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# MONITORING THE OPTICAL SPECTRUM OF BL LACERTAE

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## ABSTRACT

$BVRI$ data from November 1999 through June 2008 were compiled in order to monitor the long-term optical spectrum of BL Lac. Spectral slopes were calculated for approximately 35 nights, using either $BVR$ or $VRI$ observations. Slope-versus-$V$-magnitude figures were constructed to explore possible correlations. Spectral flattening with increase in $V$-magnitude was found for both $BVR$ and $VRI$ data sets, but with a small correlation coefficient. Ten of the 35 data sets were tested for microvariability, with only two testing positive. No correlation was found between magnitude and occurrence of microvariations or between spectral slope and microvariations. We show that there is only one synchrotron component in the optical range.

*Subject headings:* blazar: general — blazar: individual (BL Lac) — blazar: optical spectrum — blazar: microvariability

## 1. INTRODUCTION

BL Lacertae is the prototype of a subset of Active Galactic Nuclei (AGN) known for their weak emission lines, high polarization, and variability on both short and long-term timescales. Flux variations have been observed across all wavelengths, from radio to gamma-ray. A possible long-term period of $\approx 7$ years in the optical flux has been suggested by Villata et al. (2004) and microvariations on the scale of several to less than one hour have been observed by Stalin et al. (2006).

The common model of BL Lac objects suggests that the continuum emission originates from jets viewed head-on relative to the observer. The emission in the radio to UV spectrum is synchrotron radiation from electrons traveling at relativistic speeds around the magnetic field lines of the jet (Marscher & Gear 1985), while continuum emission at the highest energies is due to inverse-Compton scattering (Sambruna et al. 1999). Previous research has proposed that the magnetic field lines form a helical structure around the jet (Bezrukovs & Gabuzda 2006), twisted by the rotation of the supermassive black hole present at the center of the blazar. This helical structure helps collimate the jet flow, while tangles in the magnetic field lines are responsible for the synchrotron emission.

The cause of blazar variability remains unknown. Sources of quasar variability involving flares in the accretion disk of the host galaxy have been proposed (Xiong et al. 2000), but because blazars are oriented such that we see directly into the jet, all other sources of variability are likely overshadowed by the jet luminosity. However, Perlman et al. (2009) has recently shown that some Blazars do have a more significant thermal component than originally expected using multifrequency data. Since BL Lac was not included in their sample, we will concentrate on the jet as the origin of the variations in this paper. It has been suggested that the rapid variations may be due to shockwaves propagating within the jet. As the shocks move away from the blazar center, they encounter areas of varying density. The observed synchrotron emissions become either more or less intense in accordance with the density variations. An alternative explanation for blazar variation involves plasma ejections. The ejections, traveling at different speeds, collide as they move outwards. As they collide, they combine and create the shocks which then accelerate electrons that emit via synchrotron radiation (Pian et al. 2008).

Small variations in overall orientation of the jet may also occur. Jet precession has been suggested as the source of the observed long-term variability; the precession caused by the rotation of the parent black hole (Ostorero et al. 2004). Analysis of the optical spectrum yields information about the electrons being ejected from the system, as synchrotron radiation is dominant in the optical region. In this paper, we have calculated optical spectral slopes. The steepening or flattening of the spectral slope corresponds directly to the electron energy distribution.

$$N(\varepsilon) = N_o \varepsilon^{\rho}. \quad (1)$$

Equation (1) governs the electron energy distribution for synchrotron radiation, with $N$ as the number of electrons, $N_o$ as a normalization factor, $\varepsilon$ the energy, and $\rho$ the electron spectral index.

$$F_\nu = F_o \nu^{-\alpha} \quad (2)$$

where

$$\alpha = \frac{\rho - 1}{2}. \quad (3)$$

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Equation (2) governs the synchrotron spectral distribution resulting from the electron distribution in equation (1) and equation (3) shows the relationship between the electron index and the optically thin spectral slope $\alpha$. $F$ is the flux at frequency $\nu$. Previous papers have searched for correlation between flux and optical spectral slope. Papadakis et al. (2003) reported spectral hardening with increase in flux, but with a poor linear fit. Böttcher et al. (2003) and Stalin et al. (2006) again reported spectral hardening with increasing flux, but for short-term variability. The correlation for long-term variability becomes much less well-defined. Hagen-Thorn et al. (2007) analyzed spectral slopes for blazar AO 0235+16 and found the same correlation between flux and spectral slope, but with a correlation coefficient of $r = 0.2$. These correlations are directly related to the electron acceleration mechanisms in the jet since from equation 3 the optically thin spectral index is related directly to the electron spectral index. IF more electrons are injected at every energy simultaneously, the spectral index will not change with flux, but if there is either a differential acceleration as a function of energy, or several independent components, the the spectral index will change with brightness in some manner. A hardening of the spectrum indicates that more energetic electrons are accelerated than electrons on the lower end of the distribution.

Log fluxes of $R$-magnitudes versus spectral slope diagrams were completed by Webb et. al. (1998) during the 1997 outburst of BL Lac for $BVRI$ and $VRI$ data sets. Although a significant amount of scatter exists, a harder-when-brighter trend is easily visible, with a slope of 0.27 and correlation coefficient of $r = 0.6$.

## 2. OBSERVATIONS

The data used in this paper were compiled over the course of ten years, taken primarily by J. Webb and students at the SARA 0.9 meter telescope located at Kitt Peak National Observatory outside of Tucson, Arizona. Several Apogee CCD cameras, AP7, U55, and U42, have been used throughout this study with Johnson/Cousins $BVRI$ filters. $B$, $V$, $R$ and I band observations are included, with approximately ten observation nights tested for microvariability. For these nights, an average of $\approx 50$ images in a single band were taken (primarily in $R$-band), although some nights have microvariation series of up to $\approx 400$ images. The Howell method was used to test the significance of the low-amplitude variations (Howell et al. 1988). The data set includes only nights where either $BVRI$, $BVR$, or $VRI$ observations were collected. On nights when color data were collected, anywhere between $\approx 5$ and $\approx 60$ images were taken in each band.

Image reduction (flat fielding, bias and dark subtraction) was completed using MIRA. Photometry was then performed using the aperture photometry routine in MIRA with the comparison stars B,C,H,K from Smith et al. (1985). Aperture size varied per image set, but was set at the average Full Width Half Max (FWHM) or slightly larger. The cosmic ray filter repeatedly disrupted the line profiles of the stars, "hollowing out" the PSF of bright star images. This led to incorrect fitting of the PSF and repeatedly gave poor photometric magnitudes for the comparison stars affected. We routinely monitored the image profiles and did not cosmic ray correct images where these problems occurred. Table 1 lists the Julian date, $R$-magnitude, error, $BVR$, or $VRI$ spectral slope for 35 data points.

TABLE 1
BL Lac $R$-Magnitudes and spectral slopes

| Julian date | R mag | Error | $\alpha(BVR)$ | $\alpha(VRI)$ |
|---|---|---|---|---|
| 2451513.1 | 12.52 | 0.002 | - | -0.708 |
| 2452047.1 | 13.89 | 0.002 | - | -0.772 |
| 2452075.1 | 12.81 | 0.003 | - | -0.487 |
| 2452106.1 | 13.13 | 0.009 | - | -0.602 |
| 2452193.6 | 14.28 | 0.003 | - | -0.940 |
| 2452200.1 | 14.25 | 0.008 | - | -0.619 |
| 2452231.6 | 14.17 | 0.004 | - | -0.698 |
| 2452522.3 | 13.65 | 0.003 | - | -0.609 |
| 2452560.1 | 13.83 | 0.003 | - | -0.682 |
| 2452619.6 | 13.74 | 0.057 | - | 0.060 |
| 2452627.1 | 13.19 | 0.002 | - | -0.536 |
| 2452931.5 | 14.23 | 0.004 | - | -2.062 |
| 2452974.6 | 13.48 | 0.003 | - | -0.725 |
| 2453168.1 | 12.99 | 0.002 | - | -0.884 |
| 2453169.8 | 13.25 | 0.003 | - | -0.884 |
| 2453262.6 | 13.18 | 0.002 | - | -0.789 |
| 2453625.0 | 13.81 | 0.003 | - | -1.148 |
| 2454624.9 | 14.02 | 0.006 | - | -1.352 |
| 2454625.9 | 13.91 | 0.094 | - | -0.788 |
| 2454626.8 | 13.86 | 0.003 | - | -0.789 |
| 2452193.6 | 14.28 | 0.003 | -1.157 | - |
| 2452202.1 | 14.06 | 0.030 | -0.846 | - |
| 2452203.1 | 14.12 | 0.030 | -0.840 | - |
| 2452204.1 | 13.73 | 0.040 | -0.800 | - |
| 2452208.1 | 14.19 | 0.030 | -0.933 | - |
| 2452522.3 | 13.65 | 0.003 | -0.733 | - |
| 2452627.1 | 13.19 | 0.002 | -0.644 | - |
| 2452974.6 | 13.48 | 0.003 | -0.712 | - |
| 2454624.9 | 14.02 | 0.006 | -1.089 | - |
| 2454626.8 | 13.86 | 0.003 | -1.075 | - |

Data from reduced images were imported into IDL version 6.3 and Microsoft Excel. IDL was used for converting magnitudes to corresponding log fluxes. The program used corrects for $E(B-V)$, which has a value of 0.329 for BL Lac, as provided by the NASA/IPAC Extragalactic Database (NED)[1]. Microsoft Excel was employed for graphing and determining microvariability using the Howell method (Howell et al. 1988).

## 3. RESULTS

Figure 1 shows the 10-year light curve of BL Lac in $R$-magnitude. The outburst of 1997 is visible on the left side of the graph. Error bars are approximately the size of the data markers. Triangles indicate the 35 data sets from Table 1 in which the spectral slope was calculated. Out of the 35 data sets, ten were tested for microvariability. Only two showed statistically significant low-amplitude variations.

Twenty data sets ranging in date from November 1999 to June 2008 were used to calculate $VRI$ spectral slopes for BL Lac. Plotting log frequency on the $x$-axis versus log flux on the $y$-axis yielded the twenty slopes. No correlation was found between the Julian date versus the slope of the $VRI$ spectra. This procedure was repeated for 13 data sets where $B$,$V$, and $R$-band data had been collected. Data from Stalin et al. (2006) and Bregman et al. (1990) were combined with our data for comparison. Again, no correlation was found between the date and the spectral slopes. Figure 2 is a log frequency versus log flux plot exhibiting a range of spectral slopes. We chose

[1] nedwww.ipac.caltech.edu/

six data sets (in descending order from top to bottom: JD2451513.1, JD2452075.1, JD2452619.6, JD2454624.9, JD2452193.6, JD2452931.5) illustrating the flattest and steepest spectral slopes, and the brightest and faintest magnitudes. The flattest and steepest slopes were 0.06 and −2.06. Error bars are a combination of log flux error and estimated photometric error.

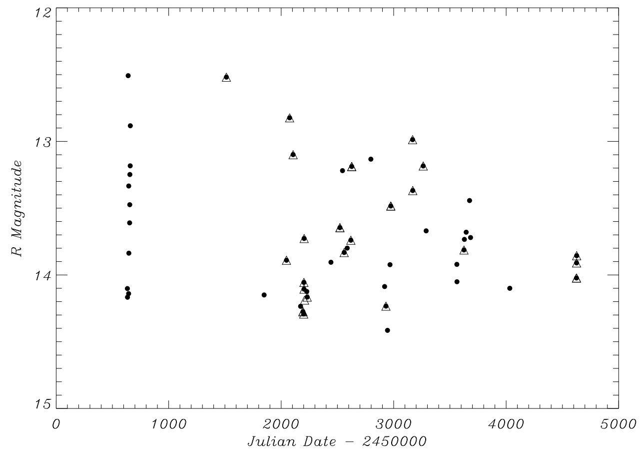


FIG. 1.— Ten-Year light curve of BL Lac. For triangular data points, spectral slopes were calculated. The initial large amplitude outburst occurred in 1997, and the last observations are from 2006.

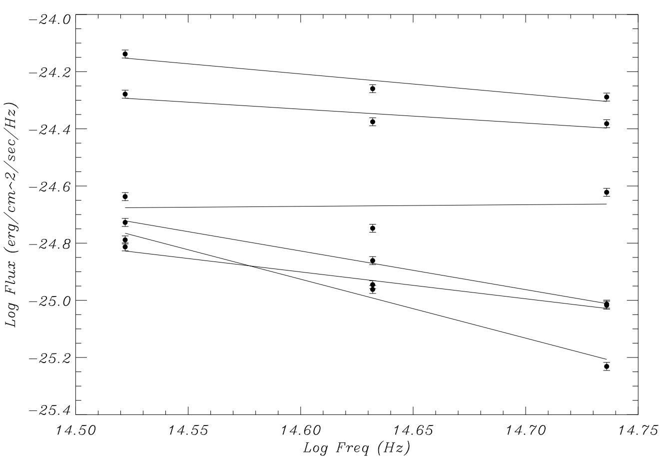


FIG. 2.— Log frequency vs. log flux for six data sets.

Both the $BVR$ and $VRI$ data illustrated a weak correlation between $V$-magnitude and spectral slope. In both instances, a fainter magnitude was associated with a steeper slope and brighter magnitudes resulted in flatter slopes. This correlation is questionable due to the low value of the correlation coefficients for both $BVR$ and $VRI$ data sets. $R^2$ is the coefficient of determination for linear regression, displaying the percentage of data which can be predicted by the trend line (Wolfram Mathworld [2]). The best values for $R^2$ are closest to one. The $BVR$ and $VRI$ data yielded $R^2$ of 0.356 and 0.263, respectively, giving a probability of 0.005 and 0.02 that they are not from the same sample. A diagram of the $VRI$ spectral slopes versus $V$ magnitudes is seen in Figure 3. Error bars are the approximate size of the data points.

Data from Webb et. al. (1998) was added to $BVR$ and $VRI$ data sets. When the V-magnitude versus spectral slope graphs were replotted, the value of $R^2$ increased for the $BVR$ data set and declined slightly for the $VRI$ data set. The new $R^2$ values for $BVR$ and $VRI$ were 0.45 (.001)and 0.23 (.032). Seven data sets were added to $BVR$ and ten data sets added to $VRI$.

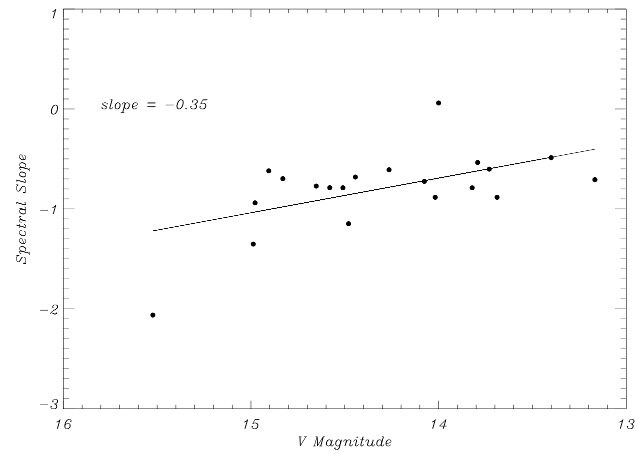


FIG. 3.— $V$ mag vs. $VRI$ spectral slope. Line has slope of −0.35 and correlation coefficient of 0.263.

Flux-flux diagrams were created for the $BVR$ and $VRI$ data sets. This was done by Hagen-Thorn et al. (2007) for AO 0235+16 in $UBVRIJHK$. The BL Lac diagrams generated similar results; namely, the data points lie along straight lines, indicating that a single power law covers the observed spectral range. Figure 4 illustrates the flux-flux diagram for the $V$ and $I$ versus $R$ band. Triangular data points represent $I$-band and round black data points represent $V$-band. Error bars are approximately the size of the data points. The slopes for both plots are close to one, indicating that the three spectral bands vary in almost identical increments. The V and I plots yielded slopes of 0.98 and 1.30, respectively. For the $BVR$ diagram, the $B$ and $V$ plots yielded slopes of 0.78 and 1.02. All of the flux-flux plots had coefficients of determination close to one. The lowest coefficient of determination was $R^2 = 0.977$ ($< .00001$) and the highest was $R^2 = 0.989$ ($< .00001$).

## 4. ANALYSIS

The synchrotron radiation model is widely used to explain the observed spectrum of BL Lac and other AGN. The combination of highly polarized emissions and the observed power law spectrum (as opposed to a black body spectrum) support this theory. The shock acceleration jet model of Bregman & Boisseau (1989) predicts spectral hardening with flux brightening, which was observed for our $BVR$ and $VRI$ data sets. The paper of Webb et. al. (1998) lists three possible models that can account for spectral variability. Webb et. al. (1998) state

[2] http://mathworld.wolfram.com/

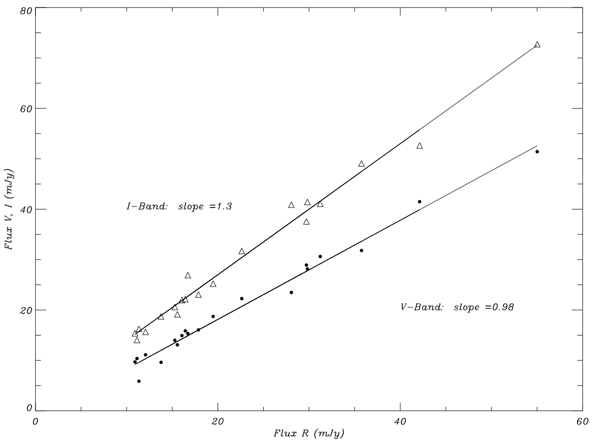


FIG. 4.— Flux $R$ vs. flux $V$,I. Triangular data points represent $I$-band, black circular points represent $V$-band.

that if the jet emission is due to synchrotron radiation, then either the spectral slope variation is indicative of electron energy distribution slope variation, the break frequency is shifting in the optical, or the synchrotron emission has more than one variable component in the optical.

In our findings, a single power law covered our optical range and the different optical bands were varying with a set ratio relative to each other. This result implies that spectral variations are due to variability in a single component. If the spectrum showed large deviations from linearity, either convex or concave, then either there were multiple sources responsible for the emission, or the break frequency was changing. The break frequency is the frequency where the electron cooling becomes more efficient and the slope of the optically thin continuum steepens. If this break frequency occurs in the observed portion of the spectrum, variations in the high energy electron distribution cutoff energy will effectively move the location of the break in frequency and result in a change in the slope of the broadband spectrum. However, this change would always be convex (a steepening of the spectrum) rather than concave (flattening of the spectrum). As can be seen in Figure 2 in no case is there significant evidence for convex curvature in the spectrum. If the break frequency occurs at frequencies higher than our observations, then we cannot rule it out because we would not detect a change in our broadband spectrum.

With the addition of our data, we can eliminate the last possibility, as we found one power law component across the optical band. Data collected from a wider range of bands from the electromagnetic spectrum are required to either refute or support the possibility that the location of the break frequency plays a significant role in the spectral changes we observed.

## 5. CONCLUSION

A weak correlation was observed between $V$-magnitude and the spectral slope. Hagen-Thorn et al. (2007) reported spectral hardening with flux increase for AO 0235+16, with a correlation coefficient of $r = 0.2$. Our coefficient of determination values were similarly low for both $BVR$ and $VRI$ spectral slopes, with $R^2$ of 0.36 (.0012) and 0.26 (.032). A study of BL Lac spectral slopes by Böttcher et al. (2003) found good correlation between slope and flux for microvariations, but saw less clear results for long-term flux variations. This result seems to be in agreement with our findings. More extensive observations are required to verify the apparent trend and support the model.

No apparent correlation exists between the spectral slope versus occurrence of microvariability, nor between the Julian date versus spectral slope.

Approximately 25 nights over the past ten years have been tested for microvariability. Some of these nights are separated by months or years. With the current data set, there is no relationship between the occurrence of microvariability and brightness. Microvariability has been observed over BL Lac's full range of magnitudes. Temporal gaps in the data sets could be hiding evidence to support otherwise, so long-term, continuous monitoring of the source is needed to make a solid conclusion.

Qian et al. (2004) used a combination of optical data from Webb et. al. (1998) and x-ray through gamma-ray data to investigate jet emissions across a wide spectrum. It was found that the flattest spectral slope corresponded to a burst in the gamma-ray. Flat optical spectra during high-energy outbursts were also reported for Mrk 501 and Mrk 421. Further investigation of this effect is a possible direction of further study.

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