THE ASTRONOMICAL JOURNAL, 122:2901–2912, 2001 December


# RAPID OPTICAL VARIABILITY OF GAMMA-RAY–LOUD BLAZARS

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*Received 2001 May 16; accepted 2001 September 20*

## ABSTRACT

We present the optical (*B*, *V*, and *R*) photometry for nine GeV and/or TeV γ-ray blazars, which were observed from 2000 through 2001 with the 1 m telescope at Yunnan Astronomical Observatory. The GeV γ-ray–loud source PKS 1510−089 was very active during our observation period, showing an apparent variation of 2.0 mag within 41 minutes in the *R* band. This is the most violently rapid variability in our optical monitoring program since 1982. Some physics parameters are calculated for this source, namely, the emission size, Doppler factor $\delta$, the efficiency ($\eta$) for conversion of accreted matter into energy, and luminosity. An $\eta = 62.2$ was obtained, strongly implying that relativistic beaming is responsible for the rapid variability of the γ-ray–loud source. The influence of variable seeing conditions on the observations was investigated. There is a weak correlation between the observed variability and the local seeing conditions for the object 1ES 2344+51.4.

*Key words:* BL Lacertae objects: general — galaxies: active — galaxies: photometry — quasars: general

## 1. INTRODUCTION

Variability is one of the important 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 over a 15 minute period. The existence of microvariations (i.e., variations with durations extending from minutes to days that are either discrete events or parts of longer term trends) in the optical flux of blazars has been well established in some blazars, such as BL Lacertae, OQ 530, AP Librae, OJ 287, OI 090.4, PKS 2155−304, and 3C 371 (Miller, Carini, & Goodrich 1989; Carini, Miller, & Goodrich 1990; Carini et al. 1991, 1992; Carini & Miller 1992; Carini, Noble, & Miller 1998; Noble et al. 1997). Variability on short timescales, from minutes to hours, is also observed in many other objects (Smith et al. 1987; Romero et al. 1997; Romero, Cellone, & Combi 1999; Heidt & Wagner 1996, 1998; Villata et al. 1997; Takalo 1994; Bai et al. 1998, 1999; Xie et al. 1999, 2001; Ghosh et al. 2000; Cellone, Romero, & Combi 2000; Fan & Lin 2000; Fan et al. 2001a, 2001b).

In recent years, high-energy γ-rays have come to play an important role in the study of AGNs. Before the launch of the *Compton Gamma Ray Observatory* (*CGRO*) in 1991, the only known extragalactic source of high-energy γ-rays was 3C 273, which had been detected with the *COS B* satellite 20 years ago (Swanenburg et al. 1978). The EGRET detector on *CGRO* has identified 66 AGNs that emit γ-rays at energies above 100 MeV (Hartman et al. 1999), and a substantial fraction of those sources that remain unidentified in the EGRET catalog are likely to be AGNs as well. In addition, five AGNs have been discovered to be TeV (>300 GeV) γ-rays sources; all of them are nearby BL Lac objects. These objects are Mrk 421 ($z = 0.031$; Punch et al. 1992), Mrk 501 ($z = 0.034$; Quinn et al. 1996), 1ES 2344+51.4 ($z = 0.044$; Catanese et al. 1998), PKS 2155−304 ($z = 0.117$; Chadwick et al. 1999), and 3C 66A ($z = 0.444$; Neshpor et al. 1998). During γ-ray flaring episodes, the γ-ray emission can greatly exceed the energy output of the AGNs at all other wavelengths, and it always accompanies flares in other bands.

All of the AGNs detected in high-energy γ-rays are radio-loud sources, with the radio emission arising primarily from a core region rather than a lobe. These types of AGNs are often collectively referred as blazars, which include BL Lac objects and flat-spectrum radio-loud quasars (Urry & Padovani 1995). The emission characteristics of blazars include high polarization at radio and optical wavelengths, rapid variability at all wavelengths, and predominant nonthermal emission at most wavelengths. The emission from blazars is believed to arise from a relativistic jet oriented at small angles to the line of sight (Blandford & Rees 1978; Blandford & Königl 1979). Through optical observations of strong γ-ray–emitting blazars, it is possible to obtain information about the mechanism that governs the production of the seed photons from the γ-ray radiation. The variability is very important for studies of theoretical models of blazar emission, and the timescale of variability can be used to estimate an AGN's physical parameters (Miller et al. 1989; Carini et al. 1990; 1991; Xie, Zhang, & Fan 1997; Ghosh et al. 2000; Cheng, Fan, & Zhang 1999; Fan, Xie, & Bacon 1999).

In the present paper, we report optical observations of γ-ray–loud blazars undertaken with the 1 m telescope at Yunnan Astronomical Observatory during 2000 and 2001. In § 2, we present the observations and data reduction; in § 3, the contribution of the host galaxy to the macrovariability is discussed; in § 4, the observational results and analysis; and in § 5, our conclusions and a discussion. Throughout this paper $q_0 = 0.5$ and $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ are adopted.

## 2. OBSERVATIONS AND DATA REDUCTIONS

The optical observations were carried out at Yunnan Astronomical Observatory with the 1 m telescope equipped with a direct CCD (1024 × 1024 pixels) camera at the Cass-

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egrain focus, whose plate scale is 0".38 pixel$^{-1}$ (field about 6'.5 × 6'.5). The CCD was bought from Princeton Instruments Company. The readout noise and gain were 3.9 $e^-$ 4.0 $e^-$ ADU$^{-1}$. The filters used are standard Johnson broadband filters, as follows: $B$ = GG 385 (2 mm) + BG 12 (1 mm) + BG 18 (1 mm), $V$ = GG 495 (2 mm) + BG 18 (2 mm), $R$ = RG 610 (3 mm) + 66.2500 (1 mm), and $I$ = RG 715 (3 mm) + 60.5050 (1 mm). The integration time is 300–400 s for $B$ and $V$ filters, and 100–200 s for $R$ and $I$ filters. Photometry was obtained by observing standard stars taken from the literature (Craine 1977; Smith et al. 1985; Smith, Jannuzi, & Elston 1991; Fiorucci & Tosti 1996; Fiorucci, Tosti, & Rizzi 1998; Raiteri et al. 1998; Villata et al. 1998) in the fields of these blazars. These standard stars are presented in Table 1.

The data reduction was made following standard procedures with the IRAF software package running on a Linux computer after bias, dark, and flat-field corrections. The bias frames (at least 15 images each night) were taken at the beginning and the end of the night's observation. The flat-field images were taken at dusk and dawn, when possible. The object and comparison stars were both reduced with the same size aperture, and the aperture was the same over the length of the each night observations. Magnitude measurements were made relative to comparison stars in the same frame with the aperture photometry routine APPHOT, using aperture size 6"–10" for different objects. Finally, we obtained the total integrated instrumental magnitudes of all the objects in the field. The source magnitude is given as the average of those derived with respect to all the comparison stars in the image frame containing the source.

We determined the differential magnitudes of $S-1$ and $2-1$ from the instrumental magnitudes of the observational source ($S$), and two well-behaved standard stars, comparison star 1 and comparison star 2, were selected. The curves $2-1$ indicate observational uncertainties and the intrinsic variability of the stars. The variability of the source is investigated by means of the variability parameter $C$ introduced by Romero (Romero et al. 1999; see also Fan et al. 2001a, 2001b and Cellone et al. 2000). The scatter of the differential magnitudes $S-1$ and $2-1$, $\sigma_{S-1}$ and $\sigma_{2-1}$, the variability parameters $C$ is expressed as $\sigma_{S-1}/\sigma_{2-1}$. If $C > 3$, then the source is variable.

TABLE 1

STANDARD STARS

| Object | Star | $B$ ($\sigma$) | $V$ ($\sigma$) | $R$ ($\sigma$) | $I$ ($\sigma$) | Ref. |
|---|---|---|---|---|---|---|
| 0219+428 (3C 66A) .......... | A | 14.02 | 13.56 | 13.36 (0.03) | 13.01 (0.03) | 1 |
| | B | 15.77 | 14.77 | ... | ... | |
| | C | 16.28 | 15.75 | ... | ... | 2 |
| | D | 17.78 | 16.90 | ... | ... | |
| PKS 0420−01 (0F035) ........ | 2 | 13.64 (0.03) | 13.15 (0.02) | 12.81 (0.02) | ... | 3 |
| | 4 | 15.69 (0.03) | 14.95 (0.03) | 14.47 (0.03) | ... | |
| | 8 | ... | 15.99 (0.03) | 15.46 (0.03) | ... | |
| | 9 | ... | 16.29 (0.03) | 15.58 (0.03) | ... | |
| 1253−055 (3C 279) ........... | 1 | 13.02 (0.03) | 12.42 (0.03) | 12.05 (0.02) | ... | 3 |
| | 2 | 13.73 (0.04) | 12.99 (0.04) | 12.56 (0.03) | ... | |
| | 3 | 15.49 (0.03) | 14.87 (0.03) | 14.53 (0.02) | ... | |
| | 4 | 16.53 (0.05) | 15.66 (0.03) | 15.13 (0.02) | ... | |
| | 5 | 16.79 (0.04) | 15.98 (0.04) | 15.47 (0.02) | ... | |
| PKS 1510−089 ............... | 1 | 12.13 (0.03) | 11.54 (0.02) | 11.14 (0.02) | ... | 3 |
| | 2 | 13.65 (0.03) | 13.17 (0.02) | 12.88 (0.03) | ... | |
| | 3 | 15.06 (0.04) | 14.35 (0.02) | 13.95 (0.03) | ... | |
| | 4 | 15.27 (0.02) | 14.59 (0.02) | 14.22 (0.03) | ... | |
| | 5 | 15.43 (0.05) | 14.70 (0.03) | 14.35 (0.05) | ... | |
| | 6 | 16.09 (0.04) | 15.16 (0.02) | 14.61 (0.02) | ... | |
| 1652+398 (Mrk 501) .......... | 1 | 13.55 (0.03) | 12.61 (0.02) | 12.11 (0.02) | ... | |
| | 2 | 14.10 (0.03) | 13.23 (0.02) | 12.79 (0.02) | ... | 4 |
| | 3 | 15.98 (0.04) | 15.24 (0.02) | 14.80 (0.02) | ... | |
| | 4 | 16.05 (0.05) | 15.30 (0.02) | 14.96 (0.02) | ... | |
| | 5 | 16.27 (0.04) | 15.51 (0.02) | 15.08 (0.02) | ... | |
| | 6 | 16.82 (0.05) | 15.67 (0.04) | 14.99 (0.04) | ... | |
| 0827+243 (OJ 248) ........... | 1 | ... | 14.16 (0.04) | 13.76 (0.02) | ... | 3 |
| | 2 | ... | 14.71 (0.02) | 14.46 (0.03) | ... | |
| | 3 | ... | 14.76 (0.04) | 14.32 (0.02) | ... | |
| | 4 | ... | 15.59 (0.02) | 15.18 (0.03) | ... | |
| | 5 | ... | 15.76 (0.03) | 15.40 (0.02) | ... | |
| PKS 1226+023 (3C 273)...... | E | 13.33 (0.07) | 12.69 (0.04) | 12.27 (0.05) | 11.84 (0.04) | 5 |
| | G | 14.12 (0.05) | 13.56 (0.05) | 13.16 (0.05) | 12.83 (0.05) | |
| 1ES 2344+51.4 ............... | C1 | ... | 12.61 (0.04) | 12.25 (0.04) | 11.90 (0.04) | 6 |
| | C2 | ... | 14.62 (0.06) | 14.20 (0.05) | 13.84 (0.04) | |
| | C3 | ... | 15.89 (0.08) | 15.40 (0.08) | 14.89 (0.08) | |
| 1101+384 (Mrk 421) .......... | 1 | 15.02 (0.03) | 14.36 (0.02) | 14.02 (0.02) | ... | 4 |
| | 2 | 16.20 (0.04) | 15.57 (0.05) | 15.20 (0.03) | ... | |
| | 3 | 16.69 (0.03) | 15.77 (0.03) | 15.24 (0.03) | ... | |

REFERENCES.—(1) Craine 1977; (2) Fiorucci & Tosti 1996; (3) Raiteri et al. 1998; (4) Villata et al. 1998; (5) Smith et al. 1985; (6) Fiorucci et al. 1998.

TABLE 2

The Observational Data from 2000 April 5 to 2001 January 19

| JD +2,400,000 | UT | Mag | σ | Band |
|---|---|---|---|---|
| 1226+023 (3C273): | | | | |
| 51640.220...... | 2000 Apr 5, 17.301 | 12.87 | 0.08 | *B* |
| 51640.223...... | 17.367 | 12.87 | 0.08 | *B* |
| 51640.226...... | 17.429 | 12.92 | 0.08 | *B* |
| 51640.230...... | 17.528 | 12.92 | 0.08 | *B* |
| 51640.234...... | 17.628 | 12.87 | 0.08 | *B* |
| 51640.238...... | 17.725 | 12.92 | 0.08 | *B* |
| 51640.242...... | 17.831 | 12.81 | 0.08 | *B* |
| 51640.247...... | 17.936 | 12.81 | 0.08 | *B* |
| 51640.251...... | 18.033 | 12.80 | 0.08 | *B* |
| 51640.254...... | 18.100 | 12.83 | 0.08 | *B* |
| 51640.257...... | 18.176 | 12.92 | 0.08 | *B* |
| 51640.260...... | 18.246 | 12.87 | 0.08 | *B* |
| 51640.263...... | 18.317 | 12.95 | 0.08 | *B* |
| 51640.266...... | 18.383 | 12.89 | 0.08 | *B* |
| 51640.268...... | 18.453 | 12.89 | 0.08 | *B* |
| 51640.271...... | 18.517 | 12.88 | 0.08 | *B* |
| 51640.274...... | 18.583 | 12.88 | 0.08 | *B* |
| 51640.277...... | 18.651 | 12.87 | 0.08 | *B* |
| 51640.279...... | 18.717 | 12.90 | 0.08 | *B* |
| 51640.283...... | 18.795 | 12.99 | 0.08 | *B* |
| 51640.286...... | 18.870 | 12.94 | 0.08 | *B* |
| 51640.290...... | 18.963 | 12.81 | 0.08 | *B* |
| 51640.292...... | 19.029 | 12.86 | 0.08 | *B* |
| 51640.295...... | 19.095 | 12.92 | 0.08 | *B* |
| 51640.298...... | 19.170 | 12.91 | 0.08 | *B* |
| 51640.301...... | 19.236 | 12.95 | 0.08 | *B* |
| 51640.304...... | 19.302 | 12.97 | 0.08 | *B* |
| 51640.307...... | 19.367 | 12.88 | 0.08 | *B* |
| 51640.309...... | 19.433 | 12.96 | 0.08 | *B* |
| 51640.312...... | 19.500 | 12.79 | 0.08 | *B* |
| 51640.315...... | 19.567 | 12.84 | 0.08 | *B* |
| 51640.318...... | 19.638 | 12.95 | 0.08 | *B* |
| 51640.320...... | 19.703 | 12.89 | 0.08 | *B* |
| 51640.323...... | 19.772 | 13.02 | 0.08 | *B* |
| 51640.326...... | 19.837 | 13.02 | 0.08 | *B* |
| 51640.147...... | 15.397 | 12.57 | 0.09 | *V* |
| 51640.144...... | 15.475 | 12.66 | 0.09 | *V* |
| 51640.141...... | 15.551 | 12.67 | 0.09 | *V* |
| 51640.149...... | 15.594 | 12.60 | 0.09 | *V* |
| 51640.151...... | 15.633 | 12.55 | 0.09 | *V* |
| 51640.153...... | 15.676 | 12.67 | 0.09 | *V* |
| 51640.156...... | 15.750 | 12.63 | 0.09 | *V* |
| 51640.158...... | 15.812 | 12.65 | 0.09 | *V* |
| 51640.161...... | 15.876 | 12.54 | 0.09 | *V* |
| 51640.164...... | 15.944 | 12.57 | 0.09 | *V* |
| 51640.166...... | 16.006 | 12.61 | 0.09 | *V* |
| 51640.169...... | 16.071 | 12.56 | 0.09 | *V* |
| 51640.172...... | 16.142 | 12.56 | 0.09 | *V* |
| 51640.175...... | 16.217 | 12.58 | 0.09 | *V* |
| 51640.178...... | 16.280 | 12.60 | 0.09 | *V* |
| 51640.180...... | 16.343 | 12.51 | 0.09 | *V* |
| 51640.183...... | 16.405 | 12.46 | 0.09 | *V* |
| 51640.186...... | 16.467 | 12.54 | 0.09 | *V* |
| 51640.188...... | 16.530 | 12.51 | 0.09 | *V* |
| 51640.191...... | 16.596 | 12.50 | 0.09 | *V* |
| 51640.193...... | 16.656 | 12.59 | 0.09 | *V* |
| 51640.197...... | 16.731 | 12.64 | 0.09 | *V* |
| 51640.199...... | 16.798 | 12.59 | 0.09 | *V* |
| 51640.202...... | 16.867 | 12.55 | 0.09 | *V* |
| 51640.205...... | 16.933 | 12.46 | 0.09 | *V* |
| 51640.208...... | 17.001 | 12.55 | 0.09 | *V* |
| 51640.211...... | 17.064 | 12.66 | 0.09 | *V* |
| 51640.213...... | 17.126 | 12.66 | 0.09 | *V* |
| 51640.217...... | 17.221 | 12.63 | 0.09 | *V* |
| 51699.228 ........ | 17.495 | 13.22 | 0.04 | *R* |
| 51699.231...... | 17.564 | 13.08 | 0.04 | *R* |
| 51699.234...... | 17.633 | 13.17 | 0.04 | *R* |
| 51700.150...... | 2000 Jun 4, 15.620 | 13.14 | 0.04 | *R* |
| 51700.155...... | 15.744 | 13.16 | 0.04 | *R* |
| 51700.161...... | 15.878 | 13.24 | 0.04 | *R* |
| 51700.173...... | 16.160 | 13.15 | 0.04 | *R* |
| 51700.177...... | 16.257 | 13.12 | 0.04 | *R* |
| 51700.181...... | 16.354 | 13.14 | 0.04 | *R* |
| 51700.185...... | 16.456 | 13.15 | 0.04 | *R* |
| 51700.190...... | 16.563 | 13.10 | 0.04 | *R* |
| 1ES2344+514: | | | | |
| 51926.999 | 2001 Jan. 17, 11.981 | 15.45 | 0.02 | *V* |
| 51927.002...... | 12.055 | 15.38 | 0.02 | *V* |
| 51927.005...... | 12.122 | 15.42 | 0.02 | *V* |
| 51927.007...... | 12.190 | 15.44 | 0.02 | *V* |
| 51927.012...... | 12.293 | 15.45 | 0.02 | *V* |
| 51927.015...... | 12.362 | 15.44 | 0.02 | *V* |
| 51927.017...... | 12.429 | 15.45 | 0.02 | *V* |
| 51927.020...... | 12.495 | 15.52 | 0.02 | *V* |
| 51927.023...... | 12.561 | 15.51 | 0.02 | *V* |
| 51927.026...... | 12.628 | 15.49 | 0.02 | *V* |
| 51927.028...... | 12.693 | 15.53 | 0.02 | *V* |
| 51927.031...... | 12.760 | 15.46 | 0.02 | *V* |
| 51927.034...... | 12.826 | 15.46 | 0.02 | *V* |
| 51927.037...... | 12.892 | 15.44 | 0.02 | *V* |
| 51927.039...... | 12.959 | 15.44 | 0.02 | *V* |
| 51927.043...... | 13.033 | 15.55 | 0.02 | *V* |
| 51927.045...... | 13.100 | 15.50 | 0.02 | *V* |
| 51927.048...... | 13.167 | 15.47 | 0.02 | *V* |
| 51927.051...... | 13.233 | 15.47 | 0.02 | *V* |
| 51927.054...... | 13.300 | 15.54 | 0.02 | *V* |
| PKS0420−01 (OF035): | | | | |
| 51927.060...... | 2001 Jan 17, 13.463 | 14.88 | 0.05 | *R* |
| 51927.065...... | 13.564 | 14.89 | 0.05 | *R* |
| 51927.068...... | 13.633 | 14.84 | 0.05 | *R* |
| 51927.071...... | 13.720 | 14.86 | 0.05 | *R* |
| 51927.074...... | 13.789 | 14.87 | 0.05 | *R* |
| 51927.077...... | 13.858 | 14.86 | 0.05 | *R* |
| 51927.080...... | 13.933 | 14.89 | 0.05 | *R* |
| 51927.084...... | 14.026 | 14.87 | 0.05 | *R* |
| 51927.087...... | 14.097 | 14.86 | 0.05 | *R* |
| 51927.090...... | 14.167 | 14.85 | 0.05 | *R* |
| 51927.093...... | 14.236 | 14.88 | 0.05 | *R* |
| 51927.096...... | 14.306 | 14.85 | 0.05 | *R* |
| 51927.102...... | 14.455 | 14.91 | 0.05 | *R* |
| 51927.105...... | 14.526 | 14.87 | 0.05 | *R* |
| 51927.108...... | 14.600 | 14.86 | 0.05 | *R* |
| 51927.111...... | 14.667 | 14.91 | 0.05 | *R* |
| 51927.114...... | 14.754 | 14.91 | 0.05 | *R* |
| 51927.117...... | 14.821 | 14.93 | 0.05 | *R* |
| 51927.120...... | 14.893 | 14.90 | 0.05 | *R* |
| 51927.123...... | 14.961 | 14.88 | 0.05 | *R* |
| 51927.126...... | 15.028 | 14.89 | 0.05 | *R* |
| 51927.128...... | 15.095 | 14.92 | 0.05 | *R* |
| 51927.131...... | 15.160 | 14.91 | 0.05 | *R* |
| 51927.135...... | 14.240 | 14.89 | 0.05 | *R* |
| 51927.138...... | 14.312 | 14.90 | 0.05 | *R* |
| 51927.140...... | 14.383 | 14.90 | 0.05 | *R* |
| 51927.144...... | 14.470 | 14.86 | 0.05 | *R* |
| 51927.147...... | 14.540 | 14.85 | 0.05 | *R* |
| 51927.150...... | 14.612 | 14.78 | 0.05 | *R* |
| 51927.153...... | 14.691 | 14.84 | 0.05 | *R* |
| 51927.156...... | 14.712 | 14.87 | 0.05 | *R* |
| 51927.159...... | 14.830 | 14.86 | 0.05 | *R* |

TABLE 2—*Continued*

| JD +2,400,000 | UT | Mag | σ | Band |
|---|---|---|---|---|
| 1101+384 (Mrk421): | | | | |
| 51666.115...... | 2000 May 1, 14.763 | 13.28 | 0.05 | *V* |
| 51666.116...... | 14.805 | 13.22 | 0.05 | *V* |
| 51666.132...... | 15.179 | 13.25 | 0.05 | *V* |
| 51666.134...... | 15.217 | 13.28 | 0.05 | *V* |
| 51666.135...... | 15.254 | 13.35 | 0.05 | *V* |
| 51666.137...... | 15.292 | 13.29 | 0.05 | *V* |
| 51666.138...... | 15.329 | 13.29 | 0.05 | *V* |
| 51666.140...... | 15.367 | 13.28 | 0.05 | *V* |
| 51666.141...... | 15.405 | 13.37 | 0.05 | *V* |
| 51666.143...... | 15.444 | 13.38 | 0.05 | *V* |
| 51666.160...... | 15.845 | 13.34 | 0.05 | *V* |
| 51666.161...... | 15.887 | 13.17 | 0.05 | *V* |
| 51666.073...... | 13.764 | 13.73 | 0.05 | *B* |
| 51666.077...... | 13.855 | 13.74 | 0.05 | *B* |
| 51666.080...... | 13.933 | 13.77 | 0.05 | *B* |
| 51666.083...... | 14.005 | 13.87 | 0.05 | *B* |
| 51666.086...... | 14.080 | 13.77 | 0.05 | *B* |
| 51666.089...... | 14.152 | 13.83 | 0.05 | *B* |
| 51666.093...... | 14.245 | 13.73 | 0.05 | *B* |
| 51666.103...... | 14.489 | 13.80 | 0.05 | *B* |
| 51666.106...... | 14.559 | 13.61 | 0.05 | *B* |
| 51666.109...... | 14.626 | 13.79 | 0.05 | *B* |
| 51666.123...... | 14.971 | 13.69 | 0.05 | *B* |
| 51666.126...... | 15.038 | 13.74 | 0.05 | *B* |
| 51666.129...... | 15.103 | 13.80 | 0.05 | *B* |
| 51666.154...... | 15.703 | 14.01 | 0.05 | *B* |
| 51666.118...... | 14.850 | 12.79 | 0.06 | *R* |
| 51666.120...... | 14.888 | 12.87 | 0.06 | *R* |
| 51666.121...... | 14.926 | 12.92 | 0.06 | *R* |
| 51666.147...... | 15.532 | 12.93 | 0.06 | *R* |
| 51666.149...... | 15.578 | 12.88 | 0.06 | *R* |
| 51666.150...... | 15.617 | 12.97 | 0.06 | *R* |
| 51666.163...... | 15.931 | 12.92 | 0.06 | *R* |
| 51666.165...... | 15.970 | 12.92 | 0.06 | *R* |
| 51666.167...... | 16.008 | 12.85 | 0.06 | *R* |
| PKS 1510−089: | | | | |
| 51666.228...... | 2000 May 1, 17.488 | 15.52 | 0.01 | *R* |
| 51666.232...... | 17.576 | 14.88 | 0.01 | *R* |
| 51666.235...... | 17.849 | 14.92 | 0.01 | *R* |
| 51666.239...... | 17.755 | 15.45 | 0.01 | *R* |
| 51666.243...... | 17.851 | 15.29 | 0.01 | *R* |
| 51666.248...... | 17.969 | 16.61 | 0.01 | *V* |
| 51666.252...... | 18.067 | 16.85 | 0.01 | *V* |
| 51666.257...... | 18.178 | 16.73 | 0.01 | *V* |
| 51694.150...... | 2000 May 29, 15.623 | 16.08 | 0.01 | *R* |
| 51694.155...... | 15.728 | 16.30 | 0.01 | *R* |
| 51694.159...... | 15.823 | 16.24 | 0.01 | *R* |
| 51694.166...... | 15.989 | 16.05 | 0.01 | *R* |
| 51694.177...... | 16.250 | 16.44 | 0.01 | *R* |
| 51694.180...... | 16.329 | 16.56 | 0.01 | *R* |
| 51694.183...... | 16.405 | 16.23 | 0.01 | *R* |
| 51694.187...... | 16.491 | 16.19 | 0.01 | *R* |
| 51694.190...... | 16.567 | 16.05 | 0.01 | *R* |
| 51694.193...... | 16.645 | 16.09 | 0.01 | *R* |
| 51694.196...... | 16.723 | 16.06 | 0.01 | *R* |
| 51694.200...... | 16.808 | 16.08 | 0.01 | *R* |
| 51694.203...... | 16.876 | 16.03 | 0.01 | *R* |
| 51694.206...... | 16.944 | 16.27 | 0.01 | *R* |
| 51694.209...... | 17.026 | 16.10 | 0.01 | *R* |
| 51694.213...... | 17.124 | 16.07 | 0.01 | *R* |
| 51694.216...... | 17.198 | 16.22 | 0.01 | *R* |
| 51694.224...... | 17.400 | 16.78 | 0.01 | *R* |
| 51694.228...... | 17.473 | 17.83 | 0.01 | *R* |
| 51694.230...... | 17.543 | 17.11 | 0.01 | *R* |
| 51694.234...... | 17.626 | 16.74 | 0.01 | *R* |
| 51694.237...... | 17.698 | 16.02 | 0.01 | *R* |
| 51927.162...... | 14.905 | 14.87 | 0.05 | *R* |
| 51927.165...... | 14.976 | 14.92 | 0.05 | *R* |
| 51927.168...... | 15.005 | 14.92 | 0.05 | *R* |
| 0827+243 (OJ248): | | | | |
| 51927.173...... | 2001 Jan 17, 16.176 | 17.08 | 0.03 | *R* |
| 51927.177...... | 16.272 | 17.13 | 0.03 | *R* |
| 51927.185...... | 16.455 | 17.21 | 0.03 | *R* |
| 51927.188...... | 16.525 | 17.24 | 0.03 | *R* |
| 51927.191...... | 16.593 | 17.34 | 0.03 | *R* |
| 51927.194...... | 16.663 | 17.41 | 0.03 | *R* |
| 51927.197...... | 16.733 | 17.23 | 0.03 | *R* |
| 51927.199...... | 16.800 | 17.45 | 0.03 | *R* |
| 51927.202...... | 16.876 | 17.50 | 0.03 | *R* |
| 51927.205...... | 16.933 | 17.34 | 0.03 | *R* |
| 51927.208...... | 17.012 | 17.43 | 0.03 | *R* |
| 51927.212...... | 17.097 | 17.25 | 0.03 | *R* |
| 51927.215...... | 17.175 | 17.21 | 0.03 | *R* |
| 51927.218...... | 17.248 | 17.07 | 0.03 | *R* |
| 51927.221...... | 17.323 | 17.29 | 0.03 | *R* |
| 51927.225...... | 17.403 | 17.15 | 0.03 | *R* |
| 51927.228...... | 17.475 | 17.16 | 0.03 | *R* |
| 51927.231...... | 17.549 | 17.17 | 0.03 | *R* |
| 51927.235...... | 17.653 | 17.02 | 0.03 | *R* |
| 51927.238...... | 17.733 | 17.09 | 0.03 | *R* |
| 51927.241...... | 17.800 | 17.42 | 0.03 | *R* |
| 51927.244...... | 17.878 | 17.26 | 0.03 | *R* |
| 51927.248...... | 17.956 | 17.21 | 0.03 | *R* |
| 51927.251...... | 18.033 | 17.25 | 0.03 | *R* |
| 51927.257...... | 18.169 | 17.07 | 0.03 | *R* |
| 51927.259...... | 18.239 | 17.22 | 0.03 | *R* |
| 51927.263...... | 18.313 | 17.21 | 0.03 | *R* |
| 51927.269...... | 18.457 | 17.18 | 0.03 | *R* |
| 51927.271...... | 18.528 | 17.29 | 0.03 | *R* |
| 51927.275...... | 18.600 | 17.02 | 0.03 | *R* |
| 51927.277...... | 18.671 | 17.03 | 0.03 | *R* |
| 51927.280...... | 18.744 | 16.97 | 0.03 | *R* |
| 0219+428 (3C66A): | | | | |
| 51928.996...... | 2001 Jan 19, 11.905 | 14.88 | 0.02 | *B* |
| 51929.000...... | 12.005 | 14.87 | 0.02 | *B* |
| 51929.004...... | 12.113 | 14.90 | 0.02 | *B* |
| 51929.009...... | 12.217 | 14.87 | 0.02 | *B* |
| 51929.013...... | 12.320 | 14.87 | 0.02 | *B* |
| 51929.017...... | 12.431 | 14.88 | 0.02 | *B* |
| 51929.022...... | 12.531 | 14.87 | 0.02 | *B* |
| 51929.026...... | 12.631 | 14.87 | 0.02 | *B* |
| 51929.030...... | 12.738 | 14.85 | 0.02 | *B* |
| 51929.035...... | 12.841 | 14.86 | 0.02 | *B* |
| 51929.039...... | 12.942 | 14.88 | 0.02 | *B* |
| 51929.043...... | 13.033 | 14.87 | 0.02 | *B* |
| 51929.046...... | 13.128 | 14.87 | 0.02 | *B* |
| 51929.050...... | 13.221 | 14.85 | 0.02 | *B* |
| 51929.054...... | 13.314 | 14.86 | 0.02 | *B* |
| 51929.058...... | 13.407 | 14.89 | 0.02 | *B* |
| 51929.062...... | 13.500 | 14.86 | 0.02 | *B* |
| 51929.066...... | 13.593 | 14.85 | 0.02 | *B* |
| 51929.070...... | 13.687 | 14.90 | 0.02 | *B* |
| 51929.074...... | 13.781 | 14.87 | 0.02 | *B* |
| 51929.078...... | 13.875 | 14.87 | 0.02 | *B* |
| 51929.082...... | 13.973 | 14.88 | 0.02 | *B* |
| 51929.086...... | 14.068 | 14.86 | 0.02 | *B* |
| 51928.988...... | 11.724 | 14.43 | 0.02 | *V* |
| 51928.992...... | 11.815 | 14.40 | 0.02 | *V* |
| 1253−055 (3C279): | | | | |
| 51666.194...... | 2000 May 1, 16.659 | 13.74 | 0.12 | *R* |
| 51666.195...... | 16.700 | 13.72 | 0.14 | *R* |
| 51666.197...... | 16.739 | 13.69 | 0.14 | *R* |
| 51666.199...... | 16.781 | 13.68 | 0.14 | *R* |

TABLE 2—*Continued*

| JD +2,400,000 | UT | Mag | σ | Band | JD +2,400,000 | UT | Mag | σ | Band |
|---|---|---|---|---|---|---|---|---|---|
| 51694.241...... | 17.797 | 16.09 | 0.01 | *R* | 51666.200...... | 16.821 | 13.72 | 0.14 | *R* |
| 51694.244...... | 17.873 | 15.82 | 0.01 | *R* | 51666.202...... | 16.859 | 13.67 | 0.14 | *R* |
| 51694.247...... | 17.947 | 16.01 | 0.01 | *R* | 51666.204...... | 16.897 | 13.63 | 0.14 | *R* |
| 1652+398 (Mrk501): | | | | | 51666.205...... | 16.943 | 13.53 | 0.14 | *R* |
| 51699.211...... | 2000 Jun 3, 17.087 | 13.12 | 0.04 | *R* | 51666.207...... | 16.981 | 13.63 | 0.14 | *R* |
| 51699.214...... | 17.158 | 13.10 | 0.04 | *R* | 51666.209...... | 17.018 | 13.71 | 0.14 | *R* |
| 51699.218...... | 17.242 | 13.09 | 0.04 | *R* | 51666.210...... | 17.057 | 13.71 | 0.14 | *R* |
| 51699.221...... | 17.311 | 13.16 | 0.04 | *R* | 51666.212...... | 17.097 | 13.47 | 0.14 | *R* |
| 51699.225...... | 17.417 | 13.12 | 0.04 | *R* | 51666.214...... | 17.137 | 13.77 | 0.14 | *R* |

The rms errors are calculated from the two selected comparison stars using the formula

$$\sigma = \sqrt{\frac{\sum (m_i - \bar{m})^2}{N-1}}\,, \tag{1}$$

where $m_i = (m_2 - m_1)_i$ is the differential magnitude of stars 1 and 2, while $\bar{m} = \overline{m_2 - m_1}$ is the differential magnitude averaged over the entire data set, and $N$ is the number of the observations on a given night.

The results of our monitoring program are listed in Table 2, where column (1) is the Julian Date (+2,400,000), column (2) the UT, column (3) the magnitude, column (4) the rms error, and column (5) the filter used.

## 3. CONTRIBUTION OF THE HOST GALAXY TO MACROVARIABILITY

Carini et al. (1991) suggested that a possible source of error and/or spurious variations could be the presence of the underlying galaxy component on AP Lib. Cellone et al. (2000) warn that varying seeing conditions may result in spurious microvariations in the light curves of an AGN embedded in a host galaxy. These spurious variations would be caused by the changing contribution of the host galaxy within the aperture used for photometry as seeing conditions changed. They further investigated such seeing-induced variations using computer models of AGNs embedded in host galaxies. They found that large seeing-induced variations were detected when smaller apertures were used for the photometry and when the host was fainter than the AGN. They recommend using an aperture with a radius no smaller than 1″.6 (equal to 2 pixels with their telescope-detector system and equal to about 4.5 pixels with ours). Thus the aperture used in our study (6″–10″) is much larger than that recommended by Cellone et al. (2000) to limit seeing-induced spurious variations to less than 0.01 mag for 1″ changes in the FWHM of the stellar point-spread function (PSF).

As discussed by Clements & Carini (2001), to examine the influence of variable seeing conditions on the observed macrovariability of the sources, only the FWHM of the stellar PSF of the check stars could be examined and compared with the light curve of sources. They found that the seeing conditions improved (the FWHM decreased), while the mean magnitude of the BL Lac increased. This trend from night to night is therefore attributed to coincidence. However, close inspection reveals that the intranight brightness variations are not correlated with the FWHM variation. In fact, each individual night's data argue that seeing in no way has affected the computed magnitudes of BL Lac. In this work, to avoid spurious variation, we examined the contribution of the host galaxy to the macrovariability in detail for all objects.

## 4. RESULTS AND ANALYSIS

### 4.1. *PKS 1510−089*

This quasar presents a pronounced UV excess, a very flat X-ray spectrum, and a steep γ-ray spectrum. Previously the maximum brightness variation of 5.4 mag in the *B* band had been obtained by Liller & Liller (1975). A bright state in 1987 was followed by a rapid dimming (Villata et al. 1997 and references therein). Small-amplitude oscillations on short timescales have also been observed by Villata et al. (1997), who found a variation of 0.63 mag in the *R* and *B* bands. This object has been included in our monitoring program since 1999. In our previous observations in 1999, it exhibited a high level of activity each night. It brightened from 17.21 to 16.65 in 40 minutes in *B*. A rapid decline of 0.55 mag in 22 minutes and a flare of 0.51 mag in 26 minutes were observed on 1999 May 15 and June 15, respectively, in the *R* band (Xie et al. 2001).

Our new observations on 2000 May 29 are displayed in Figure 1. The source was still in a very active state during our observation period. An apparent variation of about 2 mag in the *R* band within 41 minutes was observed. The source faded from 16.02 to 17.74 in 27 minutes and then brightened to 15.74 in about 13 minutes. This is the most extreme rapid variability witnessed in our optical monitoring program since 1982. Figure 1*a* represents the light curve about this maximum variation of PKS 1510−089. The differential magnitudes of two comparison stars are less than 0.02 mag during the observed night (see Fig. 1*b*). Figures 1*c* and 1*d* represent the variation of the source and comparison star 1 and comparison star 2. According to the definition of the variability parameter *C*, the corresponding variability parameter *C* is 59.6. Figure 1 indicates another small variation; the source faded from 16.02 mag to a low state of 16.57 within 38 minutes also in the *R* band, and the variability parameter *C* is about 16.36. It is possible that such large amplitude variations may also be due to instrumental variations. We checked the CCD images and the observational report and carried out repeated data analysis of this source, and we obtained very similar results using different nonvariable comparison stars. The amplitude variations of the comparison stars are also less than 0.02 mag all through the observational period.

We examined the contribution of the host galaxy to the macrovariability. The results are shown in Figure 2. In Figure 2*b*, the FWHM of the stellar PSF of the comparison star is shown as a function of observational time. Figure 2*b* is plotted according to the same observational timescale as Figure 2*a*, allowing a comparison of the magnitude varia-

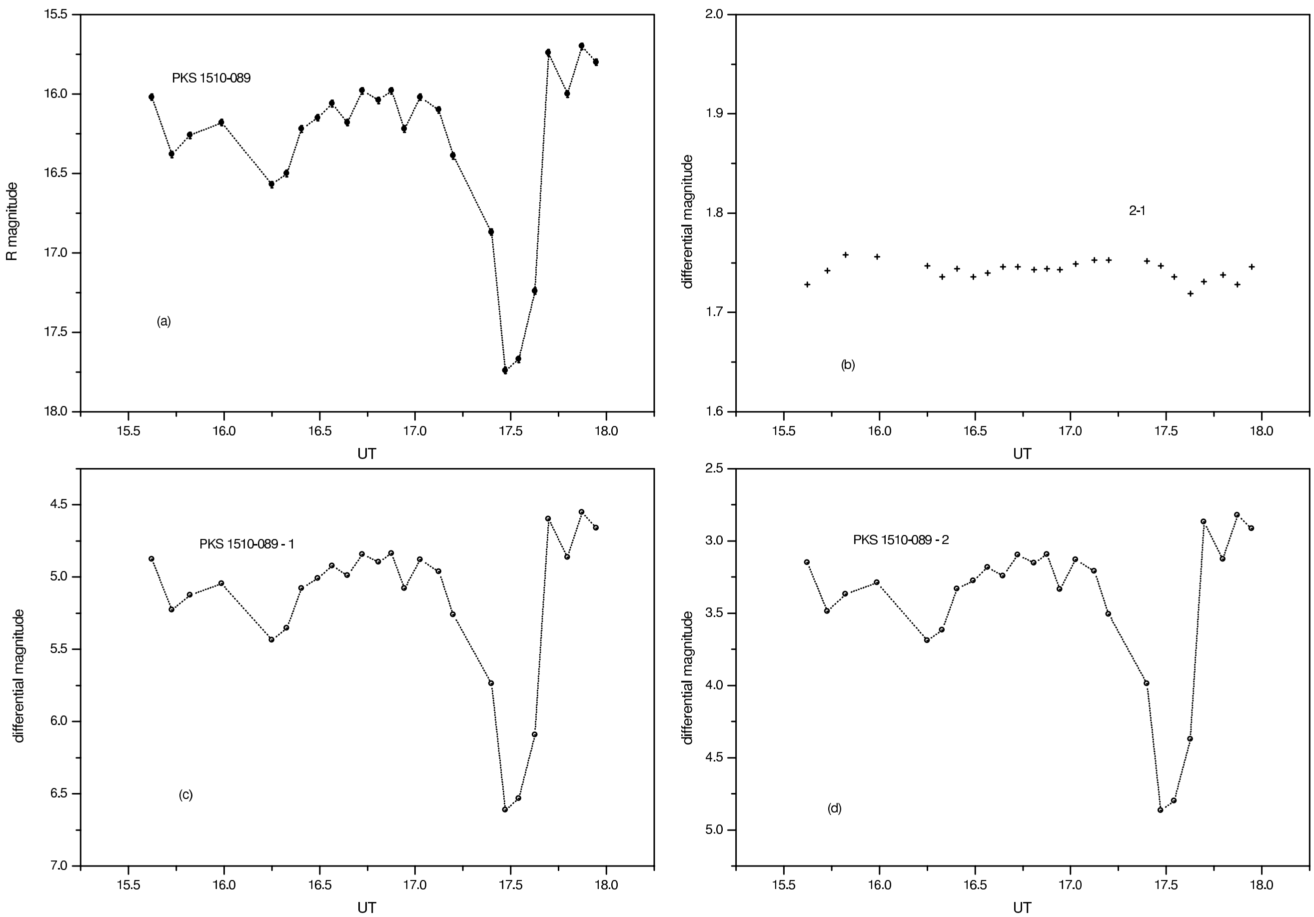


FIG. 1.—*Top left*: *R*-band light curve of PKS 1510−089 on 2000 May 29. The error bars are 0.01 mag, which is almost the same size as the plotted symbols. *Top right*: Differential magnitude of two comparison stars, star 1 and star 2 in the same frame with PKS 1510−089. *Bottom*: Differential magnitude of objects and comparison stars.

tions of PKS 1510−089 with the seeing conditions. In the observational period, the FWHM of the PSF varied by 1".2. The FWHM temporal variability (Fig. 2*b*) is different from the light curve of PKS 1510−089. In addition, the *R* magnitude of PKS 1510−089 is plotted as a function of the FWHM of the PSF of comparison star 2 in Figure 2*c*. The linear regression equation for these data gives $m_R = -0.143\,\mathrm{FWHM} + (17.225 \pm 0.98)$ with a correlation coefficient of −0.1899. We also checked the correlation between intranight brightness variations and seeing conditions. Figure 2*d* represents the *R*-magnitude change of PKS 1510−089 as a function of the change in the FWHM of the PSF from one exposure to the next. No correlation is obtained; $\Delta R = (-0.083 \pm 0.09)\Delta\,\mathrm{FWHM} + 0.012 \pm 0.088$, with correlation coefficient −0.194. This result is consistent with that of Clements & Carini (2001). This means that seeing has in no way affected the computed magnitudes of PKS 1510−089. So we concluded that the observed apparent variation of PKS 1510−089 is intrinsic to the source as determined by a rigorous check for correlations between variability and seeing conditions.

### 4.2. *OJ 248* (*0827+243*)

For this source, there are not many observations in the literature. The only optical data are given in the *V* band, namely, $V = 17.25$ (Hewitt & Burbidge 1987) and $V = 17.5$ (Maoz et al. 1993). No long-timescale variations were observed before 1997. The results of Villata et al. have revealed noticeable variability, with a decrease of 1.16 mag in the first 63 days and a subsequent increase of 1.05 mag in 58 days (Villata et al. 1997). During our previous monitoring campaign on 1999 March 12 OJ 248 brightened 0.97 mag within 23.6 minutes with a subsequent decrease of 1.0 mag in 51.3 minutes in the *R* band, and another big outburst of ∼1.23 mag was observed when the magnitude increased in 26.6 minutes from $R = 17.88$ to a maximum brightness of $R = 16.65$. In that time, OJ 248 exhibited vary rapid variations on the order of hours (Xie et al. 2001).

In our recent observation on 2001 January 17, the source was in a lower state, with average magnitude about 17.3 in the *R* band. The observations are displayed in Figure 3. Figure 3*a* represents the light curve of OJ 248; the source dimmed from 17.08 to local minimum 17.50 in 42 minutes, and then it brightened to 17.02 in the following 43 minutes. The corresponding variability parameters *C* are 5.35 and 4.99. After that, the source oscillated with variation about 0.2–0.3 mag to the local maximum of 16.97 in the *R* band. The differential magnitudes of two selected comparison stars are shown in Figure 3*b*. The results of examined seeing-induced variations are shown in Figures 3*c* and 3*d*. In the observational period, the FWHM of the PSF varied 0".92 (see Fig. 3*c*). The *R* magnitude of OJ 248 is plotted as function of the FWHM of the PSF of comparison star 1 in

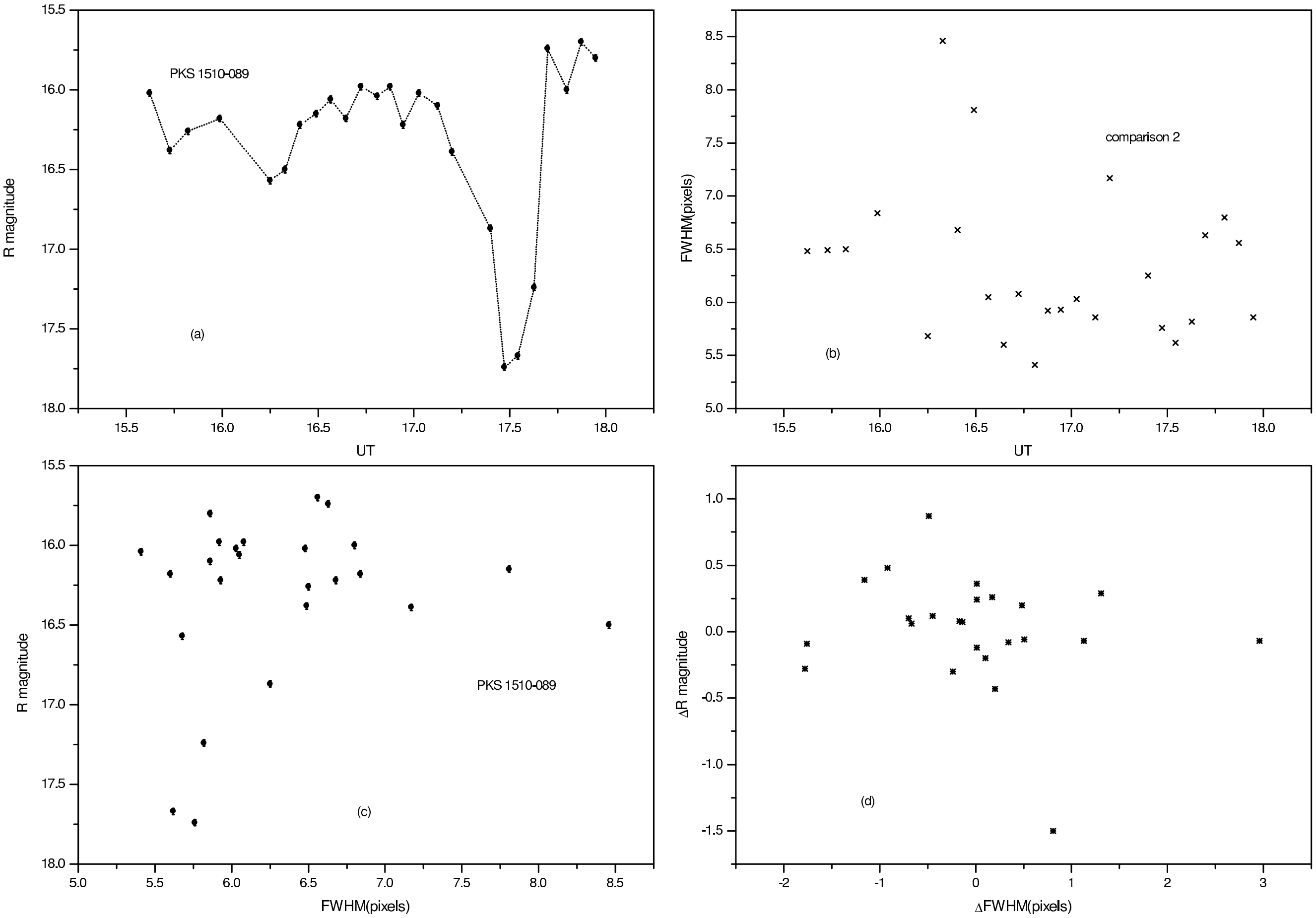


FIG. 2.—Contribution of the host galaxy to the microvariability of PKS 1510−089. *Top left*: Light curve of PKS 1510−089, same as Fig. 1*a*; (*top right*) FWHM of the PSF for comparison star 2 as a function of observational time; (*bottom left*) *R* magnitude of PKS 1510−089 as a function of FWHM of PSF of comparison star 2; (*bottom right*) change in the *R* magnitude as a function of the change in the FWHM of PSF for comparison star 2.

Figure 3*d*. The linear regression equation for this data gives $m_R = -0.0048\,\mathrm{FWHM} + (17.24 \pm 0.20)$, with a correlation coefficient of −0.0198. Although the variability parameter indicates that this variation is real, close inspection of Figure 3 reveals that the standards varied in the same sense with the same structure as OJ 248. So this variation is suspect and should not be treated as a real variation.

### 4.3. *1ES 2344+51.4*

The source 1ES 2344+51.4 ($z = 0.044$) was only recently identified as a BL Lac object (Perlman et al. 1996), based on its lack of optical emission lines with observed equivalent width greater than 5 Å and its Ca II "break strength" being smaller than 25%. This makes it the fourth-closest known BL Lac object, after Mrk 421, Mrk 501, and EXO 0423.4−0840 (Padovani & Giommi 1995). Perlman et al. (1996) derived a 2 keV X-ray flux of 1.14 $\mu$Jy, roughly one-third the flux detected for Mrk 421 and Mrk 501, and measured an optical magnitude of $m_V = 15.5$ with no galaxy subtraction. The Green Bank radio survey lists a 5 GHz flux of $231 \pm 25$ mJy, which is about one-third and one-fourth the 5 GHz flux of Mrk 421 and Mrk 501, respectively. 1ES 2344+51.4 was discovered in TeV $\gamma$-rays (>350 GeV) by the Whipple Observatory telescope and identified as a TeV BL Lac object (Catanese et al. 1998).

This is the first observation of 1ES 2344+51.4 in our optical monitoring program. During observational period on 2001 January 17, the suspected microvariation of 0.14 mag in *V* band within 26 minutes was observed from UT 12.055 to 12.495 (see Fig. 4). The corresponding variability parameter *C* is 3.45. Figure 4*a* represents the light curve of 1ES 2344+51.4, and Figure 4*b* the differential magnitudes of two comparison stars C1 and C2. The FWHM variation of comparison star C1 with observational time is shown in Figure 4*c*. The *V* magnitude of 1ES 2344+51.4 is plotted as a function of the FWHM of PSF of comparison star C1 in Figure 4*d*. The linear regression equation for this data gives $m_V = 0.013\,\mathrm{FWHM} + (15.397 \pm 0.077)$ with correlation coefficient of 0.22, the probability is 0.35. This means that there is a weak correlation between the 1ES 2344+51.4 variation and the FWHM variation. The source brightness decreased, while the FWHM of PSF increased, removing more light from the aperture. This relationship is agreement with the similar trend from night to night obtained by Clements & Carini (2001). From Figure 4, the variation in the FWHM of PSF for comparison star 1 behaves in a manner consistent with the observed variability in the source; this is likely a seeing-induced variation.

### 4.4. *3C 66A*

Object 3C 66A is the first possible TeV (>300 GeV) $\gamma$-ray source of radio-selected BL Lac objects that has a synchrotron peak in the UV band (Ghisellini et al. 1998). It exhibited substantial variations in both brightness and

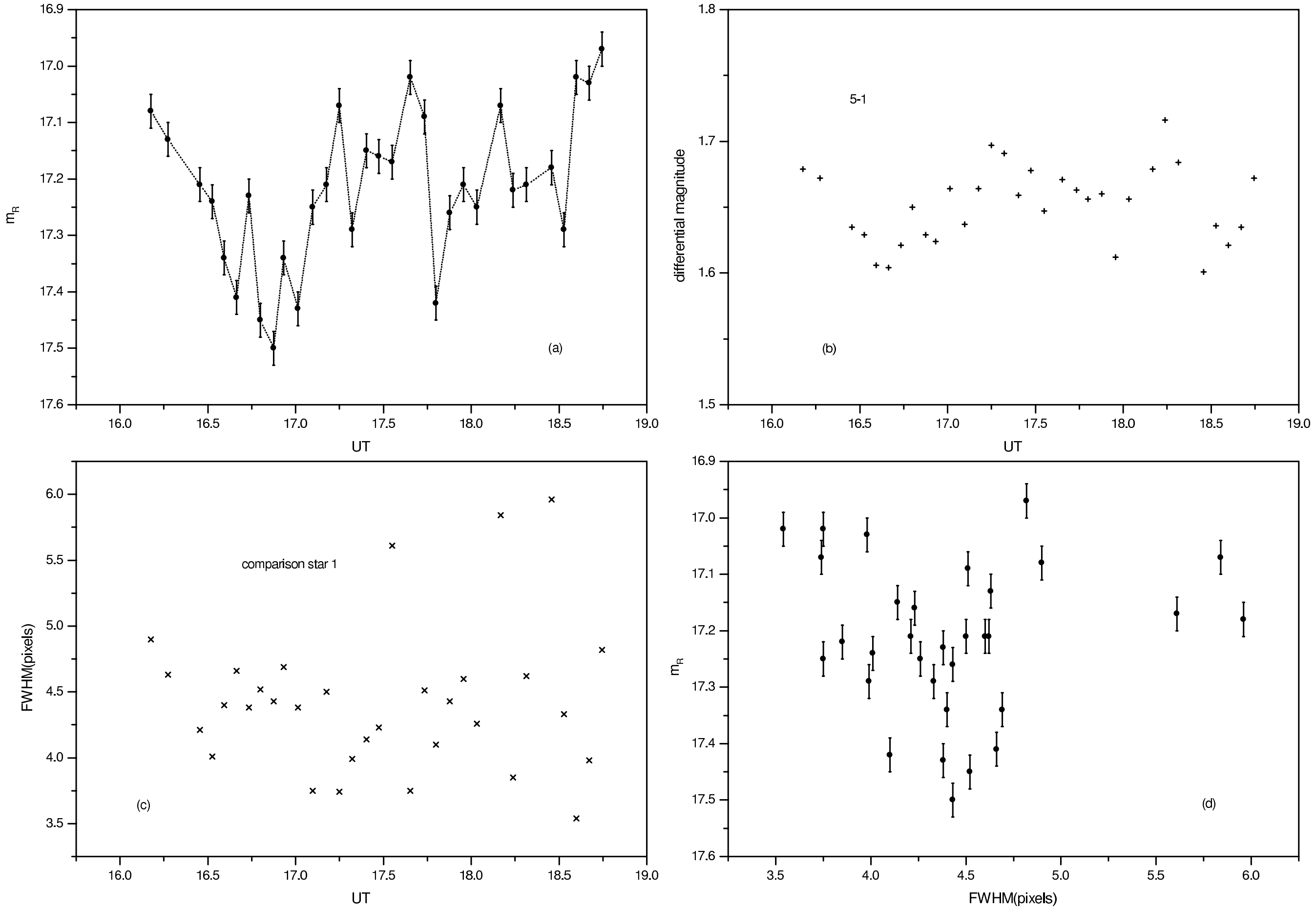


FIG. 3.—*Top left*: *R*-band light curve of OJ 248 on 2001 January 17; (*top right*) differential magnitude of two comparison star 1, 5; (*bottom left*) FWHM of PSF for comparison star 1 as a function of observational time; (*bottom right*) *R* magnitude of OJ 248 as a function of FWHM of PSF of comparison star 1.

polarization (Smith et al. 1987). Polarization for 3C 66A is from 10% to 22%. Sillanpää, Mikkola, & Valtaoja (1991) reported a variability range of 14.45–16.18 and an outburst of 0.5 mag in 8 days in the *V* band. The historic light curve showed that the largest amplitude variation is 2.75 mag in *V* band (Fan & Lin 2000). Object 3C 66A is one of the most intensively observed objects in our long-term monitoring project. Short-timescale variations have been observed in the *B* and *V* bands: a variation of $\Delta B = 0.52$ mag in timescale of 42 minutes and $\Delta V = 0.5$ mag at the 5 $\sigma$ confidence level in 38 minutes. *V* is in the range of 12.81 to 15.67 and *B* is in the range of 13.16 to 16.44 over nearly 4 yr. Our previous observations showed flares of $\Delta V = 0.6$ mag and $\Delta B = 0.7$ mag from JD 2,450,399 to 2,450,451 about 52 days (Xie et al. 1991, 1999).

Our new observational data are shown in Figure 5; 3C 66A exhibits a very stable state, with $\Delta B < 0.1$ mag. No large variation was observed. The magnitude of *B* band is 14.87. Compared with the historical observation data, the 3C 66A is in its high state. Figure 5*a* represents the light curve of 3C 66A, and Figure 5*b* the differential magnitudes of two comparison stars A and B. The variation of FWHM of comparison star B with observational time is shown in Figure 5*c*. The *B* magnitude of 3C 66A is plotted as a function of the FWHM of PSF of comparison star B in Figure 5*d*. The linear regression equation for this data gives $m_B = 2.12 \times 10^{-4}\,\mathrm{FWHM} + (14.87 \pm 0.016)$ with correlation coefficient of 0.0147.

### 4.5. *1101+384* (*Mrk 421*)

Mrk 421 ($z = 0.031$) is the brightest BL Lac object at UV, X-ray, and TeV wavelengths and also the first blazar detected in these high-energy bands. In 1992, Mrk 421 was detected as the first extragalactic source of very high energy (VHE) $\gamma$-rays at photon energies around 1 TeV using the Whipple Observatory $\gamma$-ray telescope (Punch et al. 1992). Mrk 421 has been confirmed as a source of VHE $\gamma$-rays by the HEGRA Collaboration (Petry et al. 1996). An extremely rapid burst of TeV photons from Mrk 421 has been obtained with the flux increased by a factor of 20–25 in short timescale of about $50 \pm 5$ minutes (Gaidos et al. 1996). The optical observation similar in essential respects to this TeV flare was obtained by Xie et al. (1998). Liller & Liller (1975) reported the light curve of Mrk 421 in the *B* band from 1899 to 1975. A fast brightness decline of 1.6 mag in 16 days observed in 1942 January. The maximum magnitude variation over the considered period was $\Delta B = 4.7$. The maximum magnitude variation detected by Villata et al. (1997) is about 0.4 in both *R* and *B* bands in about 60 days, the steepest variation being 0.19 mag in 1 day in *R*.

In our monitoring program on 2000 May 1, the semi-simultaneous observational results show that magnitude variations of 0.21, 0.32, and 0.18 mag in the *V*, *B*, and *R* bands were registered, respectively (see Fig. 6). The mean magnitudes in *B*, *V*, and *R* are 13.77, 13.29, and 12.89, respectively. The color indexes are $B-V = 0.48$ and

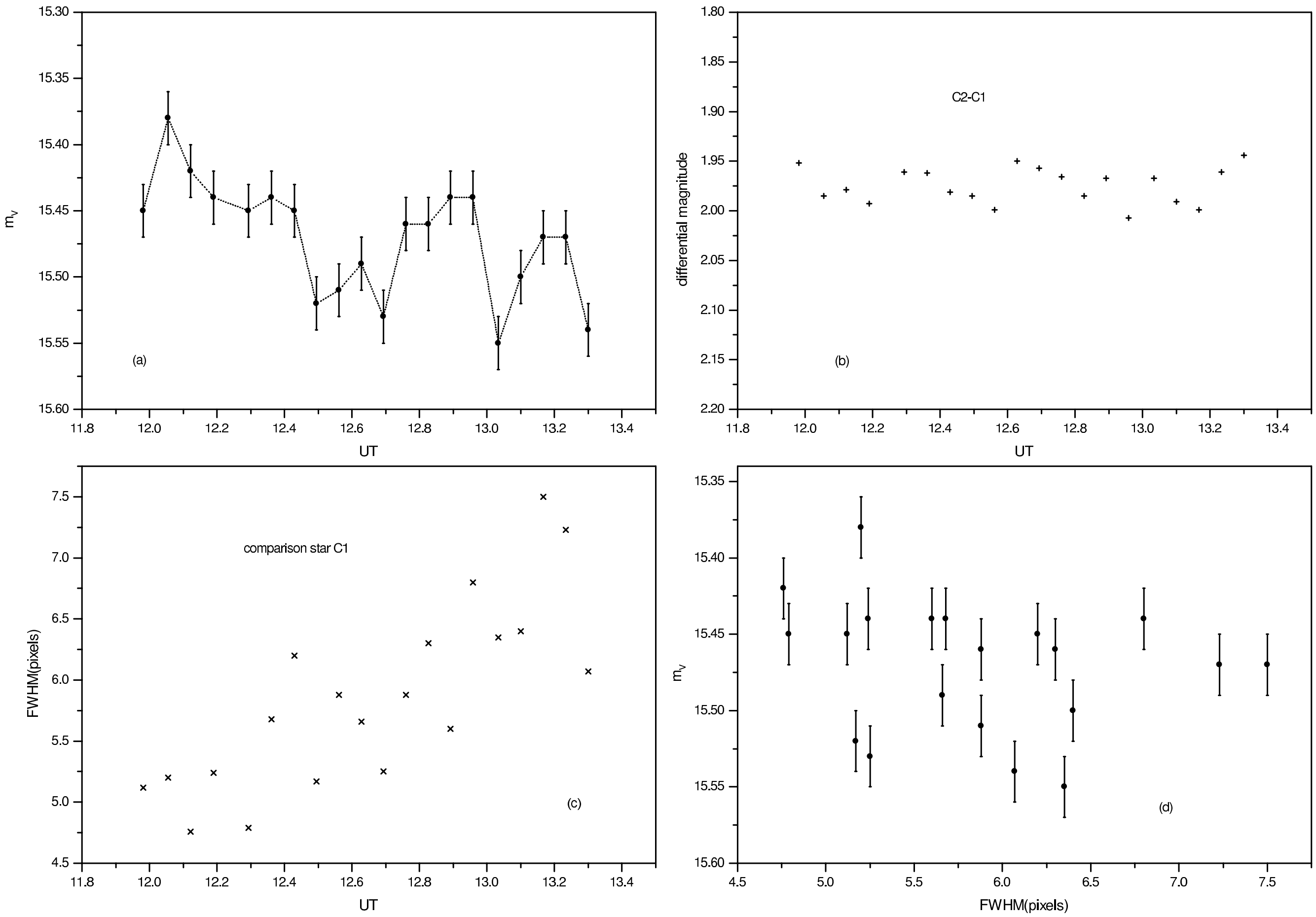


FIG. 4.—*Top left*: *V*-band light curve of 1ES 2344+51.4 on 2001 January 17, 2001; (*top right*) differential magnitude of two comparison star C1, C2; (*bottom left*) FWHM of PSF for comparison star C1 as a function of observational time; (*bottom right*) *V* magnitude of 1ES 2344+51.4 as a function of FWHM of PSF of comparison star C1.

$V-R=0.40$. The corresponding variability parameters are, respectively, 1.08, 1.96, and 1.05 for *B*, *V*, and *R*.

### 4.6. *3C 273*

The source 3C 273 is the nearest and brightest quasar with low polarization. At optical wavelength, the properties of 3C 273 are very different from those of the BL Lac objects and highly polarized quasars. The main features are an optical jet and the existence of a UV excess (blue bump) in the spectrum, the luminosity of which is comparable to or even greater than the $\gamma$ feature. The source does not exhibit high optical activity ($>1$ mag), but microvariability of 0.2–0.3 mag can be seen on a timescale of a few days (Smith et al. 1987). In 1996, the intraday flickering amplitudes observed were smaller than 0.2 mag in *V*, *R*, and *I* bands and 0.38 mag in the *B* band (Xie et al. 1999).

In this observation, no microvariation was found; the mean *B* and *V* magnitudes are 12.90 and 12.58, respectively, and the color index is $B-V=0.32$. The light curves in *B* and *V* are shown in Figure 7.

### 4.7. *3C 279* (*1253−055*)

This object is a well-known member of the blazar subclass that has been termed optically violent variables (OVVs) by Webb et al. (1990). It was the first quasar detected at energies in excess of 1 GeV with EGRET. It exhibits variation at all wavelengths, from radio to $\gamma$-rays. The simultaneous variability in X-rays and $\gamma$-rays ($>100$ MeV) suggests for the first time that they are approximately cospatial (McHardy 1996). In 1996 January–February, a variation of a factor of 4–5 over 6 hours was observed (Wehrle et al. 1998). The *Rossi X-Ray Timing Explorer* observed a large X-ray flare that lasted for 7 days with a peak flux 3 times the quiescent level (Lawson, McHardy, & Marscher 1999). In the period before 1951, a series of flares with $\Delta B=3$–4 mag are discernible, as well as a long-timescale variation from $B\sim 18$ to $B=11.27$ in about 1.5 yr. A median timescale variation of about 24 hr was observed in 1988 (Webb et al. 1990).

The first significant variation with large amplitude, $\Delta V=1.17$ mag within 40 minutes, was registered on 1996 May 22 (Xie et al. 1999). New observations were made on 2000 May 1. During this observational run, the mean magnitude was 13.67 in the *R* band. No microvariability was observed.

### 4.8. *1652+398* (*Mrk 501*)

The source is a nearby ($z=0.034$) high-energy–peaked BL Lac object that has synchrotron peaks in the UV–soft X-ray region. Mrk 501 was significantly identified as a TeV-emitting source at the Whipple Observatory in 1995 March (Quinn et al. 1996) and confirmed as a source of VHE $\gamma$-rays

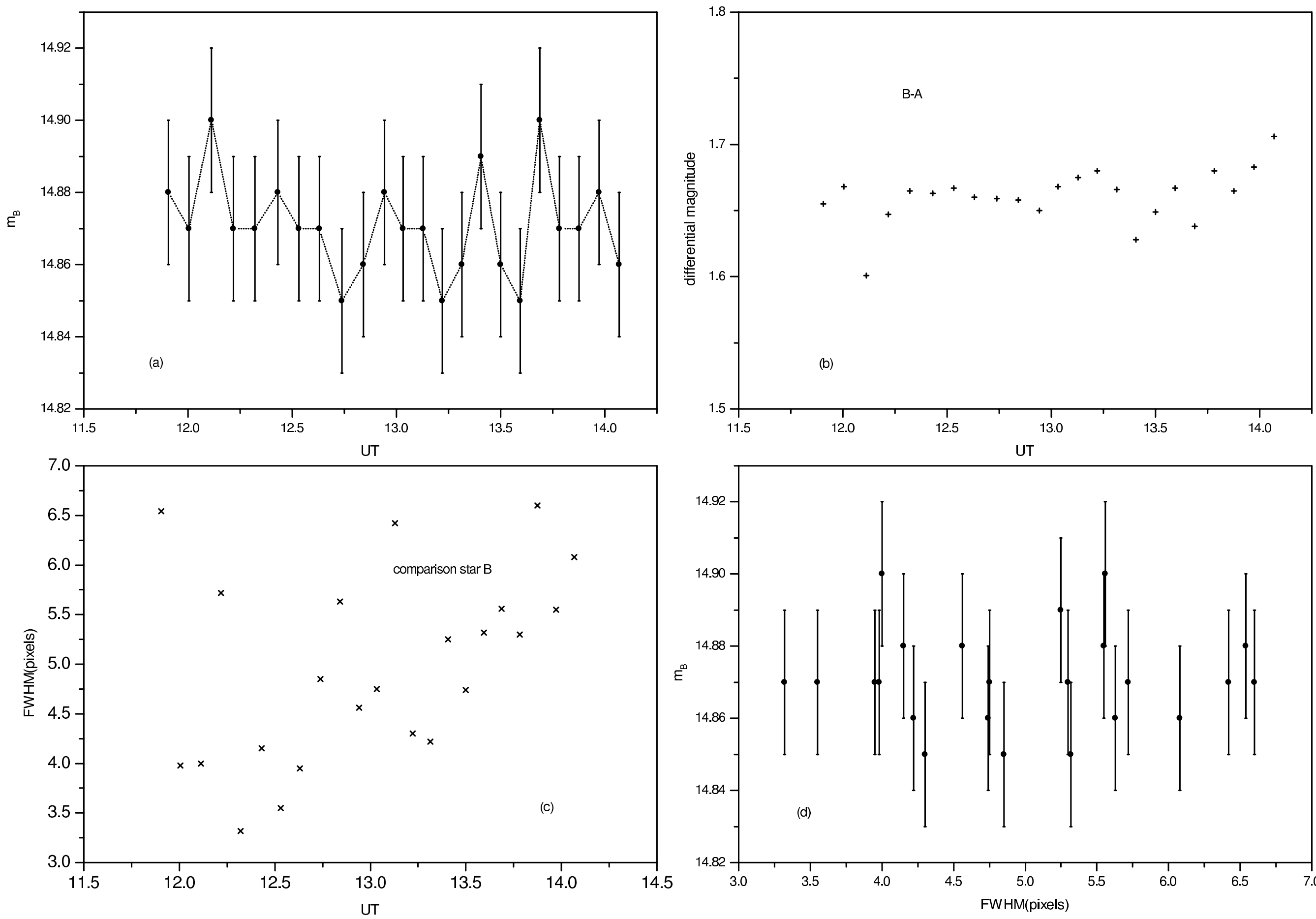


FIG. 5.—*Top left*: *B*-band light curve of 3C 66A on 2001 January 19; (*top right*) differential magnitude of two comparison star A, B; (*bottom left*) FWHM of PSF for comparison star B as a function of observational time; (*bottom right*) *B* magnitude of 3C 66A as a function of FWHM of PSF of comparison star B.

in 1996 by the HEGRA telescope (Bradbury et al. 1997). The simultaneous observations in both X-rays and TeV $\gamma$-rays indicate a short timescale of at least 1 day. The source exhibits a strong flare at both TeV and X-rays lasting 6 days, with a flux exceeding the preflare level by a factor of about 20 at TeV energies during the 2 days of maximum and with lower amplitudes (factor of 2–4) in X-rays (Sambruna et al. 2000).

Optical observations in 1992–1993 show that its intraday "flickering" amplitude is smaller than 0.22 mag in the *B* and *V* bands (Xie et al. 1996). During 1995–1996, the source was stable both in TeV $\gamma$-rays and in the optical. Variability of 0.13 mag in 12 minutes in the *V* band was observed by Ghosh et al. (2000). In the continuous 2 days of optical observation in our monitoring program in 2000, the source exhibited oscillations of about 0.14 mag in the *R* band (see

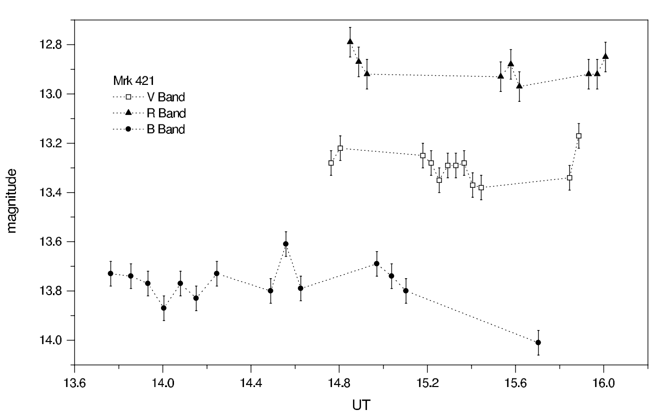


FIG. 6.—*BVR* light curves of Mrk 421 on 2000 May 1

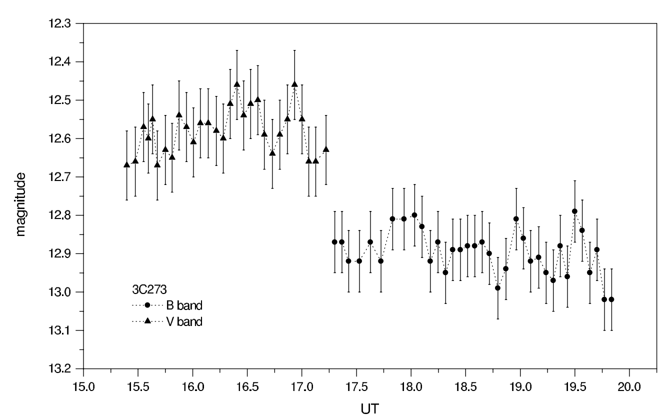


FIG. 7.—*BV* light curves of 3C 273 on 2000 April 5

Table 2). No convincing short-timescale variation was observed.

### 4.9. *PKS 0420−014*

This is a strong-variability quasar in optical band with variation timescales from less than hours to a few years. Webb et al. (1988) presented its light curve from 1969 April to 1986 January; the source is very active and exhibits variations up to 2 mag on timescale of a few years. The median timescale variation within 5 days (1.3 mag) and 23 days (1.7 mag) was observed in 1979. Wagner et al. (1995) suggested fast flux variations with timescale on the order of 1–10 days. Villata et al. (1997) registered the most noticeable variation, a decrease of 2.64 mag in 40 days from 1995 September 15 to October 15. The short-timescale variation with 0.12 mag in 40 minutes in the $R$ band was found by Villata et al. (1997). The maximum short-timescale variation was observed with 0.83 mag within 16.5 minutes in the $R$ band on 1999 January 17 by Xie et al. (2001). In that time, a decrease of 0.62 mag within 49 minutes and a subsequent increase of 0.41 mag within 26.6 minutes in the $R$ band were observed, along with the lowest state $R = 18.32$.

Our observation on 2001 January 17 showed that this source was in a high state, with average magnitude of 14.85 in the $R$ band and no short-timescale variations detected. But in our observation between 1999 January 17 and 2001 January 17, the source brightened from $R = 18.32$ to $R = 14.85$, with a variation of about 3.5 mag in 2 yr, which is consistent with the long-term variations seen by Webb et al. (1988).

## 5. DISCUSSION AND CONCLUSIONS

We have presented the results of a recent 2 year optical monitoring campaign on the behavior of nine $\gamma$-ray–loud blazars, in which four of a total of five TeV $\gamma$-ray blazars (Mrk 421, Mrk 501, 1ES 2344+51.4, and 3C 66A) were observed. For the OVV quasar, PKS 1510−089, an apparent variation of 2.0 mag in the $R$ band within 41 minutes was registered in the complete light curve, while the comparison stars varied less than 0.02 mag on all observed nights. The variability parameter of this variation is 59.6. Our previous observations also obtained 0.55 mag variation in about 50 minutes (Xie et al. 2001). Villata et al. (1997) observed the total maximum short-timescale variation being 0.63 mag in both the $R$ and $B$ bands. Our observation showed the largest short-timescale variation in this source and this variation has also been the largest detected over this timescale since 1982.

We have examined the host galaxy contribution to the microvariability for all objects. There is a weak correlation between the observed variability and the local seeing conditions for the object 1ES 2344+51.4. For other considered objects, we were unable to obtain any evidence of the influence of the seeing conditions. So, the apparent variation of about 2 mag observed in our program is intrinsic to PKS 1510−089, as determined by a rigorous check for correlations between variability and seeing conditions.

The observed variability of PKS 1510−089 by 2.00 mag within 41 minutes can be used to compute the efficiency ($\eta$) of the conversion of accreted matter into energy. If $\Delta L$ is the change in luminosity within the variability timescale $\Delta t_{\rm var}$, then $\eta$ can be written as

$$\eta \geq 5.0 \times 10^{-43} \Delta L/\Delta t_{\rm var} \qquad (2)$$

(Cavallo & Rees 1978; Fabian 1979; Xie et al. 1989; Jia et al. 1998), where $\Delta L$ is in ergs per second and $\Delta t_{\rm var}$ is in seconds. The value $\Delta L$ of the variability in our observation is $7.3 \times 10^{47}$ ergs s$^{-1}$. Using equation (2) with this value of $\Delta L$ and $\Delta t_{\rm var} = 2700$ s, we find $\eta \geq 62.2$. This value of $\eta$ strongly suggests the presence of relativistic beaming in PKS 1510−089 (Guilbert, Fabian, & Rees 1983; relativistic beaming is inferred if $\eta > 0.1$). In our previous paper (Xie et al. 1991), we obtained a formula to estimate the Doppler factor $\delta$:

$$\delta \geq (\eta_{\rm obs}/\eta_{\rm int})^{1/(4+\alpha)} , \qquad (3)$$

where $\eta_{\rm obs}$ and $\eta_{\rm int}$ are the conversion efficiency of observed and intrinsic variability, respectively, and $\alpha$ is the spectral index in the form $f_\nu \propto \nu^{-\alpha}$. In the optical band, assuming $\alpha = 1.0$ (Stocke et al. 1991) it is known that the efficiency of conversion for nuclei reaction is $\eta_{\rm int} = 0.007$ and that for pure accretion is $\eta_{\rm int} < 0.1$. The median value of 0.05 is almost equal to the value 0.057 in the thick accretion disk theory for the Schwarzschild metric (Paczyński & Wiita 1980). Thus we obtained the value of $\delta = 4.16$ by using the median value $\eta_{\rm int} = 0.05$. This value of the Doppler factor can be used to compute the size of the emission region $R$, using the light-travel time argument that

$$R \leq \frac{c\delta \, \Delta t_{\rm var}}{1+z} , \qquad (4)$$

where $c$ is the light velocity, $z$ is the cosmological redshift, and $\delta$ is the Doppler factor. The resulting value of $R$ from equation (4) is $2.5 \times 10^{15}$ cm. Note that $R$ need not be the linear dimension of a massive black hole; it could be the thickness of a thin plane shock at some distance out along a jet or the thickness of the optically thin boundary of an optically thick emission region (Marscher & Gear 1985). To explain the observed rapid variability, there are some mechanisms available, such as the eclipsing of hot spots by the accretion disk or microflares in the accretion disk (Wiita 1996). It has been suggested that a turbulent magnetic field with a relativistic jet may produce the rapidly oscillating variation seen in some blazars (Massaro et al. 1998; Nesci et al. 1998). Among these models, the relativistic model appears to be the most promising to explain the observed rapid variability in $\gamma$-ray–loud blazars.

For the four TeV $\gamma$-ray blazars, we have not observed any convincing variation. For 1ES 2344+51.4, Fan, Kurtanidze, & Nikolashvili's (2001a) observations detected no clear variation in a 2 week observation period. More recently, Kranich et al. (2000) reported that they found evidence of a 23 day periodicity variation in TeV energy for the TeV source Mrk 501. Moreover, Mrk 501 exhibited a strong flare in TeV, $\gamma$-rays, and X-rays lasting 6 days (Sambruna et al. 2000). This perhaps suggests that the optical short-timescale variability of TeV $\gamma$-ray blazars is a rare phenomenon, or that the amplitude variations are smaller than other in $\gamma$-ray–loud blazars, in part because of the synchrotron peaks in UV–soft X-ray region (Ulrich, Maraschi, & Urry 1997 and references therein; Fossati et al. 1998).

Our sincere thanks to the referee for valuable comments and suggestions that helped us to improve the presentation of our results and the paper. We acknowledge support from the National Natural Science Foundation of China and the Natural Science Foundation of Yunnan Province.

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