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OPTICAL VARIABILITY OF BL LACERTAE DURING THE MAJOR OUTBURST OF 1997

K. K. GHOSH,[1,2,3] B. D. RAMSEY,[1] A. C. SADUN,[4] S. SOUNDARARAJAPERUMAL,[2] AND J. WANG[5]
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ABSTRACT

We have undertaken an investigation of recent flux variability in BL Lac. We present optical observations taken over 22 nights documenting major as well as minor outbursts. This has been combined, for purposes of multifrequency analysis, with published X-ray and γ-ray data taken for an additional single night. On two nights in particular, including the night of the X-ray observations, a major outburst of about a full magnitude of variation was recorded. All the data have been analyzed with theoretical models. Attempts were made to use synchrotron self-Compton and external Comptonization models to explain the data; however, both classes of models were found lacking. More satisfactory results were obtained using an analytical model proposed by Wang et al. that involves the evolution of synchrotron spectra in a homogeneous jet due to the injection of relativistic electrons, taking into account radiation losses during the outbursts. It is hoped that the results of this study of BL Lac, an archetype for the class of blazars in general, represent a more generic phenomenon applicable to the entire class.

Subject headings: BL Lacertae objects: individual (BL Lacertae) — galaxies: active — galaxies: nuclei

1. INTRODUCTION

BL Lac is the prototype of the BL Lacertae class of objects (Strittmatter et al. 1972) and resides at the center of a giant elliptical galaxy which is at a redshift of 0.069 (Miller, French, & Hawley 1978; Stickel & Kuehr 1994 and references therein). It is a highly polarized object at radio ($\sim$10.0%; Gabuzda et al. 1989), infrared ($\sim$15.1%; Impey et al. 1984), and optical (23.0%; Angel & Stockman 1980) wavelengths. Both frequency dependence of polarization and frequency dependence of position angle were observed in the infrared and optical polarization measurements of this blazar (Mead et al. 1990). Sitko, Schmidt, & Stein (1985) have found that the radio and optical polarizations are correlated. BL Lac is a superluminal radio source (Vermeulen & Cohen 1994). EGRET observations between 1995 January 24 and February 14 have also detected γ-ray emissions from this object (Catanese et al. 1997). However, there is no evidence of TeV emissions from this blazar (Kerrick et al. 1995).

Optical observations of BL Lac have been carried out for about 100 years. It has been found from the historical light curves of this source that it displayed large amplitude variations (4.3 mag in the *B* band) over 400 days with the faintest magnitudes at $B = 17.99$ and $V = 16.73$ mag (Shen & Usher 1970; Webb et al. 1988; Carini et al. 1992; Fan et al. 1998). BL Lac is also known as a microvariable source that displayed variability from 0.1 to 0.2 mag hr^{-1} (Racine 1970; Miller, Carini, & Goodrich 1989; Carini et al. 1992). It underwent a major outburst during the first half of 1993 (Tornikoski et al. 1994) and another in 1997 July (Ma & Barry 1997; Maesano et al. 1997; Noble et al. 1997; Massaro et al. 1998; Nesci et al. 1998; Speziali & Natali 1998; Webb et al. 1998; Matsumoto et al. 1999). During the 1997 July optical outburst, flares in flux were also recorded in the keV (Makino et al. 1997; Madejski et al. 1997), MeV (Grove & Johnson 1997), and GeV (Bloom et al. 1997) bands for this blazar. Between the two outburst episodes of 1993 and 1997, BL Lac was almost in a steady state with small amplitude variations centering around $V = 15.5$ mag.

However, from the above we can see that BL Lac rarely displays large amplitude variations (about 1 mag or more) over a timescale of a day or less (Carini et al. 1992; Fan et al. 1998 and references therein). We observed this source during the major outburst of 1997, combined our data with published results, and found an impressive flare profile of BL Lac that shows dramatic variations of this source by more than a magnitude on the timescale of hours. In this paper we present these results in the framework of the electron injection model (Wang et al. 1999). Section 2 describes the observations and data analysis, § 3 contains the results, and § 4 presents the discussion.

2. OBSERVATIONS AND DATA ANALYSIS

BL Lac was observed on 12 nights between 1997 August 2 and October 8 at the Vainu Bappu Observatory (VBO), Kavalur, India. The log of these observations is given in Table 1. These optical observations were carried out using the 2.34 m (at the f/3.23 prime focus of the Vainu Bappu Telescope [VBT]) and the 1.02 m (at the f/13 Cassegrain focus) telescopes of VBO. *B* (4400 Å/1050 Å), *V* (5425 Å/1050 Å), and *I* (8150 Å/1700 Å) broad filters were used for our observations with the CCD camera systems. Many bias frames were obtained before, during, and after observations on each night to obtain a nightly mean bias value. Also, many sky (evening and morning twilight sky) flats were obtained with each filter to remove the pixel-to-pixel quantum efficiency variations using the median flat. The sky conditions were mostly nonphotometric and the seeing was between 2.''0 and 2.''5. The IRAF-DAOPHOT digital aperture reduction program (Stetson 1987, 1990) was used for the photometry. Two nonvariable stars with magnitude similar to that of the blazar were selected and were used as

[1] Postal address: NASA/Marshall Space Flight Center, Space Science Department, SD50, Huntsville, AL 35812; kajal.ghosh@msfc.nasa.gov, brian.ramsey@msfc.nasa.gov.

[2] Indian Institute of Astrophysics, Bangalore 560 034, India; soundar@iiap.ernet.in.

[3] NAS/NRC Research Associate; on leave from the Indian Institute of Astrophysics, India.

[4] University of Colorado at Denver, Department of Physics, Campus Box 157, P.O. Box 173364, Denver, CO 80217-3364; asadun@carbon.cudenver.edu.

[5] Yunnan Observatory, Chinese Academy of Sciences, China; jcwang@public.km.yn.cn.

TABLE 1

LOG OF OPTICAL OBSERVATIONS OF BL LAC AT VBO

Date of Observations	Telescope (m)	Number of Observations	UT (start)	Total Exposure (s)	Filter
1997 8 02	2.34	9	16:44	2700	*I*
1997 8 23	1.02	7	20:02	4200	*B*
1997 8 29	1.02	6	18:41	10,800	*B*
1997 8 31	1.02	6	18:06	10,800	*B*
1997 9 01	1.02	5	20:22	9000	*B*
1997 9 13	1.02	2	17:00	3600	*B*
1997 9 14	1.02	2	20:58	3600	*B*
1997 9 19	1.02	2	16:46	3600	*B*
1997 9 26	1.02	1	17:58	1800	*B*
1997 9 28	1.02	2	16:51	3600	*B*
1997 9 28	2.34	1	18:16	600	*B*
1997 10 08	2.34	4	16:14	7200	*V*

the comparison stars. Details of the CCD systems and of the data analysis are given in Ghosh et al. (2000).

Table 2 shows the log of observations of BL Lac that were observed on 10 nights between 1997 November 15 and 1998 April 30. Direct CCD (1530 × 1020 pixels) observations of this blazar were carried out at the f/8 Cassegrain focus of the 0.61 m reflector of the Sommers-Bausch Observatory (SBO) of the University of Colorado at Boulder. The ST-8 CCD camera system was used with 3 × 3 binning. This gives a plate scale of around 0″.9 pixel^{-1}. *B* (4400 Å/980 Å), *V* (5500 Å/890 Å), and *R* (7000 Å/2200 Å) broadband filters were used for our observations. Many bias, dark, and flat-field frames were obtained on each night.

Bias or thermal frame–subtracted and flat-field–corrected CCD images for each filter were analyzed using the MIRA A/P software package. Aperture photometry on the CCD frames was carried out using an aperture on the source and an annulus around the source, giving source plus sky and sky background counts, respectively. A similar procedure was followed with a number of comparison stars whose magnitudes were obtained from Smith et al. (1985). The ratio of the source and comparison star counts gives a difference in magnitude between the two. A comparison star with tabulated magnitude values then yields the source magnitude. The absolute error incorporates the errors associated with the published magnitudes of the comparison stars. Those errors, when properly weighted, are added to the instrumental error in quadrature to get the absolute error. Details of data and error analysis are given in Ghosh et al. (2000).

TABLE 2

LOG OF OPTICAL OBSERVATIONS OF BL LAC AT SBO AND RESULTS

Date of Observations	JD (2,450,000+)	UT	Filter	Magnitude
1998 4 29	932.826	7:49	*B*	15.009 ± 0.021
1998 4 30	933.834	8:00	*B*	15.026 ± 0.024
1997 12 31	813.633	3:11	*V*	14.876 ± 0.035
1998 4 29	932.829	7:53	*V*	13.974 ± 0.018
1998 4 30	933.837	8:04	*V*	14.020 ± 0.019
1997 11 17	769.618	4:12	*R*	14.756 ± 0.023
1997 11 19	771.713	5:07	*R*	14.510 ± 0.040
1997 12 15	797.685	4:26	*R*	14.037 ± 0.024
1997 12 31	813.591	2:11	*R*	14.188 ± 0.028
1998 1 02	815.610	2:38	*R*	14.186 ± 0.028
1998 1 09	822.611	2:39	*R*	13.970 ± 0.027
1998 1 19	832.543	1:01	*R*	13.943 ± 0.023
1998 1 30	843.597	2:19	*R*	13.374 ± 0.022

3. RESULTS

The results of our short-term differential photometry of BL Lac are plotted in Figures 1–5 for observations between 1997 August 2 and September 1. Differences in magnitudes of BL Lac and the comparison star 1 (S1) and comparison star 2 (S2) are plotted in the top two panels (*a*, *b*), and the lowest panels (*c*) of these figures show the differences in magnitudes between the two comparison stars (S1 − S2). During the interval of our observations, we have found that BL Lac displayed remarkable variations on the night of 1997 August 2. On this night we observed the object in the *I* band between 16:40 and 18:48 UT. It can be seen from the lowest panel (*c*) of Figure 1 that the two comparison stars did not vary during the interval of our observations. However, the top two panels (*a*, *b*) of this figure show the increase in brightness of this source by around 0.8 mag within 100 minutes. A similar type of variation (0.6 mag variations in 40 minutes in the *V* band) has also been detected by Matsumoto et al. (1999), who observed this

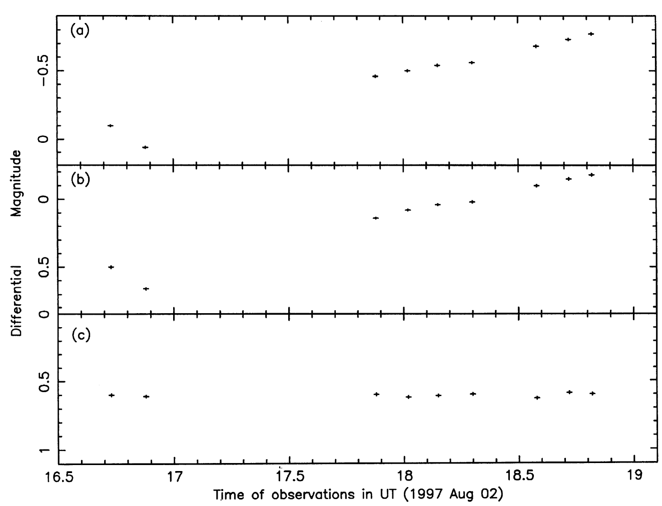

FIG. 1.—Differential intranight light curve of BL Lac in *I* band observed on 1997 August 2. (*a*) Differential magnitude between BL Lac and comparison star 1. (*b*) Same as (*a*) but for the comparison star 2. (*c*) Differential magnitude between the two comparison stars.

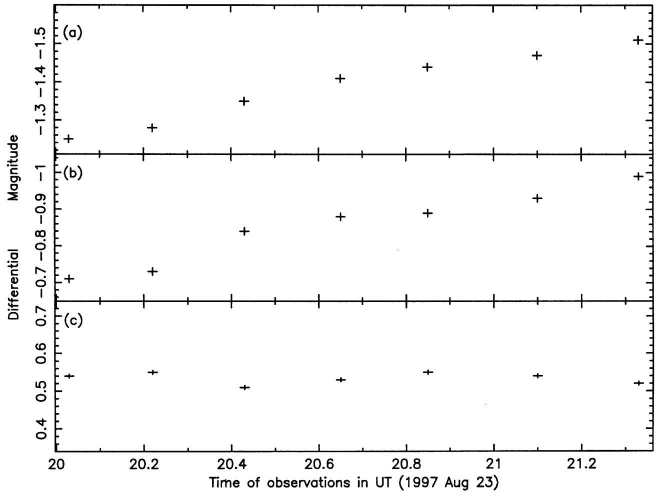

FIG. 2.—Same as Fig. 1 but for *B* band, observed on 1997 August 23

blazar on the same night between 14:57 and 19:07 UT. The observed results of Matsumoto et al. (1999), and our results that are presented in Figure 1, indicate that probably we have observed the rising phase of a large outburst of BL

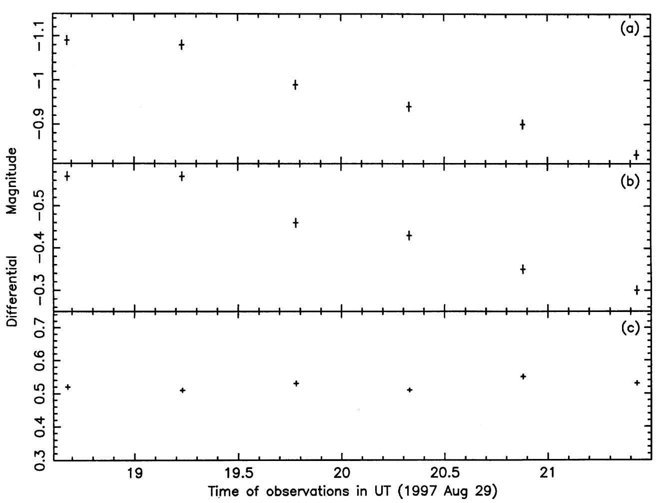

FIG. 3.—Same as Fig. 2 but for 1997 August 29

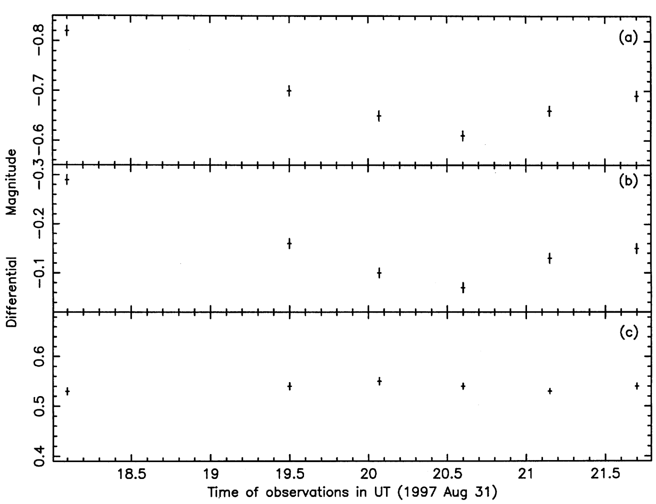

FIG. 4.—Same as Fig. 2 but for 1997 August 31

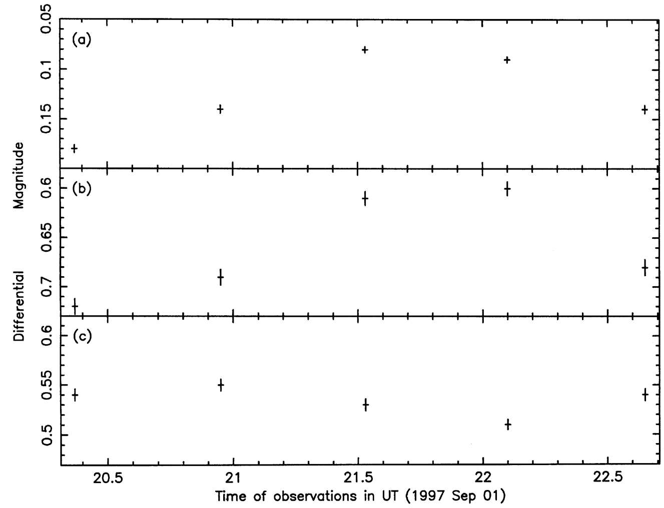

FIG. 5.—Same as Fig. 2 but for 1997 September 1

Lac. This blazar was also observed on the same night (1997 August 2) between 20:27 and 27:08 UT from Europe (Massaro et al. 1998; Speziali & Natali 1998). A combination of all these observations resulted in a continuous ~11 hr coverage of BL Lac on 1997 August 2. Results of these observations are plotted in Figure 6, and it can be seen from this figure that BL Lac displayed a large amplitude (more than 1 mag) variation within a few hours (~7 hr). We will call this type of variation a flare and will discuss this below.

Figures 2–5 display the light curves of BL Lac that were observed on different nights during 1997 August–September. These light curves show either the rising phase or the declining phase of small-amplitude oscillatory variations (or miniflares) of BL Lac. Nesci et al. (1998), Massaro et al. (1998), and Speziali & Natali (1998) have also detected similar types of oscillatory variations of this blazar.

Long-term variations of BL Lac are shown in Figures 7 and 8. Figure 7 presents the results of long-term *B*-band

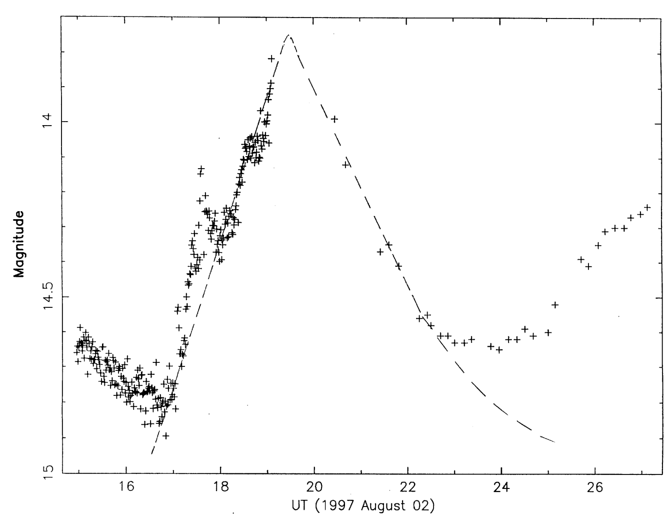

FIG. 6.—*V*-band photometric light curve of BL Lac observed on 1997 August 2. Data between 15 and 19 UT were obtained from Matsumoto et al. (1999), and those between 20 and 27 UT were obtained from Massaro et al. (1998). Dashed line shows the fit to the flare profile using the model of Wang et al. (1999).

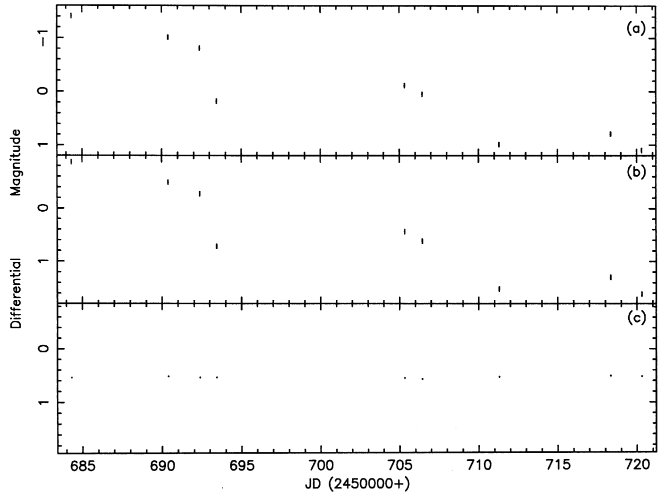

FIG. 7.—Same as Fig. 2 but for night-to-night variations

differential photometry of this blazar. It can be seen from this figure that the brightness of BL Lac decreased by 2.5 mag within 36 days and also varied on different timescales by different amplitudes during the outburst period. Matsumoto et al. (1999) have also detected similar declining episodes of BL Lac in the V band (the brightness decreased from 13.0 to 15.5 mag within 30 days) during the same interval as our observations. They have also detected frequent flares of this blazar during their whole period of observations (between JD = 2,450,634 and 2,450,716). It may be seen from the light curve of BL Lac obtained from the VSNET (Variable Star NETwork) reports that the 1997 outburst episode of this blazar lasted between 1997 July and October. We continued observation of this source and found that its brightness again increased by more than a magnitude (the brightness increased by 1.4 mag in the R band between JD = 2,450,769 and 2,450,844 and by 0.9 mag in the V band between JD = 2,450,814 and 2,450,934). These results, presented in Figure 8, also show the presence of a few flares in the R band. (Observations were carried out in this band more frequently than in the V band.) The VSNET observers also detected the short-duration brightening phases of this source (similar to that presented in Fig. 8) in 1998 April and July and more recently in 1999 July.

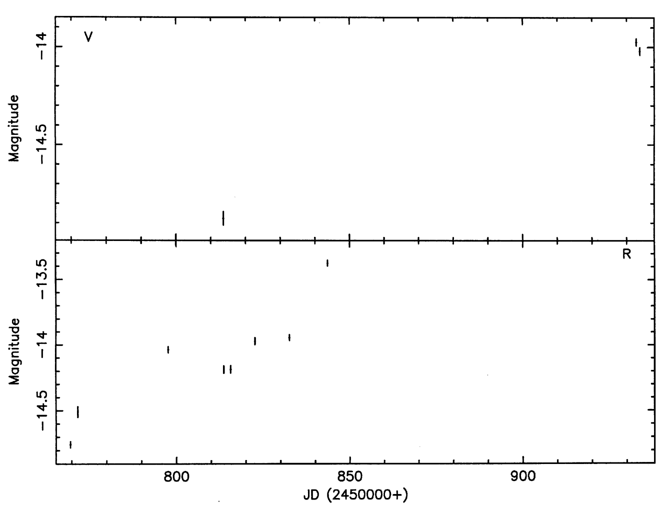

FIG. 8.—Upper and lower panels show photometric light curves of BL Lac in the V and I bands, respectively.

4. DISCUSSION

We have mentioned in the introduction that optical, X-ray, and γ-ray flares were detected in BL Lac during its 1997 outburst. Bloom et al. (1997) carried out simultaneous optical and γ-ray observations to find out the lead or lag between the peaks of optical and γ-ray flare profiles. Based on their densely sampled optical data, they have suggested that most probably there is a lag of several hours between the peak optical and peak γ-ray flares. This type of lag between soft and hard photons has also been detected among flares in other blazars (Buckley et al. 1996; Urry et al. 1997 and references therein). Thus, a multifrequency flux variability study of blazars can be used as an important tool to probe detailed emission mechanisms of these objects. *RXTE* observations for BL Lac were carried out in 1997 July 16–22. The 3–20 keV bandpass light curve of this source shows a peak around 1997 July 19.3 (Madejski et al. 1999). It may be noted that these observations were most likely undersampled. To obtain a well-sampled X-ray light curve of BL Lac, we have analyzed *ASCA* observations (obtained from the *ASCA* database) of this object that was observed between 1997 July 18.58 and 19.62. The GIS 2 and 3 counts were binned in the time interval of 1024 s and are plotted in Figure 9 (*middle panel*). It can be seen from Figure 9 that there are two peaks in the X-ray flare light curve. We used Gaussian profiles to fit these two peaks. From the results of profile fitting, we find that the first and the second peak appeared around 1997 July 18.95 and 19.29, respectively. The values of full width at half-intensity maximum (FWHM) of the first and the second peak are 3.4×10^4 s and 0.6×10^4 s, respectively. The second peak of the X-ray flare light curve coincides with the PCA *RXTE* peak (Madejski et al. 1999).

The γ-ray flare light curve (observed with the EGRET) of BL Lac during 1997 July 18–20, obtained from the published results of Bloom et al. (1997), is shown in the bottom panel of Figure 9. We have used a Gaussian profile to fit the γ-ray flare light curve. From this curve fitting, we find that the γ-ray flare peaked around 1997 July 18.85, and the FWHM value of the γ-ray flare profile is 4.7×10^4 s, which are comparable to the first peak of the X-ray flare light curve. The dashed vertical line on Figure 9 shows the end of the γ-ray flare (Bloom et al. 1997). These results demonstrate that most probably the X-ray and the γ-ray photons peaked almost around the same time, suggesting that there is little, if any, lag between the X-ray and the γ-ray photons during the outburst of BL Lac.

Using the published data and the data from the VSNET, we have constructed the V-band light curve of BL Lac between 1997 July 18 and 20, and it is shown in the top panel of Figure 9. The light curve was fitted with a Gaussian profile which shows that during this interval the optical flare clearly peaked around 1997 July 19.22 and the FWHM value of the optical flare profile is 2.7×10^4 s. It can be seen from this figure that there is a lag of approximately 7 hr between the peak optical and peak γ-ray and X-ray flares. It may be noted that the optical peak is close to the second peak of the X-ray light curve. However, it is also clear that optical photons lagged behind the γ-ray photons. These results will put serious constraints on the synchrotron self-Compton (SSC) and the external Comptonization (EC)

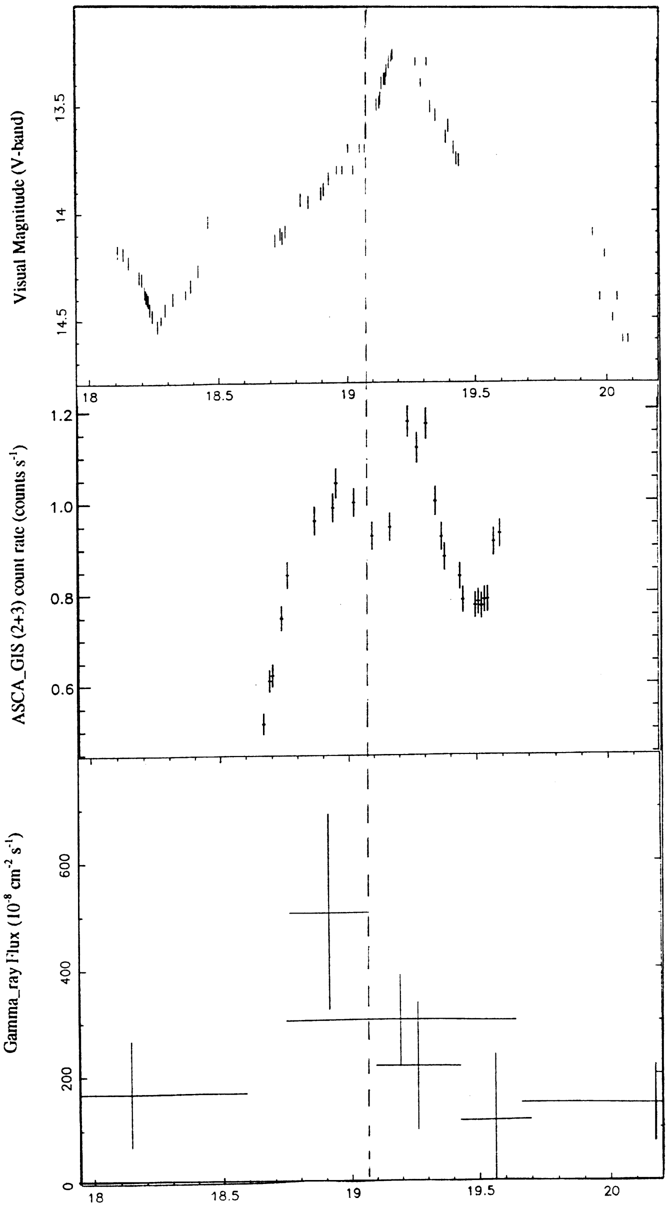

FIG. 9.—Top panel shows the optical V-band light curve of BL Lac during 1997 July 18–20. This light curve has been constructed using the published data and the data from the VSNET. Middle panel shows the *ASCA* GIS 2 and 3 combined (binned in the time interval of 1024 s) X-ray light curve of BL Lac that was observed during 1997 July 18–19. The γ-ray flare light curve (observed with the EGRET) of BL Lac during 1997 July 18–20, obtained from the published results of Bloom et al. (1997), is shown in the bottom panel. The dashed vertical line represents the end of γ-ray flare (Bloom et al. 1997).

models of blazars. It has been suggested in the SSC or EC models that either synchrotron optical radiation or the external optical radiation will be upscattered to γ-rays (Jones, O'Dell, & Stein 1974; Marscher 1980; Ghisellini, Maraschi, & Dondi 1996 and references therein). If the synchrotron optical radiation is upscattered to γ-rays, there must be a correlated flux variability of these two photon populations. However, Figure 9 shows that the optical peak lags behind the γ-ray peak.

Recently, Wang et al. (1999) have suggested an analytical model that studied the evolution of synchrotron spectra in a homogeneous jet due to the injection of relativistic electrons and radiation losses during the flares in blazars. We have used this model to fit the optical (V band) flare profile presented in Figure 6. The inputs to this model are the energy spectral index ($\alpha = 1.0$; Matsumoto et al. 1999), length of the electron injection (for a simple injection function, the injection time is $t_0 = 2.4$ hr derived from the observed flare profile), and the frequency or wavelength at which the flare has been observed. The dashed curve superimposed on Figure 6 shows the model output. The derived parameters from this model fit are as follows: (1) the magnetic field in the synchrotron emitting region is $B = 2.4$ G, ignoring electron Compton loss; (2) the spectral index of the initially injected electrons spectrum is $\gamma = 3.0$ and the energy cutoffs are $\gamma_{\rm min} = 10^4$ and $\gamma_{\rm max} = 10^5$; and (3) the value of the characteristic parameter (φ), which determines the magnitude of the flux increase, is $\varphi = 8.0 \times 10^{-2}$. Our derived values of magnetic field and the electron energy are similar to the values obtained by fitting the multifrequency spectrum of BL Lac during the flare state (Sambruna et al. 1999). It is interesting to note that relativistic electrons alone are insufficient to produce short-duration flares with large amplitudes (like the one presented in Fig. 6); regions with high magnetic fields are also required. The results of the present analysis suggest that the frequent flares displayed by BL Lac during its outburst (Matsumoto et al. 1999) may be due to the injection of relativistic electrons in the jet. Also, we suggest that the miniflares or oscillatory variations observed in this blazar (Figs. 2–5) may be due to short injection times with electron injection into the jet at a comparable magnetic field. The model of Wang et al. (1999) also predicts a lag of the emitted spectra between soft and hard photons, similar to the one observed in BL Lac between optical and γ-rays.

5. CONCLUSION

We have added to our optical study of the flux variability of BL Lac, taken over 22 nights in 1997, an additional night taken of published X-ray and γ-ray data (Bloom et al. 1997; Madejski et al. 1999). These data, combined with other published data, were then analyzed within the context of the spectral evolution model of Wang et al. (1999). Flux variability was a constant feature of the behavior of BL Lac, but on two particular nights (which included the night of X-ray data), the variation was approximately an entire magnitude. We observed that there were nearly 7 hr of delay between the optical peak and the peaks of the γ-ray and X-ray flares. SSC and EC models of blazars are among the most commonly used ones, but the major result of this study—mainly, that the optical photons lag behind the γ-ray photons—puts severe constraints on those models.

We find a good fit to the model of Wang et al. (1999), which suggests an evolution of synchrotron spectra in a homogeneous jet after the injection of relativistic electrons and includes the accompanying radiation losses during the flares. This model matches well the observed optical (V band) flare profile as presented in Figure 6. The derived parameters from this model fit, particularly the magnetic field in the synchrotron emitting region and the spectral index of the injection electrons, are similar to values obtained by others for BL Lac, using different but not inconsistent methods (Sambruna et al. 1999).

We are therefore inclined to believe, indeed, that frequent flares of BL Lac displayed during its outburst (and perhaps this is true for the entire class of objects) are probably due to the injection of relativistic electrons in the purported jet. Additionally, perhaps the miniflares detected may be due to a short injection time in particular instances.

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