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OPTICAL VARIABILITY OF BLAZARS

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ABSTRACT

In this paper we show the results of our monitoring the flux variability of 15 blazars, within the redshift range of 0.07–2.06, all with a visual magnitude range between 14 and 20 mag. Because blazars have displayed variability on diverse timescales, we have chosen to study them over both short and long timescales, ranging from minutes to years. These blazars were observed on 58 nights between 1995 March and 1998 June. Individual sources are discussed in detail. For example, one of our sources, Mrk 501, showed microvariability of as much as 0.13 mag change within 12 minutes. The usual parameters for size, mass, and luminosity are calculated. Relativistic beaming is implied by the data. We also searched for correlations between amplitude of variability, redshift, and luminosity. We found few, if any, such correlations. Discussion and conclusions are given for these and other results as implied by the data.

Subject headings: galaxies: active — galaxies: individual (3C 66A, PKS 0235+164, PKS 0528+134, PKS 0735+178, PKS 0736+017, PKS 0754+100, OJ 287, PKS 1156+295, 3C 273, 3C 279, PG 1418+546, Mrk 501, 3C 390.3, 3C 446, CTA 102) — galaxies: photometry

1. INTRODUCTION

Variability is one of the salient properties of active galactic nuclei (AGNs) and a powerful constraint on models of these sources. Observations show that AGNs are characterized by rapid and large amplitude continuum variations over the entire electromagnetic spectrum. Matthews & Sandage (1963) reported the first rapid variability in AGNs. They detected 0.04 mag flux variations in 3C 48 in 15 minutes. This result and other subsequent reports on rapid variability in AGNs were not considered seriously because these variations were attributed to instrumental errors. However, later observations with CCDs suggested that rapid variability was typical of AGNs and especially of blazars (Miller, Carini, & Goodrich 1989; Wagner & Witzel 1995 and references therein). Timescales of variability can be used to compute the size of the emitting region using the light-travel time arguments. It has been suggested that the rapid variability may originate in the jets of blazars due to interaction of relativistic shock waves with the inhomogeneous medium of the jet. (Maraschi et al. 1989; Qian et al. 1991; Marscher, Gear, & Travis 1992; Marscher 1996 and references therein). It has also been suggested that the rapid variations may be due to eclipsing of hot spots by the accretion disk (around the supermassive black hole) or due to flares in the accretion disk (Wiita 1996 and references therein). Details of other possible suggestions regarding the origin of microvariability may be seen in Wagner & Witzel (1995).

Blazars are highly variable, polarized AGNs with featureless (or weak emission and/or absorption) continuum (radio through γ-ray). These objects have also displayed variability on large timescales. Many authors (Hook et al. 1994; Christiani et al. 1996; Di Clemente et al. 1996) have found that the amplitudes of variability are correlated with the redshift and are anticorrelated with the observed luminosity of these objects (Christiani et al. 1996 and references therein). Nair (1997) also reported that the timescales and amplitudes of variation of these objects are correlated. It has been suggested that the amplitude-redshift correlation may be due to the effect of observing different spectral regions in the rest frames of these sources. Christiani et al. (1996) found no correlation between timescales and redshift or luminosity, but an anticorrelation between timescales and luminosity has been reported by Netzer et al. (1996). Thus it should be interesting to study the short and long timescales of variation of a large number of blazars spread over a wide range of redshift. In the present paper we report the results of optical observations of 15 blazars, in the redshift range of 0.07–2.06, with visual magnitude range between 14 and 20 mag (Table 1 presents source name, position, redshift, and visual magnitude). These blazars were observed on 58 nights between 1995 and 1998, giving minutes to years timescales, using three telescopes (0.61, 1.02, and 2.34 m). Section 2 of this paper pertains to observations and the data analysis, the results are presented in § 3, and the discussion and conclusions are given in § 4.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Observations and Data Analysis at VBO*

The observation log of five blazars (PKS 0528+134, PKS 1652+398, 3C 390.3, 3C 446, and CTA 102) that were observed on 39 nights between 1995 March and 1997 October, at the Vainu Bappu Observatory (VBO), Kavalur, India, is given in Table 2. The optical observations of these blazars were carried out using the 2.34 m Vainu Bappu Telescope (VBT) and the 1.02 m telescopes of VBO. CCD images of these sources were obtained at the f/3.23 prime focus of the VBT. This UV-coated and thinned Tektronics 1k CCD system had 1024 × 1024 pixels with 24 × 24 μm^2 dimensions, giving, a total area covered of 11 × 11 arcmin^2 on the sky at the prime focus of the VBT with an image scale of about 27″ mm^{-1}. CCD observations of three blazars (PKS 1652+398, 3C 390.3, and CTA 102) were also carried out at the f/13 Cassegrain focus of the 1.02 m telescope of VBO. Here the CCD used was a Thomson CSF TH 7882 CCD system of 384 × 576 pixels, each of 23 μm^2

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TABLE 1

SOURCE LOG OF OBSERVED BLAZARS

Source	Position (B1950.0) R.A.	Position (B1950.0) Decl.	Redshift z	m_V
PKS 0219+428......	02 19 30.05	+42 48 29.7	0.444	15.50
PKS 0235+164......	02 35 52.70	+16 24 04.0	0.940	15.50
PKS 0528+134......	05 28 06.82	+13 29 42.3	2.060	20.00
PKS 0735+178......	07 35 14.18	+17 49 09.3	0.424	14.85
PKS 0736+017......	07 36 42.57	+01 44 00.2	0.190	16.47
PKS 0757+095......	07 54 22.64	+10 04 39.7	0.670	14.50
PKS 0851+202......	08 51 57.20	+20 17 58.0	0.306	14.00
PKS 1156+295......	11 56 57.86	+29 31 25.8	0.729	15.60
PKS 1229+020......	12 26 33.28	+02 19 43.2	0.157	12.86
PKS 1253−055......	12 53 35.91	−05 31 08.1	0.536	17.75
OQ 530..............	14 18 06.28	+54 36 58.2	0.152	15.50
PKS 1652+398......	16 52 11.83	+39 50 25.2	0.033	13.80
3C 390.3	18 45 37.78	+79 43 06.4	0.055	15.38
PKS 2223−052......	22 23 11.17	−05 12 17.2	1.454	18.39
PKS 2232+114......	22 30 07.89	+11 28 22.9	1.037	17.33

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

dimension, giving, on this telescope, a total field of 137 × 206 arcsec^2 with an image scale of 0″.357 pixel^{-1}. The readout noise and gain for the Tek 1k system were 9.8 e rms and 8.97 e ADU^{-1}; and for the TH 7882 system were 6.5 e rms and 27.3 e ADU^{-1}, respectively. B (4400 Å/1050 Å, V (5425 Å/1050 Å), R (6550 Å/1300 Å), and I (8150 Å/1700 Å) coated filters were used for our observations with the CCD systems. Many bias frames were obtained before, during, and after observations on each night to obtain 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, except a few nights, and the seeing was between 2″.0 and 2″.5.

The IRAF (Image Reduction and Analysis Facility) software package was used for the data analysis. Bias-subtracted and flat-field–corrected CCD image frames were aligned (for geometric distortion and transformation with respect to the reference image frame) using the GEOMAP and GEOTRAN programs in IRAF. The photometric analysis was carried out using the digital aperture reduction program DAOPHOT (Stetson 1987, 1990) installed on the SUN workstations at VBO. Aperture photometry of all the stars in the field (including the blazar) was carried out using concentric circular apertures of 7″, 10″, 13″, and 15″ diameter centered on the objects. The sky background was subtracted using the values measured in annuli around the circular aperture. The growth-curve method was employed, by means of the DAOGROW program (Stetson 1990). It was found from careful analysis that the best signal-to-noise ratio (S/N) and the most reliable results could be achieved using the 7″ aperture. Finally, we obtained the total, integrated instrumental magnitudes of all the objects in the field. Stars with magnitude similar to that of the blazar were selected, and their instrumental magnitudes were plotted against time of observation. From these plots, two nonvariable stars were selected that were relatively close to the blazar. These two stars were used as the comparison stars. The errors in instrumental magnitudes were computed using the STAR ADD program available in the DAOPHOT software package. The difference in the added and recovered instrumental magnitudes of the stars was assumed to be the error in photometric measurement. These errors were compared with the formal errors obtained from the DAOPHOT analysis, and it was found that the formal errors were smaller by a factor of 2. This factor of 2 was then added in quadrature to the 1 σ formal errors for the blazar and the comparison stars, obtained from the DAOPHOT software package. Then the errors for each observed data set was computed for these objects. These errors are shown in Figures 3 and 10–13 below, which display the differential instrumental magnitude versus the data of observations.

2.2. *Observations and Data Analysis at SBO*

The observation log of 10 blazars that were observed on 19 nights between 1997 October and 1998 June with the 0.61 m reflector at the Sommers-Bausch Observatory (SBO) of the University of Colorado at Boulder, is given in Table 3. Direct CCD (1530 × 1020 pixels) imaging of these blazars were carried out at the f/8 Cassegrain focus of the telescope using an ST-8 CCD camera 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) band 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) for all the blazars of Table 3 but 3C 66A and 3C 279. Values of magnitudes of comparison stars in the fields of 3C 66A and 3C 279 were obtained from P. S. Smith (1986, private communication). The ratio of the source and comparison star counts gives a difference in magnitude between the two. A comparison star with tabulated values of the comparison star magnitude then yields the source magnitude.

The instrumental magnitude and associated error were calculated using the MIRA A/P software. The magnitude

TABLE 2

Log of Optical Observations of Blazars at VBO

Object	z	Observation Date	Telescope (m)	Number of Observations (obs)	UT (start)	Total Exposure (s)	Filter
PKS 0528+134	2.07	1997 Feb 2	2.34	1	13:57	1800	*V*
		1997 Feb 4	2.34	1	14:05	1800	*V*
		1997 Feb 6	2.34	1	16:05	1800	*V*
		1997 Feb 11	2.34	1	13:56	2400	*V*
		1997 Feb 12	2.34	1	13:39	1800	*V*
		1997 Feb 13	2.34	1	15:10	1800	*V*
		1997 Feb 14	2.34	2	14:15	3600	*V*
		1997 Mar 5	2.34	2	14:20	3600	*V*
		1997 Mar 7	2.34	1	15:09	1800	*V*
PKS 1652+398	0.033	1997 Mar 16	2.34	11	21:47	6600	*V*
		1997 Apr 29	2.34	8	20:59	7200	*V*
		1997 Apr 30	2.34	7	19:13	4200	*V*
		1997 May 2	2.34	13	19:00	7800	*V*
		1997 Jun 1	2.34	10	16:41	6000	*V*
		1997 Jun 6	1.02	3	20:21	5400	*V*
		1997 Jun 7	1.02	2	21:27	3600	*V*
		1997 Jun 8	1.02	8	16:22	9600	*V*
		1997 Jun 9	1.02	6	16:01	10800	*V*
		1997 Jun 15	2.34	5	18:50	4500	*V*
3C 390.3	0.057	1995 Mar 7	2.34	2	23:39	1200	*V*
		1995 Mar 8	2.34	2	23:16	1800	*V*
		1995 Mar 11	2.34	2	23:20	1800	*V*
		1995 Apr 8	1.02	1	23:26	1200	*V*
		1995 May 22	1.02	1	22:41	1800	*V*
		1995 May 23	2.34	1	23:03	1200	*V*
		1995 May 29	1.02	1	21:13	1800	*V*
		1995 May 25	2.34	3	22:20	2700	*V*
		1995 Jun 7	2.34	1	21:23	1200	*V*
		1995 Jun 8	1.02	2	21:01	3600	*V*
		1995 Jun 9	1.02	3	19:45	8100	*V*
		1995 Jun 29	2.34	2	20:11	1800	*V*
		1995 Jul 3	2.34	2	18:56	2400	*V*
		1995 Sep 24	2.34	1	16:46	900	*V*
		1995 Oct 13	2.34	2	14:05	1200	*V*
3C 446	1.404	1997 Jun 7	2.34	2	21:59	4800	*V*
		1997 Jun 8	2.34	3	21:40	7200	*V*
		1997 Jun 15	2.34	3	20:34	7200	*V*
CTA 102	1.037	1997 May 30	2.34	2	22:17	3600	*V*
		1997 Jun 5	2.34	3	21:30	4500	*V*
		1997 Jun 8	1.02	4	21:29	7200	*V*

was measured by taking the ratio of the reduced (sky-subtracted) flux of the image with the reduced flux of a known comparison star. A statistical weighted average among a number of comparison stars was used to reduce the error to a minimum. The magnitude was determined by taking the logarithm of this ratio.

The error associated with the instrumental magnitude is essentially Poisson statistics. This is determined by calculating the S/N from the unreduced count of each object, the background count, and the gain of the CCD camera. The standard deviation is proportional to the S/N.

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. When dealing with a single telescope and how an object varies from night to night, we are concerned primarily with the instrumental error, which typically is under 1%. When dealing with a multifrequency project in which the data on one telescope are compared with the data on another (typically at other wavelengths), then the absolute error must be quoted, which is typically a few percent. In this paper we quote the absolute error.

3. RESULTS

Results of differential and absolute photometry of 15 blazars (Tables 2 and 3) are plotted in Figures 1–13 below. It may be seen from these plots that these blazars have displayed flux variability on different timescales. We now discuss the results of each blazar individually.

3.1. *PKS 0219+428* (*3C 66A*)

The 3C 66A blazar is a member of the *Einstein* Slew Survey sample (Elvis et al. 1992). Both GeV (Dingus et al. 1996; Mukherjee et al. 1997) and TeV (Neshpor et al. 1998 and references therein) γ-rays have been detected in this highly polarized (Mead et al. 1990) blazar. This source has displayed infrared, optical, ultraviolet, and X-ray variability on different timescales (De Diego et al. 1997; Carini, Noble, & Miller 1998; Ghosh & Soundararajaperumal 1995). *V*-

TABLE 3

Log of Optical Observations of Blazars at SBO and Results

Object	JD (2,450,000+)	Date	UT	Filter	Magnitude
PKS 0219+428......	776.784	1997 Nov 24	06:48	*V*	14.985 ± 0.020
	778.677	1997 Nov 26	04:15	*V*	14.997 ± 0.018
	797.742	1997 Dec 15	05:48	*V*	14.824 ± 0.019
	813.679	1997 Dec 31	04:17	*V*	14.824 ± 0.044
	815.674	1998 Jan 2	04:10	*V*	14.826 ± 0.022
	832.702	1998 Jan 19	04:50	*V*	15.235 ± 0.024
	837.674	1998 Jan 24	04:10	*V*	15.219 ± 0.020
	843.662	1998 Jan 30	03:53	*V*	15.335 ± 0.019
	771.776	1997 Nov 19	06:37	*R*	14.454 ± 0.043
	776.757	1997 Nov 24	06:10	*R*	14.606 ± 0.022
	778.648	1997 Nov 26	03:33	*R*	14.580 ± 0.018
	797.717	1997 Dec 15	05:12	*R*	14.394 ± 0.018
	813.654	1997 Dec 31	03:42	*R*	14.473 ± 0.015
	815.705	1998 Jan 2	04:55	*R*	14.610 ± 0.016
	832.670	1998 Jan 19	04:04	*R*	14.829 ± 0.020
	837.648	1998 Jan 24	03:33	*R*	14.867 ± 0.025
	843.636	1998 Jan 30	03:16	*R*	14.968 ± 0.020
PKS 0235+164......	778.749	1997 Nov 26	05:59	*V*	17.377 ± 0.045
	813.729	1997 Dec 31	05:29	*V*	16.217 ± 0.037
	832.755	1998 Jan 19	06:07	*V*	16.005 ± 0.052
	837.723	1998 Jan 24	05:25	*V*	16.590 ± 0.045
	765.733	1997 Nov 13	05:36	*R*	16.246 ± 0.067
	776.826	1997 Nov 24	07:49	*R*	16.993 ± 0.061
	778.711	1997 Nov 26	05:03	*R*	16.746 ± 0.032
	813.704	1997 Dec 31	04:54	*R*	15.606 ± 0.032
	815.703	1998 Jan 2	04:52	*R*	15.545 ± 0.018
	822.688	1998 Jan 9	04:31	*R*	15.898 ± 0.080
	832.728	1998 Jan 19	05:28	*R*	15.401 ± 0.019
	837.701	1998 Jan 24	04:49	*R*	15.816 ± 0.028
	843.690	1998 Jan 30	04:33	*R*	15.441 ± 0.033
PKS 0735+178......	778.813	1997 Nov 26	07:30	*V*	16.862 ± 0.041
	904.703	1998 Apr 1	04:52	*V*	15.698 ± 0.033
	765.818	1997 Nov 13	07:38	*R*	16.232 ± 0.090
	776.884	1997 Nov 24	09:12	*R*	16.147 ± 0.037
	778.788	1997 Nov 26	06:55	*R*	16.290 ± 0.042
	797.778	1997 Dec 15	06:40	*R*	16.072 ± 0.047
	822.754	1998 Jan 9	06:06	*R*	15.798 ± 0.041
	837.815	1998 Jan 24	07:33	*R*	15.596 ± 0.035
	843.766	1998 Jan 30	06:38	*R*	15.906 ± 0.046
	897.695	1998 Mar 25	04:40	*R*	15.391 ± 0.035
	904.665	1998 Apr 1	03:57	*R*	15.345 ± 0.033
	909.645	1998 Apr 6	03:29	*R*	15.296 ± 0.036
	925.649	1998 Apr 22	03:34	*R*	15.455 ± 0.041
PKS 0736+017......	776.908	1997 Nov 24	09:48	*R*	16.116 ± 0.041
	797.819	1997 Dec 15	08:33	*R*	16.243 ± 0.050
	837.787	1998 Jan 24	06:53	*R*	15.980 ± 0.044
	843.750	1998 Jan 30	05:59	*R*	15.641 ± 0.053
	897.743	1998 Mar 25	05:50	*R*	15.472 ± 0.050
	904.732	1998 Apr 1	05:34	*R*	15.944 ± 0.046
PKS 0754+100......	776.955	1997 Nov 24	10:54	*R*	16.501 ± 0.060
	797.857	1997 Dec 15	08:33	*R*	16.243 ± 0.050
	813.780	1997 Dec 31	06:42	*R*	16.618 ± 0.061
	837.787	1998 Jan 24	06:10	*R*	16.479 ± 0.052
	843.723	1998 Jan 30	05:21	*R*	16.305 ± 0.063
	897.779	1998 Mar 25	06:42	*R*	16.121 ± 0.052
	904.756	1998 Apr 1	06:09	*R*	16.160 ± 0.049
	925.687	1998 Apr 22	04:29	*R*	16.276 ± 0.053
PKS 0851+202......	822.829	1998 Jan 9	07:53	*V*	15.317 ± 0.035
	797.888	1997 Dec 15	09:18	*R*	14.763 ± 0.039
	822.796	1998 Jan 9	07:06	*R*	15.229 ± 0.038
	837.757	1998 Jan 24	06:10	*R*	15.576 ± 0.042
	843.806	1998 Jan 30	07:20	*R*	15.511 ± 0.055
	897.839	1998 Mar 25	08:07	*R*	15.554 ± 0.052
	904.780	1998 Apr 1	06:42	*R*	15.725 ± 0.040

TABLE 3—*Continued*

Object	JD (2,450,000+)	Date	UT	Filter	Magnitude
	925.687	1998 Apr 22	04:29	*R*	15.387 ± 0.038
PKS 1156+295......	897.891	1998 Mar 25	09:23	*R*	13.775 ± 0.028
	904.819	1998 Apr 1	07:40	*R*	14.457 ± 0.029
	993.741	1998 Jun 29	05:47	*R*	15.496 ± 0.046
PKS 1226+023......	822.948	1998 Jan 9	10:45	*B*	13.979 ± 0.449
	822.920	1998 Jan 9	10:04	*V*	12.933 ± 0.420
	822.896	1998 Jan 9	09:30	*R*	12.719 ± 0.397
	843.867	1998 Jan 30	08:48	*R*	12.699 ± 0.369
PKS 1253−055......	897.924	1998 Mar 25	10:10	*V*	15.009 ± 0.424
	904.873	1998 Apr 1	08:57	*V*	14.597 ± 0.374
	843.927	1998 Jan 30	10:14	*R*	14.630 ± 0.427
	904.899	1998 Apr 1	09:34	*R*	14.104 ± 0.402
PG 1418+54	977.854	1998 Jun 13	08:30	*V*	16.052 ± 0.031
	962.844	1998 May 29	08:15	*R*	15.387 ± 0.042
	984.864	1998 Jun 20	08:43	*R*	15.260 ± 0.033
	993.841	1998 Jun 29	08:11	*R*	15.140 ± 0.035

and R-band optical photometric observations of 3C 66A were carried out on nine nights between 1997 November and 1998 January (Table 3). V, R, and $V-R$ magnitudes versus date of observations of this blazar are plotted in Figure 1. It can be seen from this figure that the V, R, and $V-R$ color index fluxes of this source varied by 0.51, 0.57, and 0.22 mag, respectively, during the interval of our observations (Table 3). Figure 1 also shows that the $V-R$ variation is somewhat better correlated with the variation of R magnitude than the V magnitude variation of 3C 66A. Dramatic variations of $V-R$ color index [$\Delta(V-R) = 0.22$ mag] took place between 1997 December 15 (JD 2,450,797.7) and 1998 January 2 (JD 2,450,815.7) when the V magnitude of this source remained almost constant and the R magnitude decreased by 0.22 mag. These flux variations can be used to compute the changes of the mean spectral index (assuming that the spectral energy distribution follows a power law), using the following equation:

$$\Delta\alpha = 0.4 \frac{\Delta(V-R)}{\log(7000/5500)} . \quad (1)$$

(Massaro et al. 1998). Using the value of $\Delta(V-R) = 0.22$ mag in equation (1), we find $\Delta\alpha = 0.84 \pm 0.12$. This result indicates that the spectral index of the source, between V and R bands, flattened ($\Delta\alpha = 0.84 \pm 0.12$) when the bright-

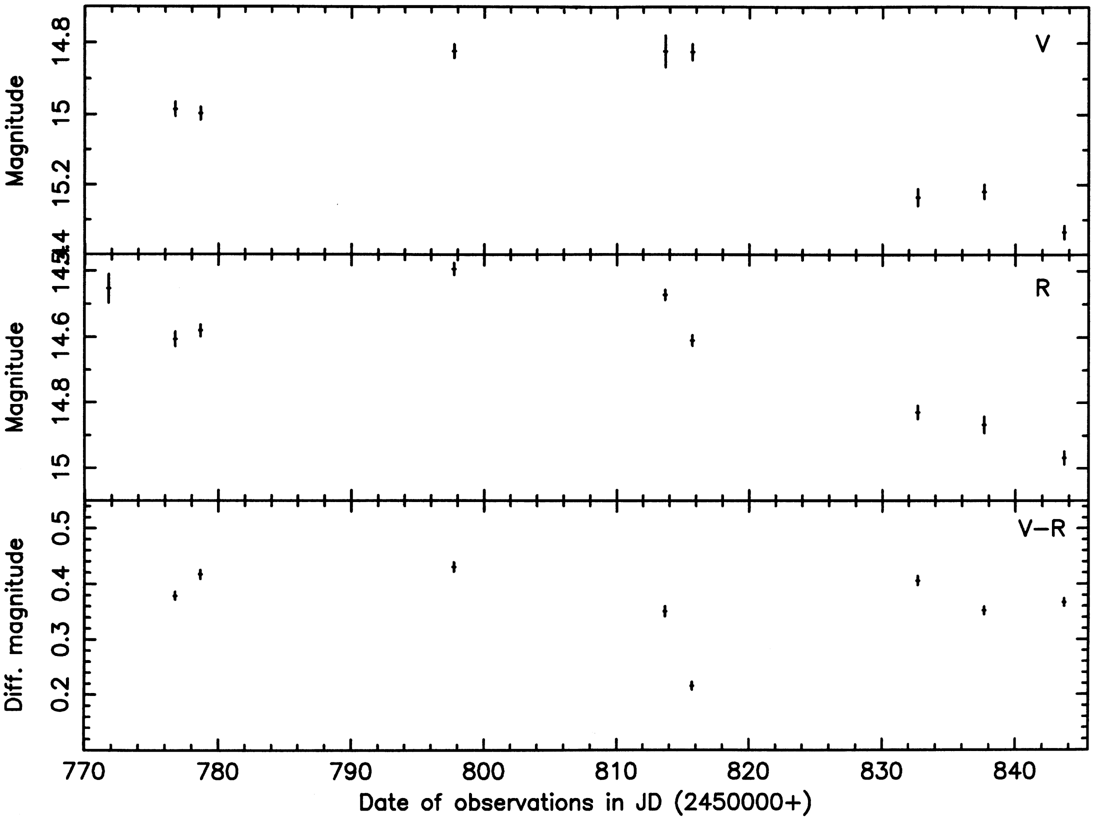

FIG. 1.—V- and R-band photometric light curves of 3C 66A (*top*, *middle*). Lowest panel shows the plot of the $V-R$ color index of 3C 66A.

ness of the source in V remained almost constant and decreased in R. Between 1998 January 19 and 30 (JD 2,450, 832.6 and 2,450,843.6) the brightness of the source decreased (Fig. 1 and Table 3) and the $V-R$ color index increased and correlated well with the variation of the source brightness.

3.2. *PKS 0235+164* (*OD +160*)

PKS 0235+164 belongs to both the 1 Jy (Kuhr et al. 1981) and the *Einstein* Slew Survey samples (Elvis et al. 1992). This highly polarized (Mead et al. 1990) optically violently variable (OVV) blazar is an X-ray (Ghosh & Soundararajaperumal 1995; Urry et al. 1996; Kubo et al. 1998) and γ-ray–emitting source (Hartman et al. 1992; Hunter et al. 1993b). Short timescale variations at radio frequencies have been detected in PKS 0235+164 (Kraus et al. 1998 and references therein). It is also known as an optical intraday variable BL Lac object (Noble & Miller 1996; Heidt & Wagner 1998). Optical observations (at V and R bands) of this blazar were carried out at the SBO on nine nights between 1997 October and 1998 January (Table 3). The V, R, and the $V-R$ color index fluxes of this source are shown in Figure 2. It may be seen from this figure and Table 3 that the brightness of this source in V and R bands increased by 1.37 mag and 1.35 mag, respectively, between 1997 October 26 (JD 2,450,778.7) and 1998 January 19 (JD 2,450,832.7), when the $V-R$ color index of the source remained almost constant. Around the end of our observations the source brightness decreased by 0.6 mag (in V band) and 0.4 mag (in R band) and the $V-R$ color index increased by 0.17 mag, in the interval of five days (from JD 2,450,832.7 to JD 2,450,837.7). This change in the $V-R$ color index [$\Delta(V-R) = 0.17$] corresponds to the steepening of the spectral slope by 0.65 ± 0.14 [$\Delta\alpha = 0.65 \pm 0.14$, computed using eq. [1]].

3.3. *PKS 0528+134* (*OG +147*)

PKS 0528+134 is a flat-spectrum radio-loud Quasar (FSRQ; Wall & Peacock 1985; Padovani & Urry 1992). It is one of the strongest γ-ray blazars that emits most of the power in the MeV energy range (Dingus et al. 1996; Hunter et al. 1993a; Mukherjee et al. 1996) with a spectral break around 10 MeV (Bottcher & Collmar 1998; Collmar 1998; Zhang, Li, & Wu 1998). Different models have been suggested to explain the emission mechanism of this MeV-luminous blazar, and recently Ghosh, Ramsey, & Sivaram (1999) have suggested that these MeV γ-rays may be produced through the inverse Compton scattering of electrons in the blob of a jet, with the UV photons of the accretion disk. Rapid structural changes in the radio jet of PKS 0528+134 have been detected, and it has also been found that enhanced γ-ray activity is related to the appearance of newer components in the jet (Britzen et al. 1999). This blazar has also displayed X-ray and optical variability (Sambruna et al. 1997 and references therein). Optical differential photometric CCD observations were carried out on nine nights at the VBO using the 2.34 m telescope during 1997 February through March (Table 2). Differences in magnitudes of PKS 0528+134 and the comparison star1 (S1) and the comparison star2 (S2) are plotted in the top and middle panels of Figure 3, and the bottom panel of this figure shows the differences in magnitudes between the two comparison stars (S1−S2). It can be seen from the bottom panel of this figure that these two stars did not vary during the interval of our observations. However, the blazar displayed irregular variability (Fig. 3, *top* and *middle*). Within

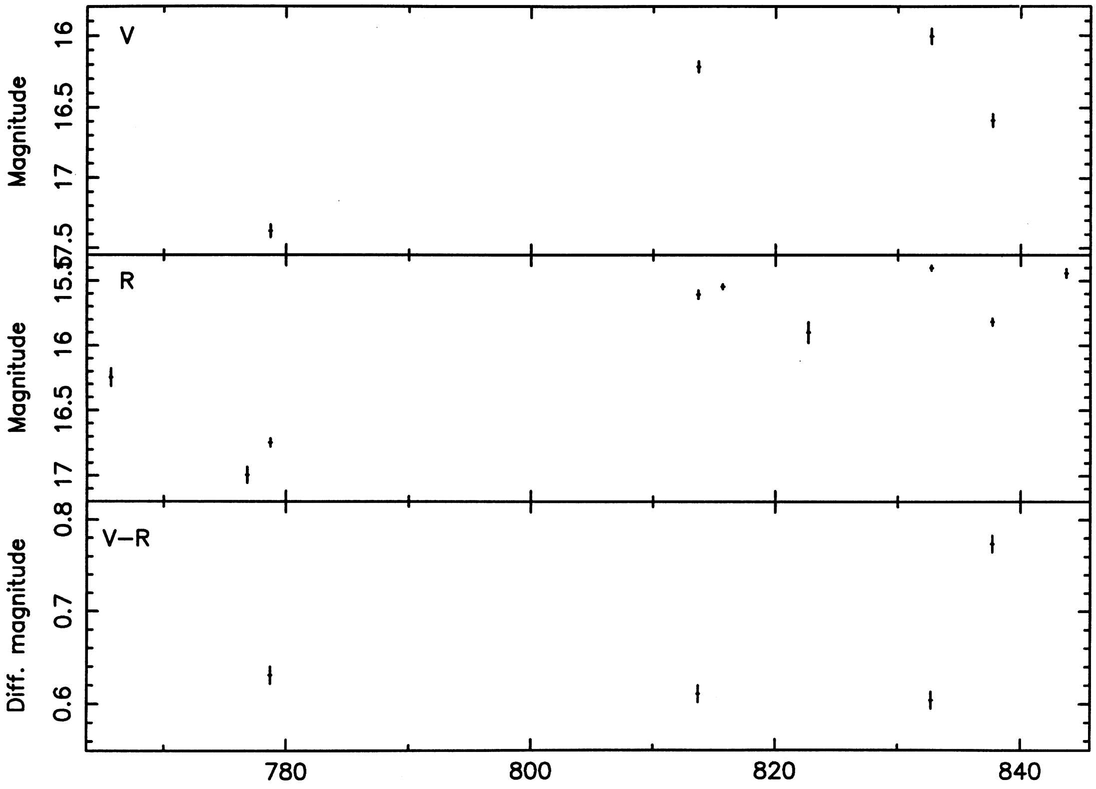

FIG. 2.—Same as Fig. 1, but for PKS 0235+164

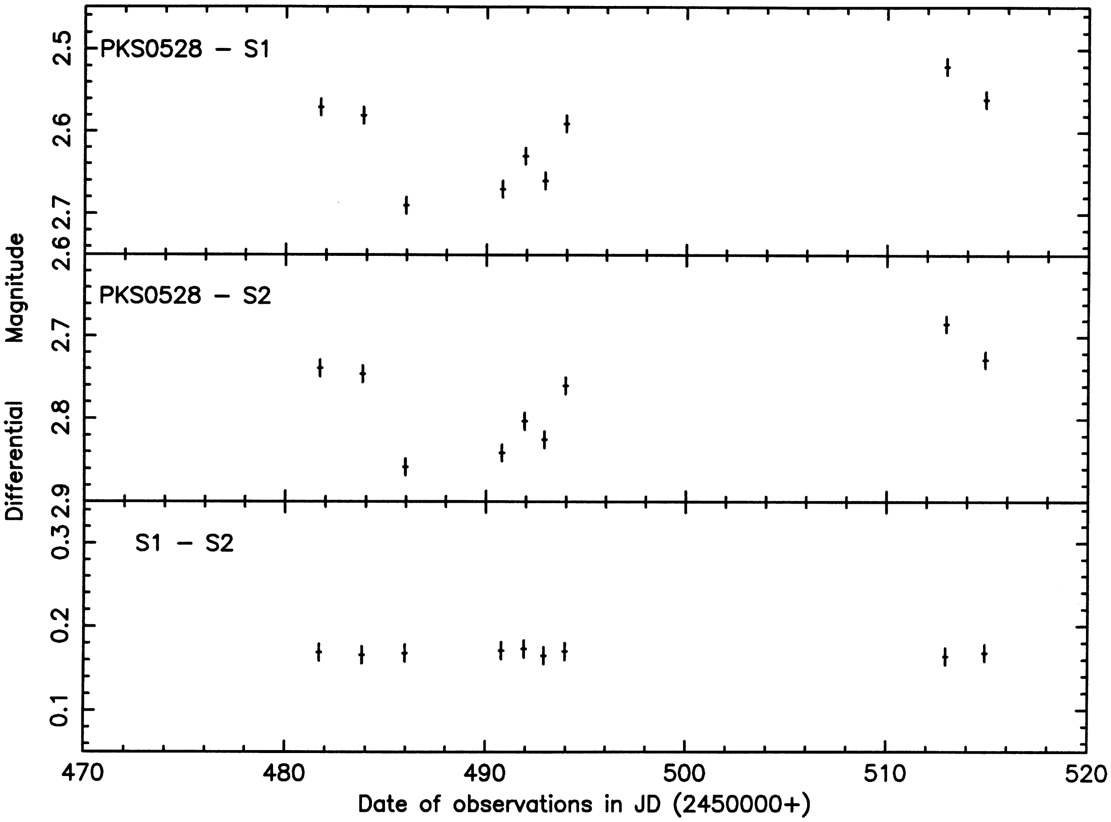

FIG. 3.—V-band differential photometric light curve of PKS 0528 + 134

two nights (1997 February 4–6; JD 2,450,484 and 2,450,486) PKS 0528 + 134 varied by around 0.1 ± 0.01 mag in the V band. This type of small amplitude fluctuation has also been detected by Raiteri et al. (1998), but they also detected a brightness increase of 0.65 mag in 15 days.

3.4. *PKS 0735 + 178 (OI +158)*

PKS 0735 + 178 is both radio- (Kuhr et al. 1981) and X-ray–selected (Elvis et al. 1992) BL Lac object. However, the multifrequency spectrum of this γ-ray blazar (Nolan et al. 1995) suggests that it is a low-energy peaked BL Lac object (LBL) (Urry et al. 1996; Sambruna, Maraschi, & Urry 1996; Kubo et al. 1997). Based on *VLBA* observations of this source at 22 and 43 GHz, Gomez et al. (1999) have detected a twisted jet with two sharp apparent bends (around 90°) within 2 mas of the core. Long-term optical variability of this source shows the possibility of 14.2 yr period (Fan et al. 1997 and references therein). PKS 0735 + 178 is also known as an optical and infrared intraday variable blazar (Bai et al. 1998; Massara et al. 1995; Heidt & Wagner 1996). We observed this source on 11 nights between 1997 November and 1998 April at the SBO (Table 3). Figure 4 shows the plot of V- and R-bands fluxes and the $V - R$ color index of this blazar. Night-to-night flux variations of PKS 0735 + 178 in the R band is clearly evident from this figure. Also Figure 4 shows that the brightness of this source increased by more than 1 mag in both V ($\Delta V = 1.17 \pm 0.03$ mag) and R ($\Delta R = 0.94 \pm 0.03$ mag) bands and the $V - R$ color index decreased by 0.22 mag during the interval of our observations. Variation of the $V - R$ color index indicates that the spectral index steepened by 0.84 ± 0.11 ($\Delta\alpha = 0.84 \pm 0.11$) when the source brightness increased by around 1 mag.

3.5. *PKS 0736 + 017 (OI +061)*

PKS 0736 + 017 is a FSRQ blazar (Padovani & Urry 1992; Wall & Peacock 1985) that resides at the center of an elliptical galaxy (Wright, McHardy, & Abraham 1998). This highly polarized blazar was observed on six nights in R band (Table 3) as plotted in Figure 5. Table 3 and Figure 5 show that this blazar displayed small amplitude ($\Delta R = 0.34 \pm 0.05$) variation on the timescale of six days. It also varied by around 0.65 ± 0.05 mag during the interval of our observations (between JD 2,450,776.9 and 2,450, 897.7).

3.6. *PKS 0754 + 100 (OI +090.4)*

PKS 0754 + 100 is a highly polarized (Mead et al. 1990) and highly variable ($\Delta B > 2$ mag during flare states) blazar that displayed variability on different timescales from hours to years (Pustilnik, Lyutyi, & Neizvestnyj 1981; Pica et al. 1988; Smith et al. 1987; Xie et al. 1991; Noble et al. 1997). The multifrequency (radio through X-ray) spectrum of this object suggest that it is an LBL blazar (Ghosh & Soundararajaperumal 1995). We observed this source on eight nights in the R band between 1997 November and 1998 April (Table 3). Figure 6 shows the plot of the R-band fluxes versus date of observations. Irregular variability of this blazar timescales of days to weeks can be seen from Figure 6 and Table 3.

3.7. *PKS 0851 + 202 (OJ 287)*

PKS 0851 + 202 is a member of the 1 Jy (Kuhr et al. 1981) and the *Einstein* Slew Survey sample (Elvis et al. 1992). OJ 287 is a superluminal source (Porcas 1987) and a γ-ray blazar (Hartman 1998). Long-term X-ray flux variability has been detected in this flat X-ray spectrum object

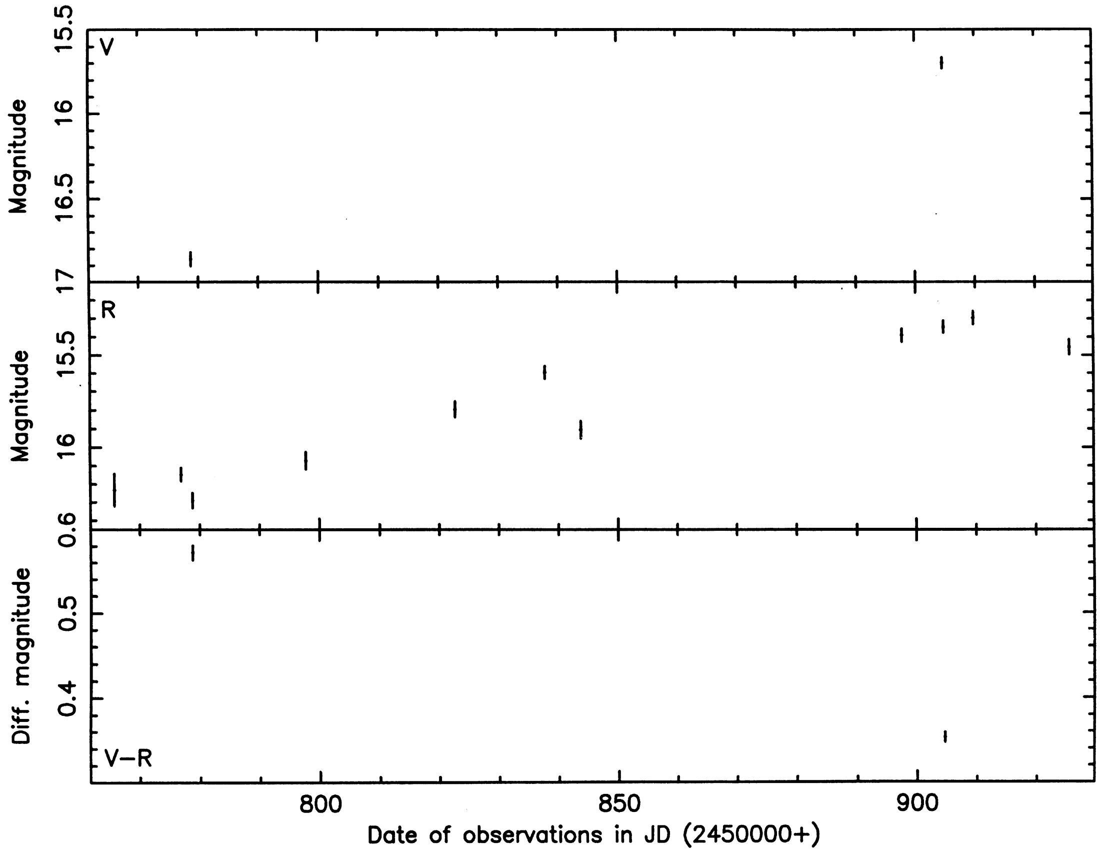

FIG. 4.—Same as Fig. 1, but for PKS 0735+178

(Makino 1989; Ghosh & Soundararajaperumal 1995; Urry et al. 1996; Kubo et al. 1997). Both sharp and broad emission lines are present in the optical spectrum of OJ 287 (Stickel et al. 1991 and references therein). This intranight optical and infrared variable source (Brindle 1996) also shows long-term optical variation that have been explained in the framework of a binary black hole model (Valtonen, Lehto, & Pietila 1999 and references therein). *R*-band photometric observations of this blazar were carried out on seven nights during 1997 December and 1998 April (Table 3). Figure 7 shows the plot of the *R*-band flux of OJ 287 that declined by more than 1 mag, during the interval of our observations (between JD 2,450,797.8 and 2,450,904.7). Also it shows that OJ 287 brightened by 0.34 ± 0.04 mag at the end of our observations (between JD 2,450,904.7 and 2,450,925.7).

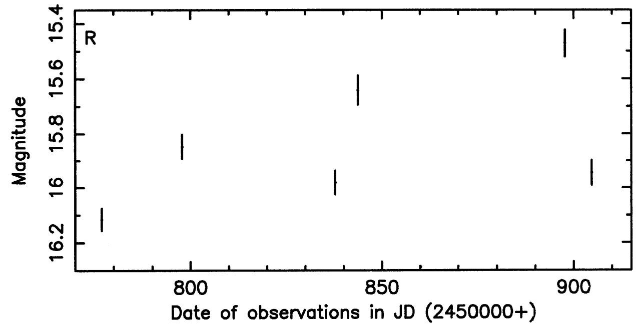

FIG. 5.—*R*-band photometric light curve of PKS 0736+017

3.8. *PKS 1156+295* (*4C +29.45*)

PKS 1156+295 is an OVV quasar ($\Delta V > 5$ mag during the optical outburst of spring 1981, Wills et al. 1983) with a flat radio spectrum ($\alpha = -0.1$). This highly polarized (Mead

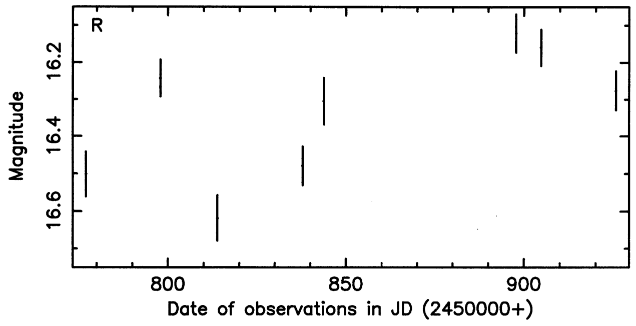

FIG. 6.—Same as Fig. 5, but for PKS 0754+100

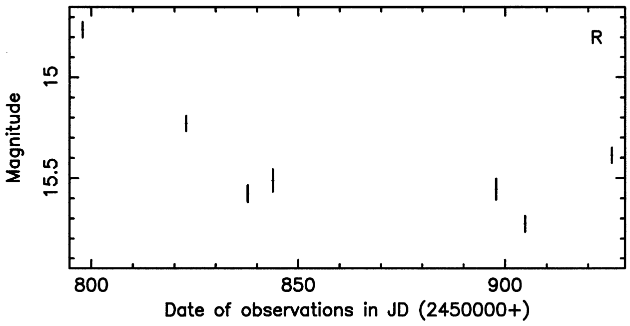

FIG. 7.—Same as Fig. 5, but for PKS 0851+202

et al. 1990) γ-ray blazar (Webb et al. 1994; Mukerjee et al. 1997) has shown rapid flux variability in γ-rays (Sreekumar et al. 1996). PKS 1156+295 has also displayed short- and long-term optical flux variability (Noble & Miller 1996; Guibin et al. 1998; Raiteri et al. 1998). Results of our *R*-band observations of this source are shown in Figure 8. It may seem from this figure that the brightness of this blazar in the *R* band decreased by 0.7 ± 0.03 and 1.7 ± 0.04 mag in the interval of a week (JD 2,450,897.9 to 2,450,904.8) and three months (JD 2,450,897.9 to 2,450,993.7), respectively.

3.9. *PKS 1226+023* (*3C 273*)

The 3C 273 blazer is a FSRQ (Wall & Peacock 1985; Padovani & Urry 1992) with superluminal jet (Zensus 1989) and was detected in γ-ray during EGRET phase 3 observations when it was in a high γ-ray state (von Montigny et al. 1997). Recently, Courvoisier (1998) and Turler et al. (1999) described this blazar in detail. We observed this object on two nights during 1998 January and could not detect any variations of this source. Results of our observations in B, *V*, and *R* bands are presented in Table 3.

3.10. *PKS 1253−055* (*3C 279*)

The 3C 279 blazar is a FSRQ, and this superluminal source is one of the brightest EGRET blazars (Hartman 1992; Kniffen et al. 1993) that displayed γ-ray flux variability on timescales of a few days (Sreekumar et al. 1996). Simultaneous radio through γ-ray observations of this active blazar (Villata et al. 1999) have constrained theoretical models to explain radiation mechanisms at different frequencies (Wehrle et al. 1998). Results of our observations of this source are presented in Table 3. It can be seen from this table that the brightness of this blazar in *V* and *R* bands increased by 0.6 ± 0.4 and 0.5 ± 0.4 mag, respectively, during the interval of our observations.

3.11. *PG 1418+546* (*OQ 530*)

The OQ 530 blazar is a member of the 1 Jy BL Lac sample (Kuhr et al. 1981) and is a highly polarized quasar (Mead et al. 1990). The multifrequency (radio through γ-ray) spectrum of this source suggests that it is an LBL object (Fossati et al. 1998 and references therein). This intraday optically variable blazar (Heidt & Wagner 1996) has also displayed rapid optical variability (Miller & Carini 1991). We observed this blazar on four nights during 1998 June–July (Table 3), and the results are plotted in Figure 9. This figure shows weak variations of this source on timescales of weeks.

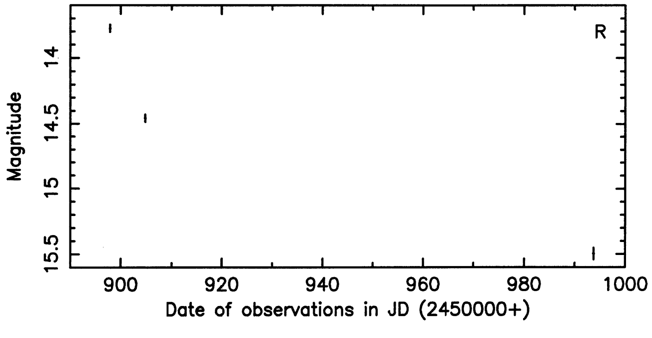

FIG. 8.—Same as Fig. 5, but for PKS 1156+295

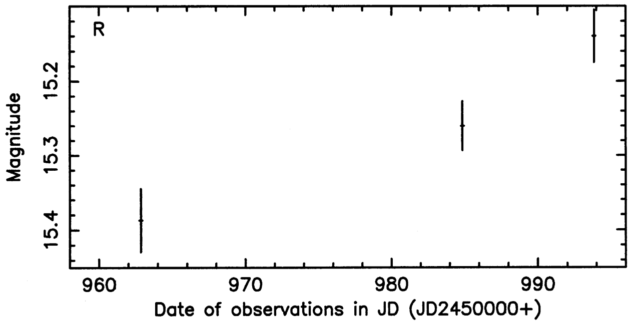

FIG. 9.—Same as Fig. 5, but for PG 1418+546

3.12. *PKS 1652+398* (*Mrk 501*)

Mrk 501 is a member of the 1 Jy (Kuhr et al. 1981) and the *Einstein* Slew Survey sample (Elvis et al. 1992) and is a well-known TeV γ-ray blazar (Bradbury et al. 1997; Aharonian et al. 1997, 1999). Even though Mrk 501 is a radio-loud blazar, the multifrequency spectrum of this source is very similar to that of an X-ray–selected BL Lac or high-energy peaked BL Lac object (HBL) (Ghosh & Soundararajaperumal 1995; Sambruna, Maraschi, & Urry 1996; Kubo et al. 1997). Mrk 501 has displayed optical variability on timescales of weeks (Heidt & Wagner 1996). To search for rapid variability on timescales of minutes to hours, we have carried out *V*-band CCD differential photometric observations of this blazar on 10 nights between 1997 March and June, at the VBO. In total, we obtained 72 CCD frames of Mrk 501 of 6.5×10^4 s exposure (Table 2). This blazar displayed rapid variability on seven nights. Figure 10*a* shows the differential magnitude variation of Mrk 501 that was observed on 1997 March 16. The top and middle panels show the differential magnitude between Mrk 501 and the two comparison stars, S1 and S2. The bottom panel displays the differences in magnitude between the two comparison stars. It can be seen from this figure (*top* and *middle*) that the brightness of this source decreased and increased by around 0.13 ± 0.02 mag in the interval of 14 and 12 minutes, respectively. Figure 10*b* shows that this blazar was not very active (only 0.04 mag variation in 29 minutes and then remained almost steady) until it displayed rapid variability on 1997 April 29. Figure 10*c* displays the brightness variation of this source by 0.08 mag in 12 minutes, on 1997 June 1. Here we do not present the results of seven other nights that were very similar to the results presented in Figures 10*a*–10*c*. Figure 10*a* shows large amplitude (0.13 ± 0.02 mag) variation on a short timescale (~ 12 minutes) when Mrk 501 was not in a flare state (Fig. 10*d*). This will be a new result, if it is real. Thus it is important to check the reality of such results that are primarily based upon a single observational data point. Artificial rapid variations in brightness can be caused by the variable seeing for an object with an extended galaxy component. Mrk 501 resides at the center of an extended host galaxy, and variable seeing may introduce rapid variations similar to the one presented in Figure 10*a*. To check the reality of the observed variability we have carried out photometric analysis using apertures of $4''$ and $10''$ diameter rather than the $7''$ diameter aperture that was used earlier. We obtained rather than similar results (0.11 ± 0.02 mag variability) using the variable aperture photometry.

Also, we have carried out another test to check the results presented in Figure 10*a*. On the night of 1997 March 16, we

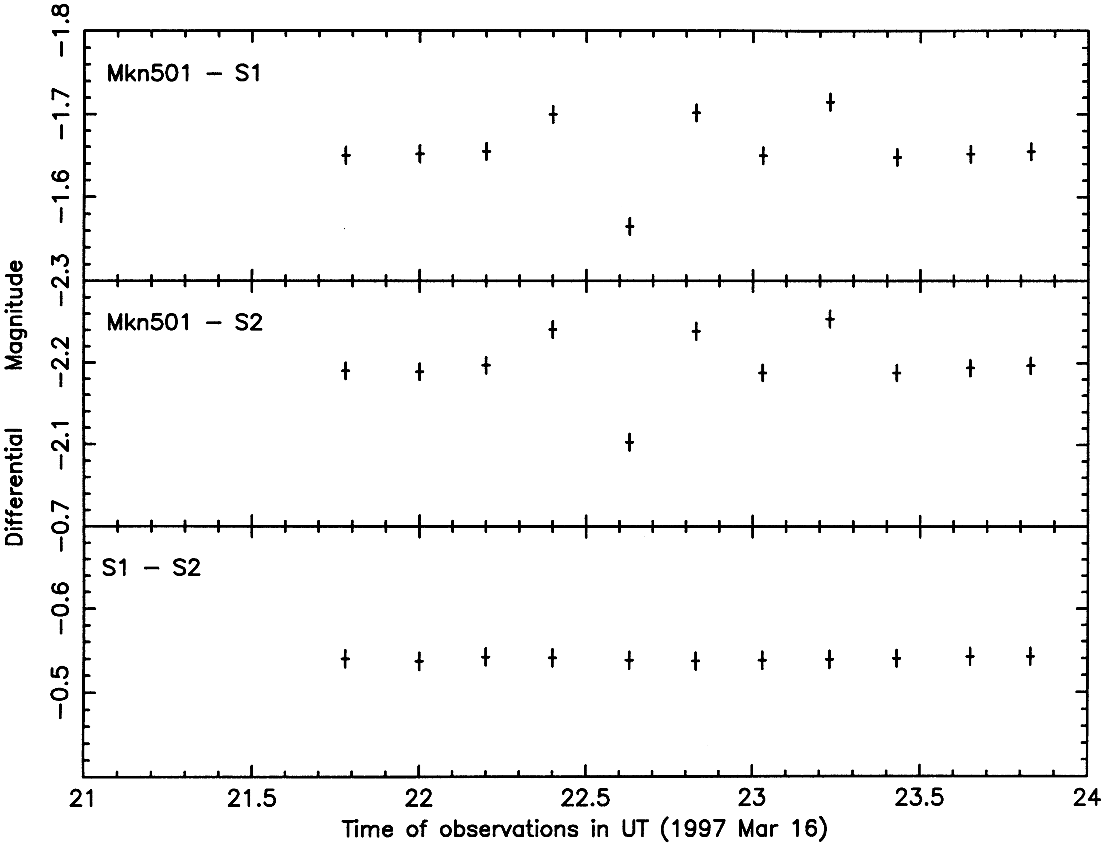

FIG. 10*a*

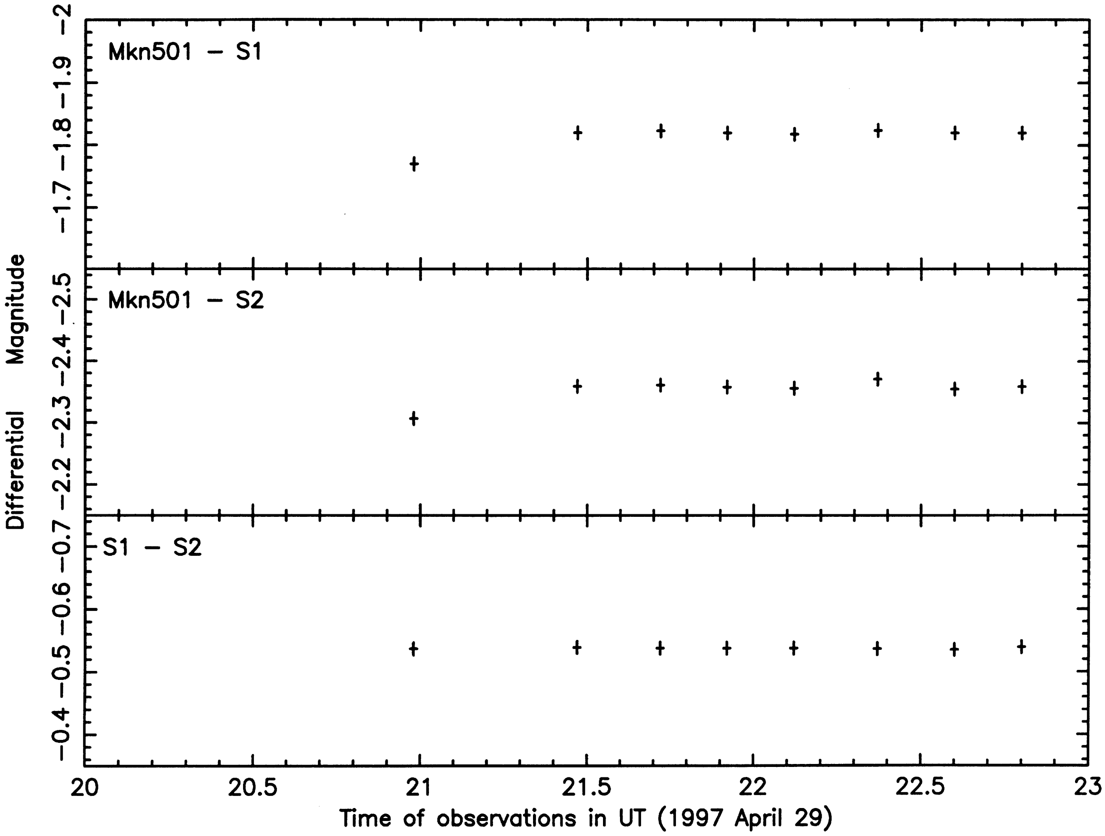

FIG. 10*b*

FIG. 10.—(*a*) Differential intranight light curve of Mrk 501 in V band observed on 1997 March 16. (*b*) Same as Fig. 10*a* but for 1997 April 29. (*c*) Same as Fig. 10*a*, but for 1997 June 01. (*d*) Same as Fig. 3, but for Mrk 501.

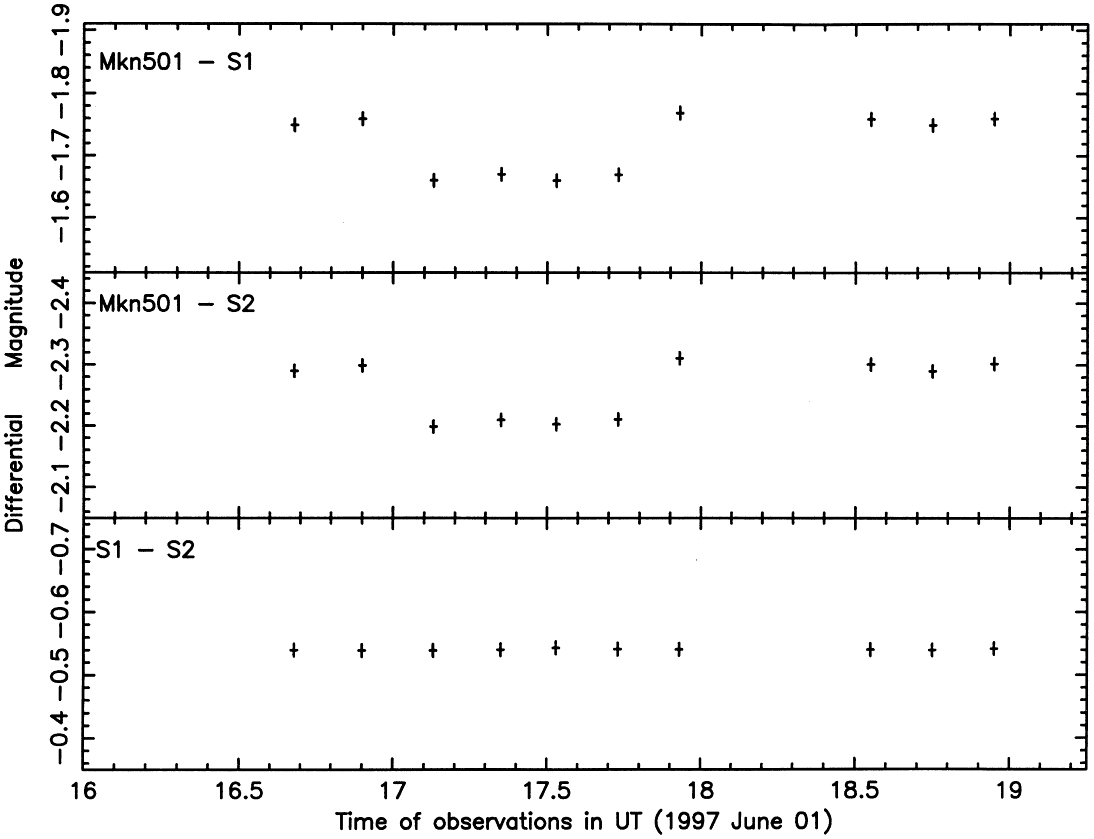

FIG. 10*c*

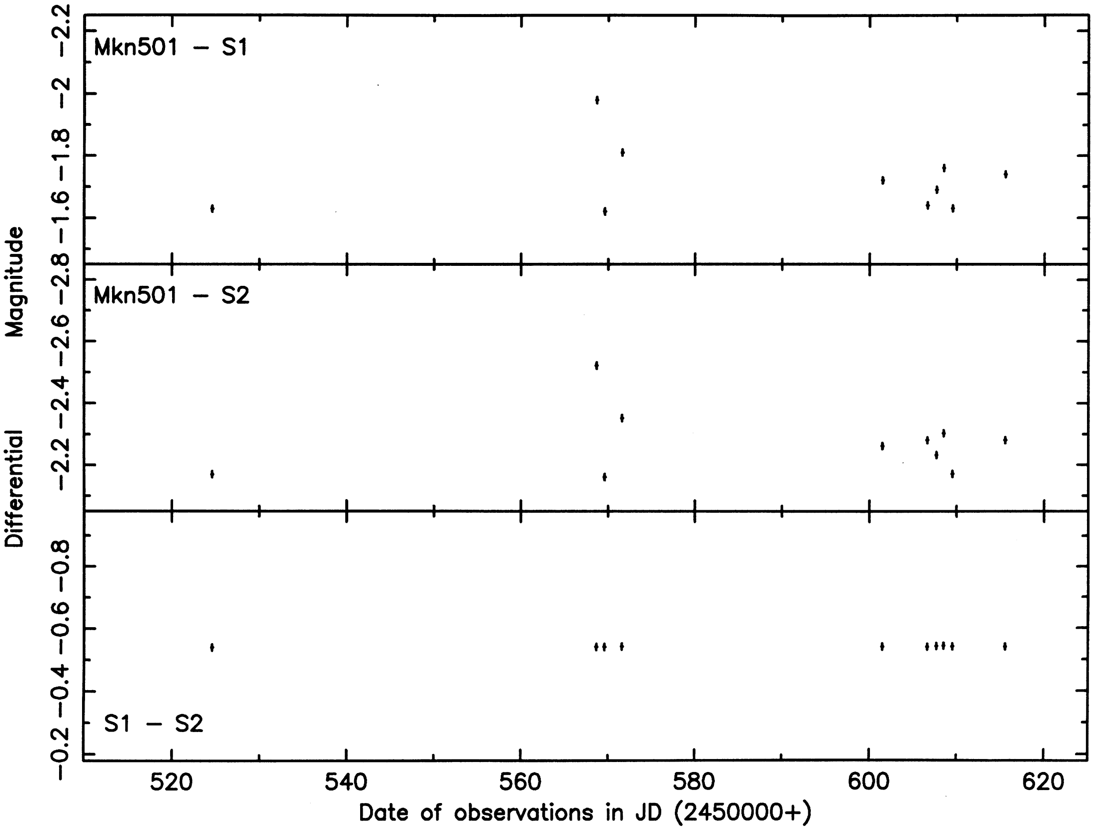

FIG. 10*d*

obtained observations of 11 CCD image frames of Mrk 501 and Figure 10*a* shows the plot of these results. It may be seen from this figure that the first and last three CCD frames did not display any variations of Mrk 501. Using these six frames, we created an average image frame and then subtracted this frame from all the aligned CCD image frames. Then the subtracted CCD image frames were used for photometry and we obtained the similar light curve that is shown in Figure 10*a*. We also obtained similar type of light curve of Mrk 501 from our observations that were carried out on 1997 May 2 (around 0.1 mag in 22 minutes).

Similar type of variability (decrease and increase of brightness on timescales of minutes) of other blazars has also been reported by different authors (Bai et al. 1998; Guibin et al. 1998 and references therein). Based on all these results, we will consider that the rapid variations detected in Mrk 501 (Figs. 10*a*–10*c*) are real and not due to the artifact of seeing. Significance of these variations will be discussed in the next section.

3.13. *3C 390.3* (*NRAO 582*)

The 3C 390.3 blazar is a double-lobed, broad line radio galaxy, which is also known as a highly polarized quasar (Angel & Stockman 1980; Ledden & O'Dell 1985; Burbidge & Hewitt 1992) and a superluminal source (Porcas 1987). Variability at different frequencies (radio through X-ray) has been detected in this object (Ghosh & Soundararajaperumal 1991; Grandi et al. 1999; O'Brien et al. 1998; Dietrich et al. 1998 and references therein). The multifrequency (radio through X-ray) spectrum of 3C 390.3 is very similar to that of the radio-selected BL Lacs or LBLs (Ghosh & Soundararajaperumal 1995). We observed this blazar on 15 nights between 1995 March and October (Table 2). During the interval of our observations, we could detect short-term (on the timescales of hours) small-amplitude (0.05 ± 0.02 mag) variations of 3C 390.3 only on three nights and such variations were absent on the remaining eight nights. These small-amplitude variations were only at a 2–2.5 σ detection limit, so here we will not consider these variations to be real. Figure 11 shows the long-term flux (V-band) variations of 3C 390.3. It may be seen from this figure that this blazar displayed night-to-night variations by 0.12 ± 0.02 mag (between 1995 March 7 and 8) and 0.16 ± 0.02 mag (between 1995 May 22 and 23). Low-amplitude variations on longer timescales were also present in this source.

3.14. *PKS 2223−052* (*3C 446*)

The 3C 446 blazar is a member of the 2 Jy sample (Wall & Peacock 1985) with a curved jet (Fejes, Porcas, & Akujor 1992). This highly polarized quasar (Mead et al. 1990) is optically variable (Barbieri et al. 1990). References on radio through X-ray observations of this blazar can be seen in Fossati et al. (1998). PKS 2223−052 was observed on three nights during 1997 June at the VBO (Table 2). Differential magnitudes of 3C 446 in V band is plotted in Figure 12. This figure shows that this blazar displayed weak variations ($\Delta V = 0.15 \pm 0.02$ mag) in the interval of a week (between 1997 June 8 and 15).

3.15. *PKS 2232+114* (*CTA 102*)

CTA 102 is a member of the 2 Jy sample (Wall & Peacock 1985) and a γ-ray blazar (Lin et al. 1996; Nolan et al. 1993; Mukherjee et al. 1997). This source has displayed optical

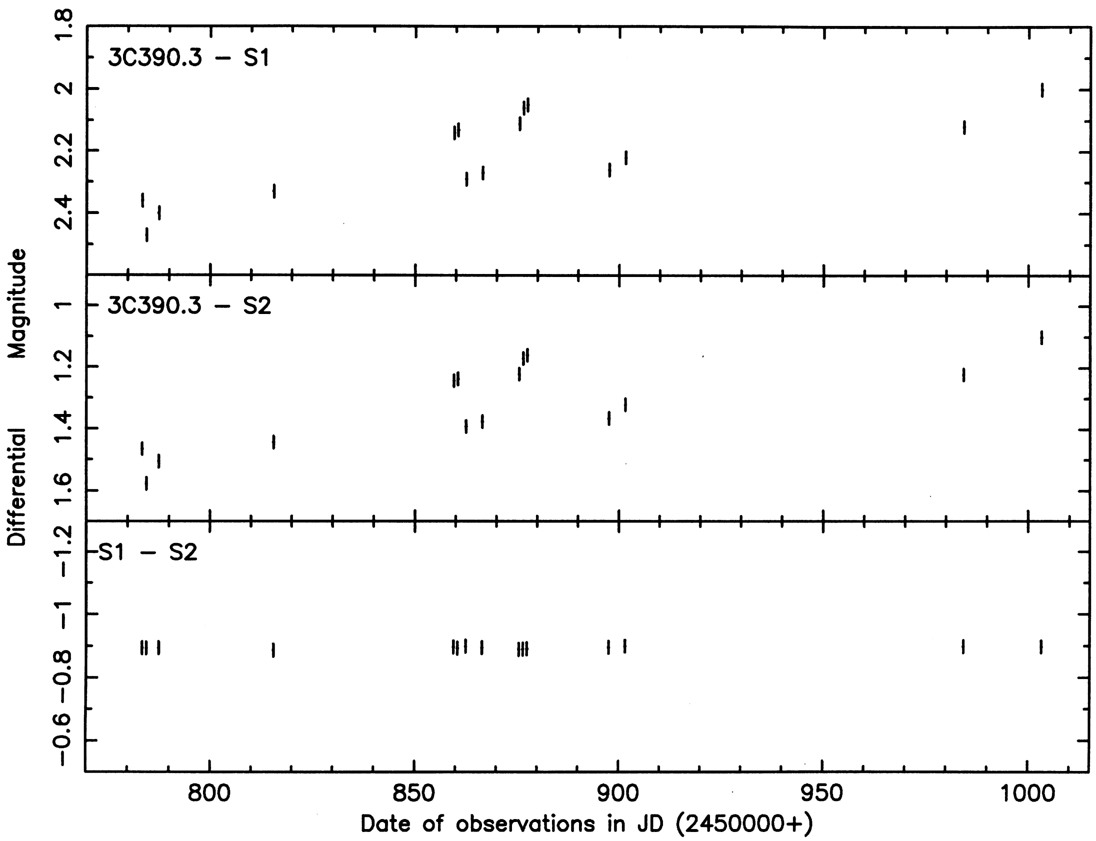

FIG. 11.—Same as Fig. 3, but for 3C 390.3

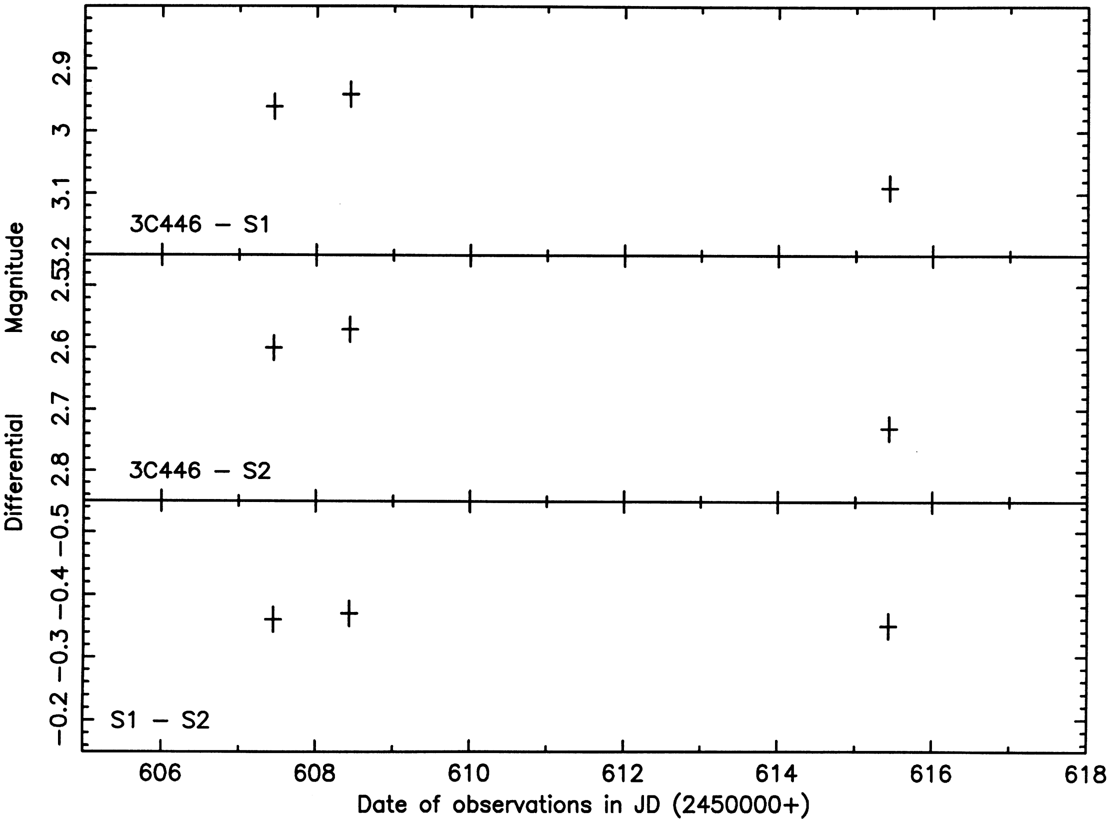

FIG. 12.—Same as Fig. 3, but for 3C 446

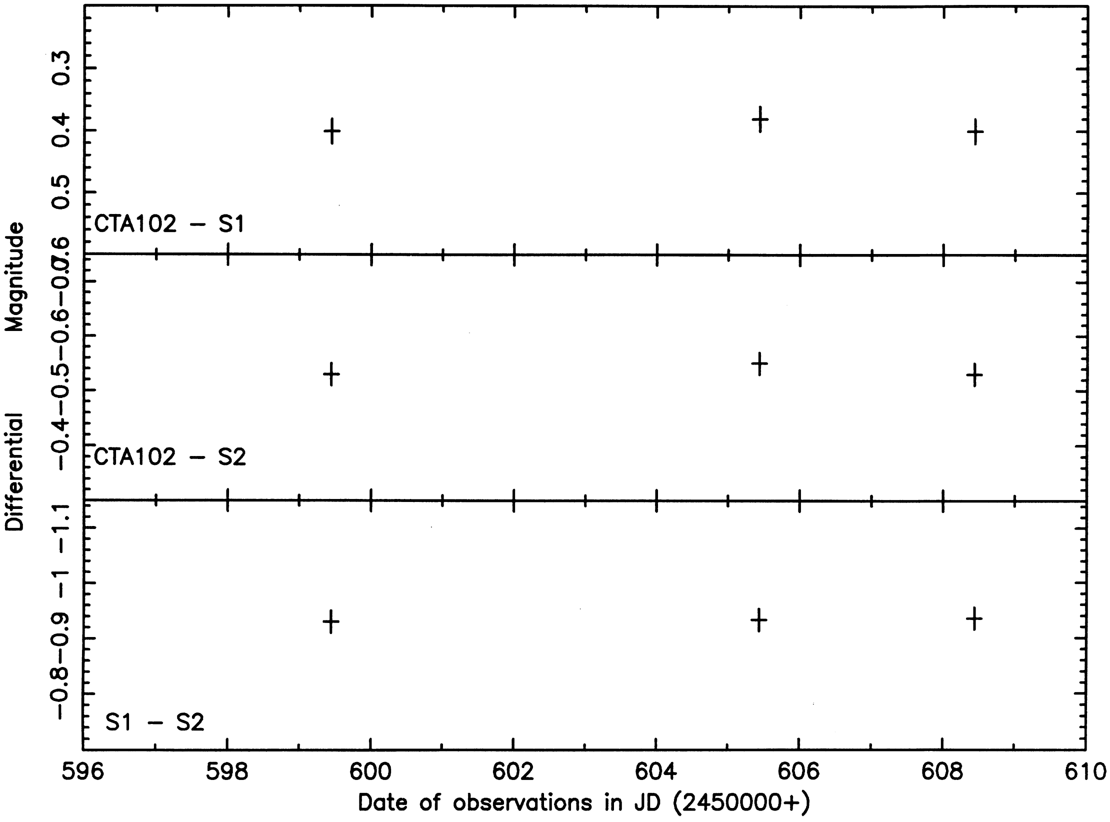

FIG. 13.—Same as Fig. 3, but for CTA 102

variability with an oscillating behavior (Raiteri et al. 1998). Changes in structures of radio jets have also been detected in this blazar (Rantakyroe et al. 1996; 1998). We carried out V-band CCD differential photometric observations of this blazar on three nights at the VBO, during 1997 May through June. Figure 13 shows the plot of V-band brightness versus date of observations of CTA 102. It may be seen from this figure that this blazar did not vary during the interval of our observations.

4. DISCUSSION AND CONCLUSIONS

The five blazars, PKS 0528+134 (OG +147), PKS 1652+398 (Mrk 501), 3C 390.3 (NRAO 582), PKS 2223−052 (3C 446), and PKS 2232+114 (CTA 102), were all observed for microvariability studies on timescales from minutes to hours. From the results of our observations we have found that only OJ 287 and Mrk 501 displayed microvariability on timescales of hours and minutes, respectively, and the remaining four blazars (poor sampling, around two to four observations per night per blazar) did not show any such variations. On seven nights (out of ten) we detected short timescale variability of Mrk 501. Small, medium, and large amplitude variability of this blazar are presented in Figure 10*b* (0.04 mag in 29 minutes), Figure 10*c* (0.08 mag in 12 minutes) and Figure 10*a* (0.13 mag in 12 minutes), respectively. There is a possibility that such variations may also be due to instrumental variations. To check this, we carried out repeated data analysis of this source and obtained very similar results using different nonvariable comparison stars. Next, we looked at the results of other blazars that were observed on the same night using the same instrumentation. We could not detect any such rapid variations (or even variations within the night on timescales of hours) in other blazars (3C 446, CTA 102). Thus we concluded that the observed variations in Mrk 501 were intrinsic to the source. Such rapid variations have also been detected in other blazars (Guibin et al. 1998; Raiteri et al. 1998; Wagner & Witzel 1995 and references therein).

The observed variability of Mrk 501 by 0.13 mag within 12 minutes is an important result that can be used to compute the efficiency (η) for conversion of accreted matter into energy. If ΔL is the change in luminosity within the time interval Δt, then η can be written as

$$\eta \geq 5.0 \times 10^{-43} \frac{\Delta L}{\Delta t} \tag{2}$$

(Guibin et al. 1998), where ΔL is in ergs s^{-1} and Δt in seconds. Extinction- and K-corrected value of ΔL is 2.1×10^{44} ergs s^{-1}. Using equation (2) with this value of ΔL, and Δt equal to 720 s, we find $\eta \geq 0.15$. This value of η suggest the presence of relativistic beaming in Mrk 501 (Guilbert et al. 1983; relativistic beaming is inferred if $\eta > 0.1$). Now the value of Δt an be used to compute the Doppler beaming factor, δ, and is given by

$$\delta \geq 1.6 \times 10^{12} \frac{L_{\text{sync}}}{c^3(\Delta t)} \left(\frac{L_{\text{sync}}}{L_{\text{SSC}}}\right) \frac{v_{\text{SSC}}^2}{v_{\text{sync}}^4} \tag{3}$$

(Kubo et al. 1998), where L_{sync} and L_{SSC} are the synchrotron and the SSC luminosities, v_{sync} and v_{SSC}, respectively, are the peak frequencies of the synchrotron and the SSC components of the multifrequency (radio through γ-ray) spectrum of Mrk 501, respectively, and c is the velocity of light (details can be seen in Kubo et al. 1998). Values of L_{sync}, L_{SSC}, v_{sync}, and v_{SSC} for Mrk 501 have been obtained from Kubo et al. (1998) and using $\Delta t = 720$ s, we obtained a value of $\delta = 4.3$, from equation (3). Again this value of δ can be used to compute the size of the emission region, R, using the light travel time argument that

$$R \leq \frac{c\delta\Delta t}{1+z} . \tag{4}$$

The resulting value of R from equation (4) is 9×10^{13} cm. Most probably this is the size of the emitting region. This emitting region may be a blob within the jet that produces the observed variability. There are other mechanisms like eclipsing of hot spots by the accretion disk or microflares in the accretion disk (Wiita 1996) that may also explain the rapid variability of blazars. However, these mechanisms may not be able to explain the rapid oscillating variations of blazars (Nesci et al. 1998 and references therein). It has been suggested that the turbulent magnetic field in the relativistic jet may produce the rapidly oscillating variations seen in some blazars (Massaro et al. 1998; Nesci et al. 1998). Among different models, the relativistic model appears to be the most promising to explain the observed rapid variations in Mrk 501. Future, multiband microvariability studies of blazars will be very useful to check the relativistic jet model in detail.

Results of long-term variability of 15 blazars are presented in Table 3 and Figures 1–9, 10*d*, and Figures 11–13. These results can be used to determine relationships between the redshift, luminosity, and the amplitude of variability of these blazars. To find out the amplitude of variability (from our results), we have selected all observed variations on different timescales and then computed the amplitude of variability per day for all the observed blazars. The values of the highest amplitude of variability of these blazars were then plotted against their redshift and luminosity (assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$, and K-correction and correction for the galactic extinction were applied). From these plots we do not find any relationship between the amplitude of variability and the redshift or between the amplitude of variability and the luminosity of our set of 15 blazars. These results are not in agreement with earlier results obtained by different investigators, who found that the amplitude of variability are correlated with the redshift and anticorrelated with the luminosity of blazars (Hook et al. 1994; Christiani et al. 1996; Di Clemente et al. 1996). Since most of the blazars of Table 1 were observed for long-term variability studies (only five blazars of Table 2 were observed for short- and long-term variability studies, and only Mrk 501 displayed variability on timescales of minutes), it is not possible to search for the shortest timescale of variability. Therefore with these data it is not possible to study the relationship between the timescales of variability and the redshift or the luminosity.

From V- and R-band photometry of 3C 66A we have found two type of variations of the $V-R$ color index (Fig. 1 and Table 3). When the brightness of this source in the V band was almost constant and the brightness in the R band decreased, the $V-R$ color index decreased, which indicates a flattening of the spectral index of 3C 66A between the V and R bands. Then we have also seen that when the brightness decreased in both V and R bands the spectrum became steeper. Such variations of V, R, and $V-R$ have also been found in PKS 0235+164 between JD 2,450,832.7 and

2,450,837.7 (Fig. 2). However, it is important to mention here that in PKS 0235+164, the spectral index remained almost constant (the $V-R$ color index did not vary) when the source brightness gradually increased in both V and R bands, between JD 2,450,778.7 and 2,450,832.7. Again, it can be seen from Figure 4 that the spectral slope of PKS 0735+178 steepened when the source brightness gradually increased in both V and R bands ($V-R$ color index decreased). It has been found by different investigators that the amplitude of the variations is systematically larger at higher frequency, which suggests that the spectrum becomes steeper when the brightness of the source decreases and flatter when it increases (Racine 1970; Gear, Robson & Brown 1986; Massaro et al. 1998; Ghisellini et al. 1997; Maesano et al. 1997). From our observations we have also found that the amplitude of the variations in the V band is larger than that of the R band. However, there were occasions when the amplitude of the variations was comparable in both V and R bands or was larger at the R band than that at the V band. Here we should mention that these results are not due to artifact of the observational errors, because the amplitude of the variation is much larger than the errors in measuring the $V-R$ color index. Thus, based on our results we suggest that it may not be correct to generalize that the amplitude of the variation in blazars is systematically larger at higher frequency. This complex variation of the $V-R$ color index needs to be addressed in future models of blazars.

It can be seen from Figures 1–13 that most of the observed blazars displayed smaller amplitude oscillating behavior superposed on the long-term steady increase or decrease of the brightness of the source. Such variations are also clearly evident during the major outburst of blazars, and it cannot be explained using the decay timescales in terms of pure radiative cooling of a relativistic electron population emitting by a synchrotron mechanism (Nesci et al. 1998 and references therein). If most of the optical radiation is emitted from the jets of blazars through the synchrotron mechanism, the oscillating behavior indicates the oscillation of the local magnetic field in the jet. Probably variations in the populations of energetic electrons that carry frozen magnetic fields with them produce oscillations of the local magnetic field in the jet, and that may result in the oscillating behavior of the source. Also, this oscillating magnetic field may be able to explain the complex variations of the $V-R$ color index of the observed blazars.

Further analysis should be done on the microvariability data, especially of Mrk 501, and on any future data taken of that object and others. Nonlinear time series analysis ideally suited for this kind of work would include singular value decomposition (principle component analysis), phase-space plots, and wavelet transforms. Such analysis may allow us to discriminate between the prevailing models of microvariability, as described in § 1.

We found little correlation between amplitude of variability, redshift, and luminosity. Some groups have found such correlations, and others have not. It is suggested that further studies be made of these variables, with more sources, and better grouping according to classification. Perhaps then we can find correlations if they exist, and be able to interpret their meaning.

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