points}}$	290	1094	611	4015	396
Min	14.49	14.76	13.75	13.01	12.35
Max	16.08	16.26	15.21	14.50	13.74

#### 4. *UBVRI* light curves

The *UBVRI* light curves of BL Lacertae from May 2000 to January 2001 are presented in Fig. 1. It is possible to identify

two well-defined phases: the first one starts with a moderate brightness increase, and sees the source in a relatively low brightness state; it ends after one hundred days, when the brightness drops to the minimum value (JD = 2451788,  $R = 14.50$ ). After that, a rapid brightening of more than 1 mag in a couple of weeks leads to the outburst phase, lasting again about one hundred days. The last available observations witness a final dimming to the pre-outburst levels.

In both the two mentioned phases, flux oscillations of several tenths of mag on day time scales are present, and it is interesting to notice that the total variation amplitude is



**Fig. 2.** Light curve in the *R* band during the core WEBT campaign.

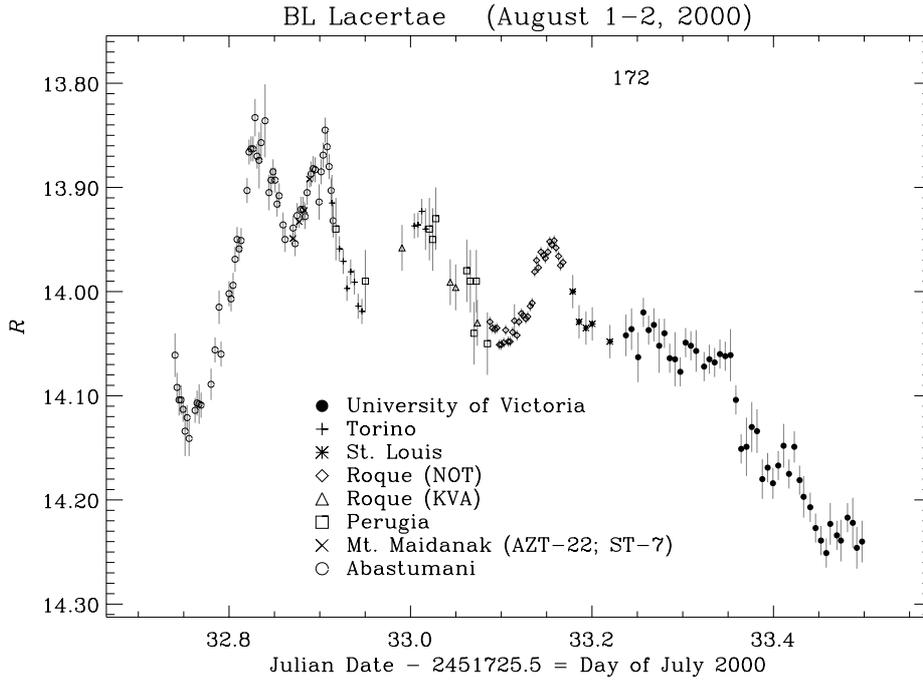
approximately the same (about 0.9 mag) in the pre-outburst and in the outburst periods, similar to the results reported for the 1997 outburst of BL Lac (Miller 1999).

One striking feature of Fig. 1 is the exceptional sampling obtained during the core WEBT campaign of July–August 2000, especially in the *R* band.

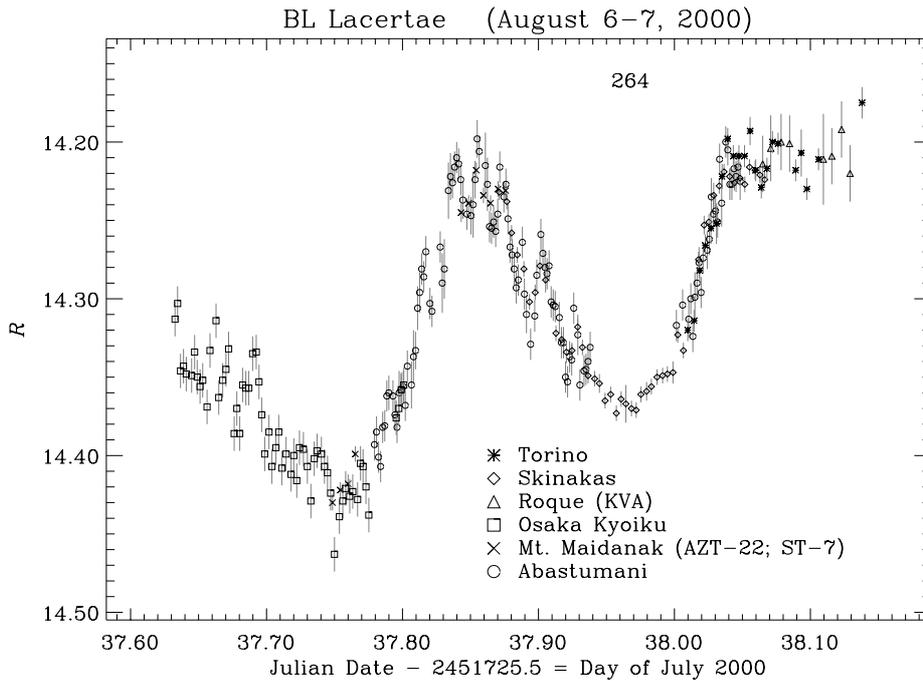
The details of the brightness behaviour in the *R* band during the core WEBT campaign are visible in Fig. 2. The most spectacular variability was detected (with high precision and

very good intranight sampling) during the last part of the campaign, plotted in the lower panel of Fig. 2. The boxes indicate periods of particularly interesting variations, which are shown in subsequent figures.

Data taken on August 1–2, August 6–7, and August 8–9, 2000 are plotted in Figs. 3, 4, and 5, respectively. The participating observatories are distinguished by different symbols demonstrating how the observing task moves from east to west as the Earth rotates.



**Fig. 3.** Light curve of BL Lacertae in the *R* band on August 1–2, 2000.



**Fig. 4.** Light curve of BL Lacertae in the *R* band on August 6–7, 2000.

One can notice that, in principle, it is possible to obtain a full-day observing coverage, when both the most eastern and western observatories work, thus succeeding in filling the “Pacific gap”. In practice, this gap is often present in the WEBT light curve, but it is limited to a few hours, which allows one to follow the brightness behaviour almost continuously.

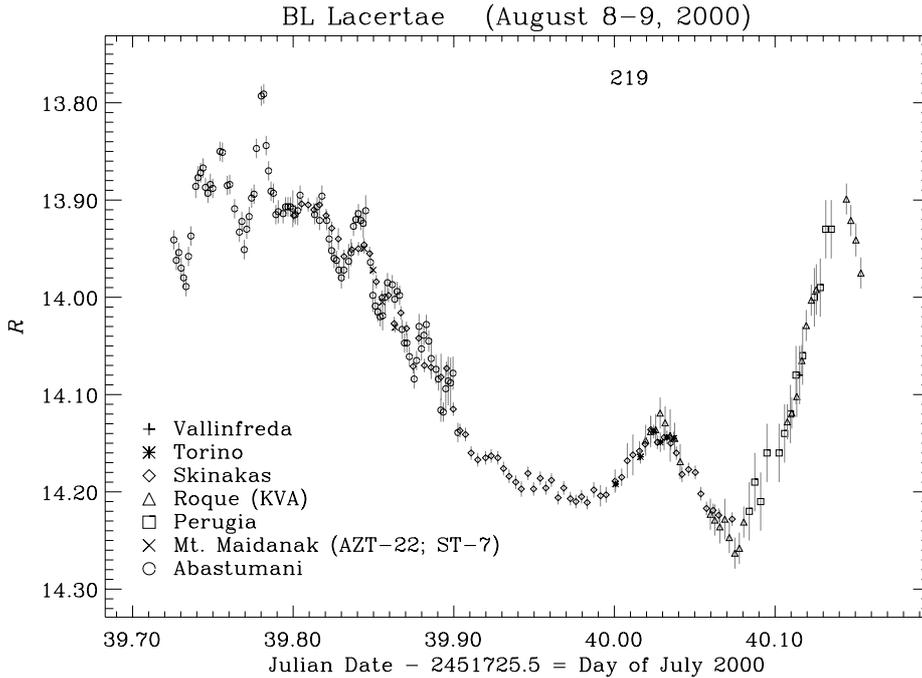
The most impressive variations were detected on August 8–9: a half-mag brightness fall in about 7 h, immediately followed by a very steep brightening of  $\sim 0.4$  mag in 1.7 h.

By looking at the individual flaring episodes in the light curve of Fig. 2, we can see that the most significant rising

branches (on July 19, 23, 31, August 1, 3, 6, 7, 9) present brightening rates ranging from  $0.11$  to  $0.22$  mag  $h^{-1}$ . Moreover, one can notice that, in general, rising slopes are steeper than dimming ones. However, since the observed events might be the result of the superposition of different “single” flares, any speculation about the time scales of the underlying brightening and dimming mechanisms is likely not very significant.

## 5. Colour indexes

We have seen that the brightness behaviour of BL Lacertae in the period examined here appears as the superposition of



**Fig. 5.** Light curve of BL Lacertae in the  $R$  band on August 8–9, 2000.

rapid flares, typically lasting for about a day or less, on a long-term trend, which is responsible for a transition from a relatively low brightness level to a higher brightness level around  $JD = 2451\ 800$ . It is now interesting to analyse the data in order to understand if the mechanism causing rapid flares is of the same nature as the one determining the long-term flux variations. One piece of information is likely to come from colour index analysis, which can reveal whether flux variations imply spectral changes or not.

Since the BL Lacertae host galaxy is relatively bright, we first subtracted its contribution from the observed fluxes in order to avoid contamination in the colour indexes.

According to Scarpa et al. (2000), the  $R$  magnitude of the BL Lacertae host galaxy is  $R_{\text{host}} = 15.55 \pm 0.02$ , adopting a host galaxy colour  $V - R = 0.61$ ; Mannucci et al. (2001) derived an average effective colour for elliptical galaxies with  $M_V < -21$  of  $B - V = 0.99 \pm 0.05$ . The inferred  $B$ -band host galaxy magnitude is thus  $B_{\text{host}} = 17.15$ .

Actually, the above magnitudes represent extrapolations to infinity, while an aperture radius of 8 arcsec (to be compared with the 4.8 arcsec half-light galaxy radius given by Scarpa et al. 2000) was suggested in the data reduction for the source measure, together with radii of 10 and 16 arcsec for the edges of the background annulus. By using these parameters and a de Vaucouleurs  $r^{1/4}$  profile, we estimated that the host galaxy contribution to the observed fluxes is only 59.65% of the whole galaxy flux.

We then transformed both the observed and the host galaxy  $B$  and  $R$  magnitudes into dereddened fluxes by using the coefficient of Galactic extinction in the  $B$  band  $A_B = 1.420$  given by NED and by deriving extinction in the Cousins'  $R$  band by means of Cardelli et al. (1989):  $A_R = 0.9038$ . Fluxes relative to zero-mag values were taken from the photometric calibration of Bessell (1979). The  $B$  and  $R$  host galaxy fluxes (2.175 mJy and 4.266 mJy, respectively) were reduced by a factor 0.5965 and

then subtracted from the observed fluxes, and the point source (reddened) magnitudes derived from the “cleaned” fluxes.

$B - R$  colour indexes were calculated by coupling  $B$  and  $R$  data taken by the same instrument within 20 min (in most cases the time separation between the coupled data is in the range 2–4 min). Only  $B$  and  $R$  data with errors not greater than 0.04 and 0.03 mag, respectively, were considered.

The plot of the resulting 620  $B - R$  indexes as a function of time (see Fig. 6) suggests that colours are more sensitive to rapid variations than to the long-term trend.

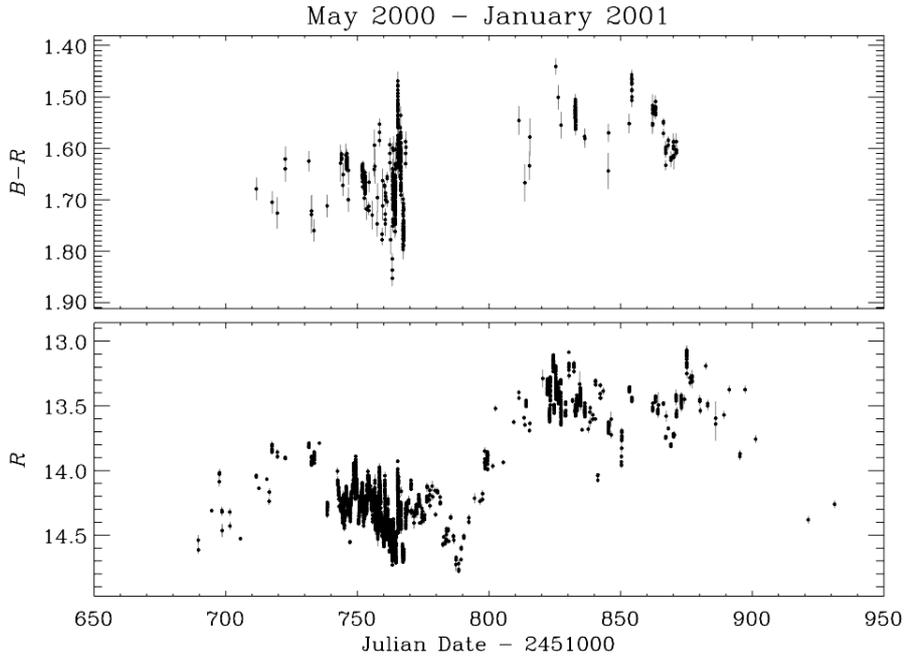
Moreover, during well sampled flares the  $B - R$  index strictly follows the flux behaviour, as shown by Fig. 7, which presents an enlargement of Fig. 6 during the fourth week of the core WEBT campaign. In this sense, we can say that fast flares are due to a chromatic mechanism, which causes a spectral flattening when the source brightens.

Figure 8 (upper panel) shows the  $B - R$  versus  $R$  plot. Points are distributed over two separated regions of the figure, according to the brightness level of the source, with a boundary at  $R \sim 14.1$ . However, inside each region, the colour indexes seem to follow a trend with a similar slope: a bluer-when-brighter behaviour, as already noticed in Fig. 7 for the short-term flares. On the contrary, the long-term variations appear as essentially achromatic.

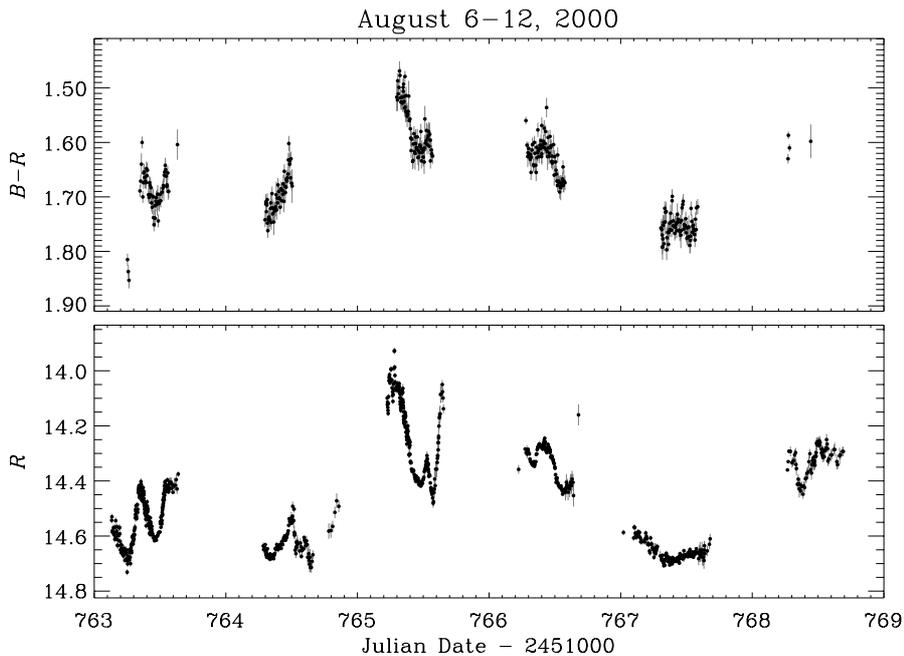
In order to verify the supposed existence of two different mechanisms acting on different time scales, we have tried to model the long-term trend as a modulated base contribution to the source flux density, on which the short-term flares are superposed. We expect that, once fluxes are corrected for this contribution, the  $B - R$  versus  $R$  plot will contain the signature of one component only, i.e. the chromatic one.

The first step has been to define a flux base level lapping on the flux minima of the  $R$  light curve.

Data in the  $R$  band were first binned daily for removing effects due to intranight dense sampling, and then binned



**Fig. 6.** Temporal evolution of  $B - R$  colour index (upper panel) and  $R$  magnitude (lower panel) after subtracting the host galaxy contribution from the fluxes.



**Fig. 7.** Temporal evolution of  $B - R$  colour index (upper panel) and  $R$  magnitude (lower panel) during the last week of the core WEBT campaign, after subtracting the host galaxy contribution from the fluxes.

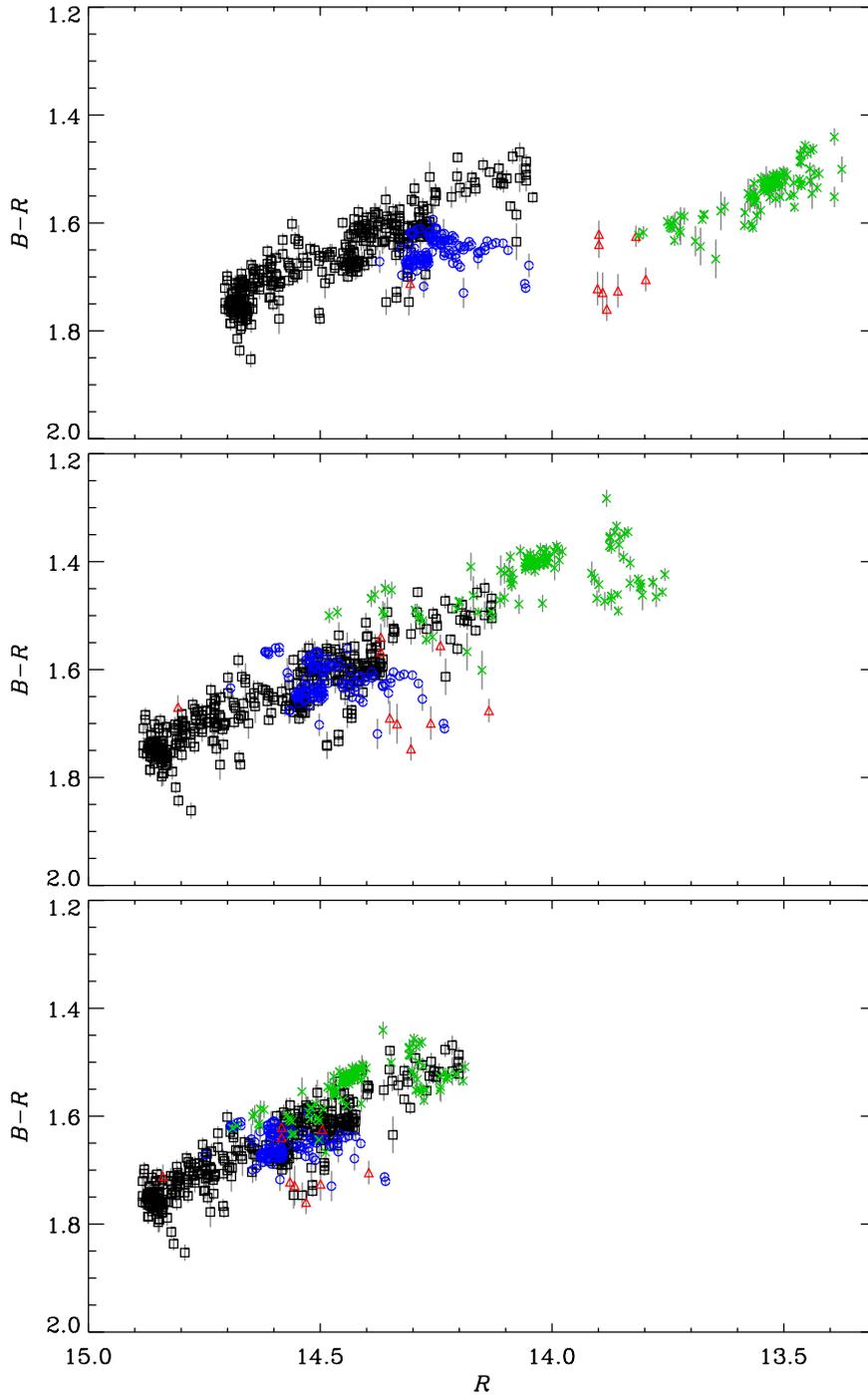
over 10 d; the binned light curve was then fitted with a cubic spline interpolation (Press et al. 1992). The  $R$  light curve was divided into two zones, corresponding to the pre-outburst ( $\text{JD} < 2451\,790$ ) and outburst phases. The previously derived spline was then proportionally rescaled to pass through the minima of each zone. The result can be seen in Fig. 9, where the upper, grey (green in the electronic version) line traces the original cubic spline interpolation, while the lower, dark (blue) line shows the rescaled spline, representing the pursued base-level modulation due to the achromatic mechanism mentioned above<sup>2</sup>.

<sup>2</sup> A 10 d smoothing time scale appeared as the most suitable choice: a shorter one would have been too sampling dependent; a longer

The same spline was used to find the base-level modulation for the  $B$ -band fluxes, by proportionally rescaling it to pass through the minimum flux. The resulting flux ratio of the base levels is  $F_R/F_B = 2.332$  ( $B - R = 1.787$ ).

By seeing Fig. 9, one might object that only a few minimum points are very close to the base level, even when the sampling is good and many local minima could be identified. The point is that local minima are most likely not states where the flaring activity is out: they are presumably due to the superposition

one would have smoothed too much the evident long-term variations which are visible in the best-sampled periods. In any case, changes of the binning interval in the range 5–30 d do not affect the final results sensitively.



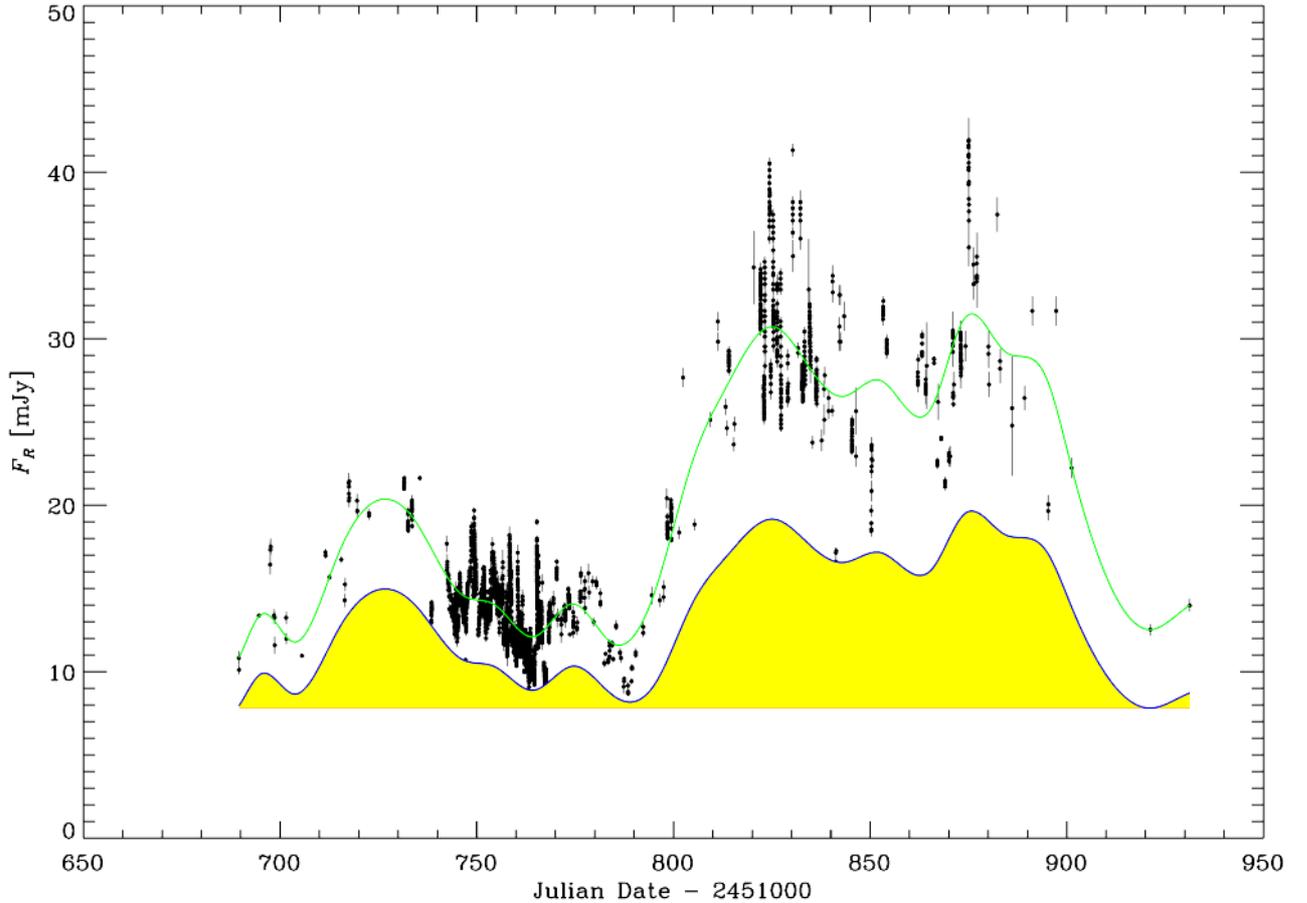
**Fig. 8.**  $B-R$  colour index versus  $R$  magnitude (after subtracting the host galaxy contribution from the fluxes) for uncorrected data (upper panel), for data corrected by subtracting the base-level modulations modelled as a cubic spline (middle panel), and for data further corrected for Doppler factor variations (lower panel); different symbols refer to different flux levels of the spline (see Fig. 9):  $<10$  mJy (black squares), between 10 and 12.5 mJy (blue circles), between 12.5 and 15 mJy (red triangles), and  $>15$  mJy (green crosses).

of different events started at different times. On the contrary, the detection of “no flaring” may be a very rare event, if ever happens.

Fluxes were then “corrected” for their respective base levels by subtracting the shaded (yellow) area shown in Fig. 9 from the  $R$  fluxes, and analogously for the  $B$  fluxes. “Corrected”  $B-R$  and  $R$  values were finally obtained by  $B-R = 2.5 \log(F_R/F_B) + 0.868$ ,  $R = -2.5 \log F_R + 17.125$ , where the constants take both

the zero-mag fluxes and the Galactic extinction coefficients into account.

The new  $B-R$  versus  $R$  plot is shown in Fig. 8 (middle panel): apart from a few points mainly coming from the low-brightness peak of the spline (red triangles, see caption to the figure), most of the points are now following a single linear trend, confirming the starting assumption that an achromatic mechanism produces the base-level variations.

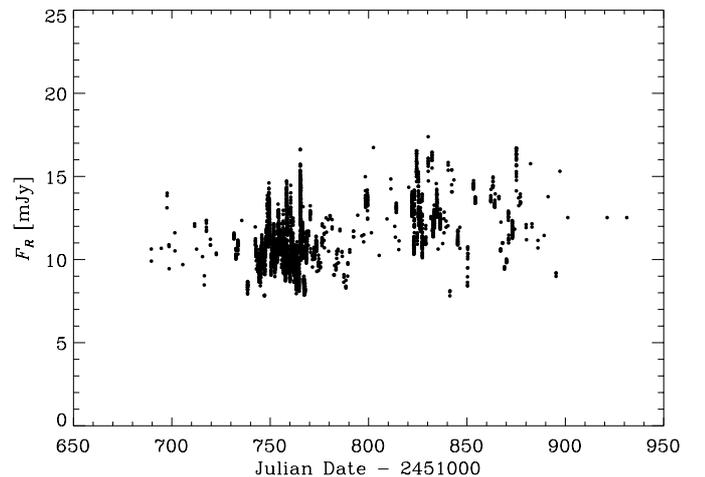


**Fig. 9.** *R*-band fluxes (mJy) after subtraction of the host galaxy contribution as a function of JD; cubic spline interpolation through the binned light curve is represented by the grey (green) line; the rescaled spline (see text for explanation) is shown by the dark (blue) line.

However, one can notice that the distribution of data points corresponding to the outburst phase [grey (green) crosses] still extends to higher brightness levels. This is the consequence of the greater amplitude exhibited by the flux variations in the outburst state (see Fig. 9). We have already noticed that, in the logarithmic scale of magnitudes, variation amplitudes are comparable in the pre-outburst and in the outburst phases, which means that flux amplitudes are proportional to the flux level.

We can thus further refine our model for the flux base-level variations, by assuming that the achromatic mechanism is also responsible for the brightness-dependence of the variation amplitudes. A simple explanation for this is obtained by assuming that the base-level oscillations are the result of the variation of the relativistic Doppler factor  $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$ , where  $\Gamma$  is the Lorentz factor of the bulk motion of the plasma in the jet and  $\theta$  is the viewing angle, since fluxes are enhanced proportionally to a certain power of  $\delta$  by relativistic boosting.

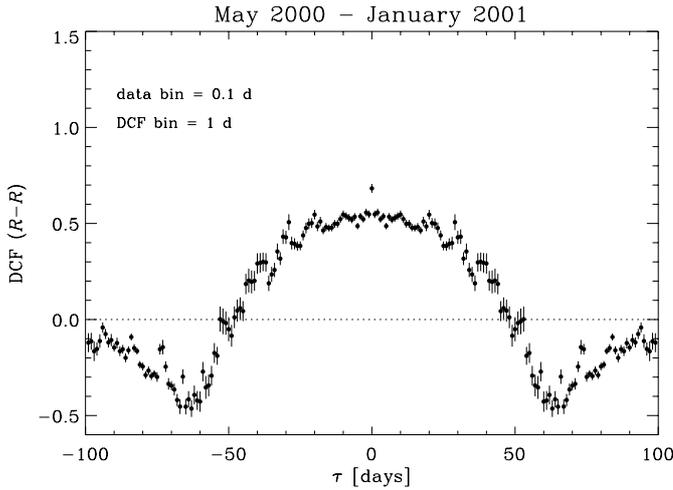
In order to clean the observed fluxes for this effect, we derived “corrected” fluxes by rescaling each original flux by the ratio between the minimum value of the spline and the value of the spline at the considered time. In this way, we obtain fluxes normalized to the value of  $\delta$  where the spline has its minimum, thus eliminating the effects of the  $\delta$  variation, in terms of both the base-level variations and the different variation amplitudes. The resulting “cleaned” light curve is shown in



**Fig. 10.** *R*-band fluxes after subtraction of the host galaxy contribution and correction for the mechanism responsible for the base-level variations (see text for explanation).

Fig. 10: the variation amplitude is now comparable over all the period, which should mean that we are now seeing the behaviour of the chromatic component alone.

As for the colour indexes, we derived  $B - R$  and  $R$  values from corrected fluxes as already done in the previous case; the bottom panel of Fig. 8 displays the final result: all data fall in a



**Fig. 11.** Autocorrelation function for the uncorrected, galaxy-subtracted  $R$ -band fluxes.

narrower brightness range, as expected, and the linear correlation appears better defined.

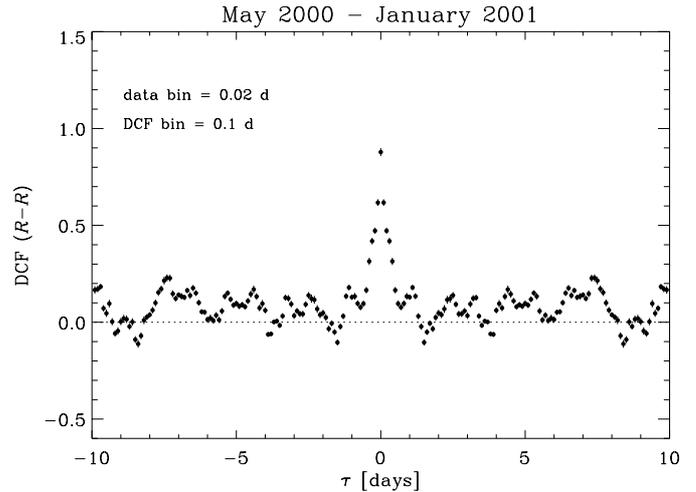
## 6. Time correlations

In the Introduction we mentioned a number of studies devoted to the search for periodicities in the BL Lacertae light curves. The derived periods range from 0.31 to 14 yr. The light curves obtained by the WEBT collaboration extend to  $\sim 240$  d, so that possible periodicities longer than, say, a couple of months cannot be looked for. On the other hand, the dense sampling allows one to test the existence of characteristic times of variability down to very short periods.

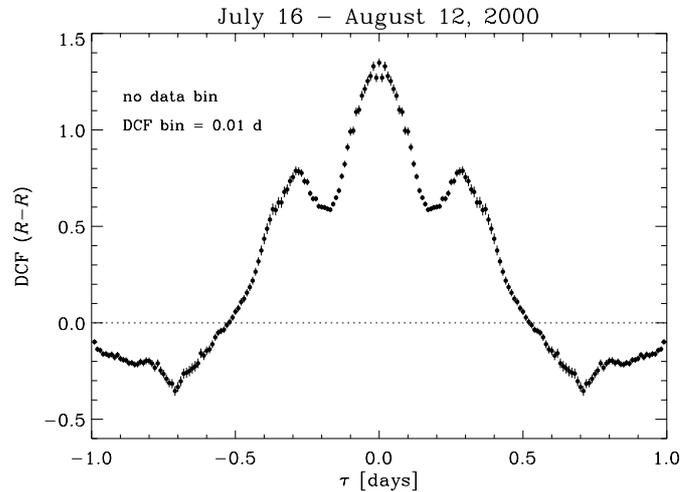
We applied the discrete correlation function (DCF) method (Edelson & Krolik 1988; Hufnagel & Bregman 1992) to the BL Lacertae fluxes, paying attention to the edge effects, as warned by Peterson (2001). Figure 11 shows the autocorrelation of the uncorrected, galaxy-subtracted  $R$ -band fluxes, with a 100 d maximum lag. The central, wide maximum tells us that the  $R$  light curve continues to correlate with itself for time shifts shorter than a month; for larger time lags the pre-outburst phase starts to overlap significantly with the outburst one, and the DCF drops to negative values, implying anticorrelation. No significant feature appears, which means that no reliable characteristic variability time scale is found.

Correction of fluxes for variation of the Doppler factor as described in the previous section removes the signature of the long-term trend. As one can see in Fig. 12, where the autocorrelation for the corrected  $R$ -band fluxes is presented (zoomed on smaller time lags), also in this case no significant time scale is recognizable.

However, if we restrict the DCF analysis to the data from the core WEBT campaign (see Fig. 2), we see that a not negligible signal comes out at a  $\sim 7$  h time scale, as shown by Fig. 13. This feature is particularly evident in the second and fourth weeks of the core campaign. Nevertheless, one has to notice that its significance might be affected by the lack of information during observing gaps.



**Fig. 12.** Autocorrelation function for the  $R$ -band fluxes after subtracting the host galaxy contribution and correcting for Doppler factor variation.



**Fig. 13.** The same as Fig. 12, but restricted to the core WEBT campaign and zoomed on short time scales.

In the above analysis we have neglected that not only fluxes, but also time scales are affected by Doppler boosting. A reliable temporal analysis should take this into account.

It is known that time intervals are changed by a factor  $\delta^{-1}$  by relativistic Doppler effect. Under the assumption that fluxes  $F$  are modified proportionally to  $\delta^3$ , we have that  $\delta(t)/\delta_{\min} = [F(t)/F_{\min}]^{1/3} = [s(t)/s_{\min}]^{1/3}$ , where  $s(t)$  is the value of the spline representing the flux base-level variations at time  $t$ , and  $s_{\min}$  is the spline minimum. Consequently, the corrected time  $t'_n$  for the  $n$ th data point can be calculated as

$$t'_n = t'_{n-1} + \Delta t_n \left[ \frac{\int_{t_{n-1}}^{t_n} s(t) dt}{\Delta t_n s_{\min}} \right]^{1/3},$$

where  $\Delta t_n = t_n - t_{n-1}$  is the observed time interval between the  $(n-1)$ th and  $n$ th data points.

By applying the above time correction to the  $R$ -band light curve, the total duration of the observing period dilates from 241.71 to 285.57 d.

As for the *R*-band flux autocorrelation, time correction does not introduce any significant change in the results: the  $\sim 7$  h characteristic time scale of variability is confirmed, and no other signal comes out.

Finally, DCF analysis has been applied to search for the possible existence of time delays between the flux variations in the *B* and *R* bands: no significant measurable (greater than a few minutes) delay has been found.

## 7. Discussion and conclusions

15 625 (=  $5^6$ ) observations were performed in the period May 2000–January 2001 by 24 telescopes of the WEBT collaboration to monitor the optical variability of BL Lacertae.

An exceptional sampling was reached, especially during the core WEBT campaign (July 17–August 11, 2000), where time gaps were limited to a few hours and they were essentially due to the lack of observers in the Pacific area.

Well-defined intranight trends were detected, with variations up to 0.4 mag in less than 2 h.

Colour index analysis performed after subtracting the host galaxy contribution from fluxes suggests the existence of at least two variability mechanisms: the first one is essentially achromatic, and is responsible for the long-term trend, while the second one, causing the fast flares superposed on the long-term trend, implies spectral changes, the spectrum becoming flatter when the source gets brighter. A similar behaviour was already found in the BL Lac object S5 0716+71 by Ghisellini et al. (1997).

As mentioned in the Introduction, Clements & Carini (2001) argued that the bluer-when-brighter behaviour might be due to a greater host galaxy contribution when the AGN is fainter. Since we subtracted the host galaxy contribution and still found the bluer-when-brighter trend (and only for short-term variations), we conclude that spectral changes are not related to the host galaxy contribution, but are an intrinsic property of fast flares.

The behaviour of the achromatic component determining the flux base-level modulations can be interpreted in terms of variation of the relativistic Doppler factor  $\delta$ . By assuming that fluxes are enhanced proportionally to  $\delta^3$  by relativistic boosting, a maximum variation of  $\delta$  of a factor 1.36 is inferred. This change in  $\delta$  can be due to either a viewing angle variation of few degrees ( $\Delta\theta \sim 1\text{--}4^\circ$ ) or a noticeable change of the bulk Lorentz factor (more than 50%). From this point of view our interpretation would suggest that the flux base-level modulations are more likely explained by a geometrical effect than by an energetic one.

In a geometrical scenario such as that proposed by Villata & Raiteri (1999), where viewing angle variation is due to rotation of an inhomogeneous helical jet, a rate of few degrees (say,  $1\text{--}3^\circ$ ) in a month (as can be inferred from the steepest base-level variations, see Fig. 9) would imply an upper limit to a possible periodicity of 10–30 yr. Indeed, in that model, a perfect helix would give rise to a perfect periodicity of well-defined outbursts; if the helical path presents distortions, the outburst phase (which can last for a significant fraction of the

period) is consequently disturbed by modulated events whose steepest variations represent a lower limit to the rotation rate.

We performed discrete autocorrelation analysis in order to search for the existence of intermediate-short characteristic time scales in our observing period. Variability on a typical time scale of  $\sim 7$  h was found during the core WEBT campaign.

Cross-correlation analysis on the *B* and *R* fluxes does not reveal any significant time lag between variations in the two bands.

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