COLOR BEHAVIOR OF BL LACERTAE OBJECT OJ 287 DURING AN OPTICAL OUTBURST

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ABSTRACT

This paper studies the color behavior of the BL Lac object OJ 287 during an optical outburst. Upon revisiting the data from the OJ 94 monitoring project, and from an analysis of the data obtained with the 60/90 cm Schmidt Telescope of NAOC, we found a bluer-when-brighter chromatism in this object. The amplitude of variation tends to decrease with frequency. These results are consistent with the shock-in-jet model. We ran some simulations and confirmed that both amplitude difference and time delay between variations at different wavelengths can result in the bluer-when-brighter phenomenon. Our observations confirmed that OJ 287 underwent a double-peaked outburst about 12 years after 1996, which provides further evidence for the binary black hole model in this object.

Key words: BL Lacertae objects: individual (OJ 287) – galaxies: active – galaxies: photometry

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Blazars, as a subset of active galactic nuclei, are characterized by rapid and strong variability, and are those objects with their relativistic jets pointed basically toward the observer (Urry & Padovani 1995). The jet is believed to originate from and be accelerated by a rotating supermassive black hole surrounded by an accretion disk. Blazars can be divided into two groups: BL Lac objects and flat spectrum radio quasars. The former show no or very weak emission lines in their optical spectra, while the latter show strong emission lines.

The BL Lac object OJ 287 is one of the best-observed blazars. It is also the only blazar that shows a convincing period of 12 years after 1988, which provides further evidence for the binary black hole model in this object. Later observations led other researchers to establish new models, but all based on a binary black hole system (Lehto & Valtonen 1996; Sillanpää et al. 1997; Katz 1997; Villata et al. 1998; Valtaoja et al. 2000; Liu & Wu 2002; Villforth et al. 2010).

The color behavior of OJ 287 during the outburst was investigated by Sillanpää et al. (1996). They found that the object showed a stable V–R color from 1994 to 1996. However, their colors were calculated using the average magnitudes over one day. Since the brightness of this object can change on intraday timescales, using the average brightness will dilute the color change, especially on short timescales. In order to find the genuine color, we revisited the data from the OJ 94 monitoring project and used our own data to determine the relationship between the color and magnitude of this object.

This paper is organized as follows. The revisit of the OJ 94 data is described in Section 2. Section 3 presents our monitoring procedure and results. Section 4 shows the simulations of the color behavior resulting from different amplitudes and different rates of variation at different wavelengths. The conclusions are given in Section 5.

2. REVISIT OF OJ 94 DATA

In order to verify the predicted optical outburst of OJ 287 in late 1994 (Sillanpää et al. 1988), an international, multi-waveband project was launched. This is the OJ 94 project. It started in the fall of 1993 and ended in 1997. More than 50 workers from 10 countries were involved. The monitoring was carried out at multiple wavelengths in the UV, optical, infrared, and radio regimes. As a result, over 8000 data points were collected during the monitoring period.

As mentioned in Section 1, the brightness of OJ 287 can change over one day, as shown in Figure 1. Other cases of intraday variability (IDV) in OJ 287 were reported by Carini et al. (1992). When the magnitude of an object changes little in one day, it is possible to use the average magnitude over that time to calculate the color. But when the magnitude changes obviously on short timescales, it is not valid to calculate the color using the average magnitude. In order to obtain the genuine color, we reprocessed the data of OJ 94 in two ways.

The first was by direct match. If the time interval of a V and an R magnitude was less than 5 minutes, they were matched and a color was computed. If one magnitude had multiple matches, the one with the smallest time interval was used. The color–magnitude diagram is given in Figure 2. In principle, direct match is the most reasonable method to calculate the color. However, this method might be biased by the possible small systematic differences between the different telescopes involved in the OJ 94 project. Thus we used a second method to calculate the color of OJ 287.

The second method was binning and match. The data were binned in half an hour, and then the binned V and R magnitudes were used to compute the color. The color–magnitude diagram is displayed in Figure 3. The binning of the data helped to eliminate or reduce the possible systematic differences between different telescopes. The binning time of half an hour was chosen because the variability timescale of most blazars is longer than this, except for a few cases (e.g., Sasada et al. 2008; Rani et al. 2010a).

We used the linear least-squares method to calculate the interdependency and found that the slope in Figure 2 is 0.02868, with a correlation coefficient of 0.3022, and the significance level is 0.05. The slope in Figure 3 is 0.01818, with a correlation coefficient of 0.3022, and the significance level is 0.05. For comparison, the slope of Sillanpää et al. (1996) is just 0.00967 by converting their result from the slope of V–R diagram. Therefore, we revisited the OJ 94 data and used two new
methods to calculate the color of OJ 287. The object was found to have a bluer-when-brighter chromatism during its outburst in 1994–1996. This is different from, and should be more reasonable than, the result found by Sillanpää et al. (1996).

3. MONITORING AND RESULTS

3.1. Observations and Data Reduction

Our optical monitoring program of OJ 287 was performed with a 60/90 cm Schmidt telescope located at the Xinglong Station of the National Astronomical Observatories of China (NAOC). Prior to 2006, there was a Ford Aerospace 2048 × 2048 CCD camera mounted at its main focus. The CCD has a pixel size of 15 μm, and its field of view is 58′ × 58′, resulting in a resolution of 1.7 pixel⁻¹. At the beginning of 2006, the 2k CCD was replaced by a new 4096 × 4096 CCD. The field of view is now 96′ × 96′, resulting in a resolution of 1.7 pixel⁻¹. The telescope is equipped with 15 color intermediate-band filters, covering a wavelength range from 3000 to 10000 Å.

This paper includes data from 2005 January 29 to 2009 April 13. Excluding nights with bad weather and those devoted to other targets, the actual number of nights for OJ 287 observations was 234. For the vast majority of nights, only one or two exposures were made in each band. On a few nights, more exposures were made for the IDV search. We used filters in the $e$, $i$, and $m$ bands to observe in 2005–2006, and then changed to the $c$, $R$, and $o$ bands from the end of 2006 December. At the beginning of 2009, the $R$ band was changed back to the $i$ band. The wavelengths of the $c$, $e$, $i$, $m$, and $o$ bands were 4210, 4920, 6660, 8020, and 9190 Å, respectively. The $R$-band data have been published by Villforth et al. (2010). The data at other wavelengths are reported here.

The data reduction procedures included positional calibration, bias subtraction, flat-fielding, extraction of instrumental aperture magnitude, and flux calibration. The average FWHM of the stellar images was about 3.5″ during our monitoring. So during the extraction, the radius of the aperture was set as 3 pixels and the radii of the sky annulus were set as 7 and 10 pixels, respectively. We used the comparison stars 4, 10, and 11 in Fiorucci & Tosti (1996) for the flux calibration of OJ 287. Their BATC $c$, $e$, $i$, $m$, and $o$ magnitudes were obtained by observing them and three BATC standard stars HD 19445,
HD 84937, and BD +17 4708 on a photometric night, and are listed in Table 1. Then the magnitude of OJ 287 was calibrated relative to the mean period (Valtonen et al.2006). Both outbursts are due to the tidal effect, while the second one was due to the tidal effect, i.e., tidally induced accretion flow would enhance the emission from the jet.

From 2005 January 29 to 2006 November 19, the overall amplitude in the $e$, $i$, and $m$ bands was 2.34, 2.24, and 2.14 mag, respectively. The overall amplitude in the $c$, $R$, and $o$ bands from 2006 November 26 to 2009 January 9 was 2.64, 2.59, and 2.55 mag, respectively. The amplitude of variation tended to decrease with frequency. No IDV was found for OJ 287 on the V band.

### 3.3. Color–Magnitude Diagram

The color behavior of OJ 287 was studied based on our data. In 2005–2006, we used the $e$ and $m$ bands to calculate the relationship between color and magnitude. Then the $c$ and $o$ bands were used from the end of 2006. The results are shown in Figures 5 and 6, respectively.

The linear least-squares method was used to calculate the correlation coefficient. The slope we obtained in Figure 5 is 0.137, with a correlation coefficient of 0.6689, and the significance level is 0.05. In Figure 6 the slope is 0.1164, with

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**Table 1**

| Star ID | $c$ | $e$ | $i$ | $m$ | $o$ |
|---------|-----|-----|-----|-----|-----|
| 4       | 15.198 | 14.920 | 14.020 | 13.650 | 13.598 |
| 10      | 15.082 | 15.010 | 14.510 | 14.280 | 14.366 |
| 11      | 15.479 | 15.490 | 14.840 | 14.590 | 14.708 |

**Table 2**

| Date (UT) | Time | Julian Date | Exp | $c$ | $c_{err}$ | dfmag11 |
|-----------|------|-------------|-----|-----|----------|--------|
| 2006 Nov 26 | 18:10:49.0 | 2454066.25751 | 300 | 15.811 | 0.043 | 0.053 |
| 2006 Nov 26 | 18:27:08.0 | 2454066.26884 | 300 | 15.847 | 0.035 | 0.004 |
| 2006 Nov 26 | 18:42:40.0 | 2454066.27963 | 300 | 15.823 | 0.035 | 0.016 |
| 2006 Nov 26 | 18:57:53.0 | 2454066.29020 | 300 | 15.788 | 0.039 | 0.037 |
| 2006 Nov 26 | 19:13:26.0 | 2454066.30100 | 300 | 15.849 | 0.037 | 0.034 |

**Table 3**

| Date (UT) | Time | Julian Date | Exp | $e$ | $e_{err}$ | dfmag11 |
|-----------|------|-------------|-----|-----|----------|--------|
| 2005 Jan 29 | 14:57:32.0 | 2453400.12329 | 300 | 15.774 | 0.249 | 0.023 |
| 2005 Jan 29 | 15:24:21.0 | 2453400.14191 | 480 | 15.628 | 0.236 | 0.023 |
| 2005 Jan 30 | 16:32:48.0 | 2453401.18944 | 240 | 15.549 | 0.073 | 0.134 |
| 2005 Jan 30 | 16:44:07.0 | 2453401.19730 | 240 | 15.520 | 0.071 | 0.024 |
| 2005 Jan 30 | 16:58:03.0 | 2453401.20698 | 240 | 15.551 | 0.066 | 0.101 |

**Table 4**

| Date (UT) | Time | Julian Date | Exp | $i$ | $i_{err}$ | dfmag11 |
|-----------|------|-------------|-----|-----|----------|--------|
| 2005 Jan 29 | 15:02:48.0 | 2453400.12694 | 180 | 14.683 | 0.087 | 0.000 |
| 2005 Jan 30 | 16:28:41.0 | 2453401.18659 | 150 | 14.632 | 0.045 | 0.051 |
| 2005 Jan 30 | 16:48:34.0 | 2453401.20039 | 150 | 14.705 | 0.047 | 0.025 |
| 2005 Jan 30 | 17:16:22.0 | 2453401.21970 | 150 | 14.668 | 0.046 | 0.024 |
| 2005 Jan 30 | 17:30:36.0 | 2453401.22958 | 150 | 14.631 | 0.048 | 0.050 |

**Table 5**

| Date (UT) | Time | Julian Date | Exp | $m$ | $m_{err}$ | dfmag11 |
|-----------|------|-------------|-----|-----|----------|--------|
| 2005 Jan 30 | 16:38:03.0 | 2453401.19309 | 240 | 14.374 | 0.036 | 0.011 |
| 2005 Jan 30 | 16:52:59.0 | 2453401.20346 | 240 | 14.276 | 0.038 | 0.023 |
| 2005 Jan 30 | 17:06:48.0 | 2453401.21306 | 240 | 14.241 | 0.037 | 0.022 |
| 2005 Jan 30 | 17:20:50.0 | 2453401.22280 | 240 | 14.265 | 0.035 | 0.074 |
| 2005 Jan 30 | 17:35:00.0 | 2453401.23264 | 240 | 14.259 | 0.041 | 0.018 |

**Table 6**

| Date (UT) | Time | Julian Date | Exp | $o$ | $o_{err}$ | dfmag11 |
|-----------|------|-------------|-----|-----|----------|--------|
| 2006 Nov 26 | 18:20:04.0 | 2454066.26394 | 300 | 14.439 | 0.048 | 0.050 |
| 2006 Nov 26 | 18:36:34.0 | 2454066.27539 | 300 | 14.422 | 0.046 | 0.067 |
| 2006 Nov 26 | 18:51:29.0 | 2454066.28575 | 300 | 14.397 | 0.051 | 0.109 |
| 2006 Nov 26 | 19:07:10.0 | 2454066.29664 | 300 | 14.480 | 0.070 | 0.006 |
| 2006 Nov 26 | 19:22:04.0 | 2454066.30699 | 300 | 14.450 | 0.064 | 0.101 |
a correlation coefficient of 0.626, and the significance level is 0.05. Figures 5 and 6 show a strong bluer-when-brighter chromatism.

The chromatism in Figures 5 and 6 is much stronger than in Figures 1 and 2. The reason may be that the wavelength differences of the c and o bands (4980 Å) and the e and m bands (3100 Å) are much larger than those of the V and R bands (1070 Å).

The same bluer-when-brighter phenomenon was found for OJ 287 by some authors. A strong correlation is observed by Brown et al. (1989) between the near-infrared flux levels and the near-infrared spectral slopes of OJ 287, in the sense that the spectra are steeper when the sources are fainter. Carini et al. (1992) found that there does not appear to be a well-defined correlation between the brightness and color of OJ 287; however, there is a general indication that when the source is brighter, it tends to be bluer. According to a comparison of the outburst of 1994 with those of 1971 and 1983, Hagen-Thorn et al. (1998) found that there is a clear correlation between the power of the outburst and color indices of the variable component in each event: the larger the outburst, the bluer the source. Vagnetti et al. (2003) pointed out that eight BL Lac objects including OJ 287 tend to be bluer when brighter. Fiorucci et al. (2004) reported that a large number of BL Lac objects such as OJ 287 display the bluer-when-brighter phenomenon. Wu et al. (2006) also discovered a bluer-when-brighter chromatism in this object. Villforth et al. (2010) studied the optical spectral index variations and found a bluer-when-brighter trend. In fact, bluer-when-brighter chromatism tends to be a general feature of BL Lac objects (Vagnetti et al. 2003; Rani et al. 2010b).

4. SIMULATION OF COLOR BEHAVIOR

Wu et al. (2007) mentioned that the difference in amplitude and rate of the variations at different wavelengths may both lead to color change. Here we ran some simulations to clarify this. We created two light curves. The first was made by the following steps. The baseline was a sine curve with an amplitude of 2.0. A fluctuation with a random amplitude less than 0.2 was added to the sine curve. Then a random error less than 0.15 was added to each point. The second light curve was produced by changing the variation amplitudes or phases of the first light curve. Then we studied the color behavior based on the two simulated light curves.
1. Effect of amplitude difference. The two light curves are different in variation amplitude, with the second light curve having an amplitude of 2.5, as shown in the left panel of Figure 7. The color–magnitude diagram is displayed in the right panel of Figure 7. Although the points trace a zigzag route, the object evolves basically along the diagonal path on the color–magnitude diagram. A simple linear fit to the points gives a correlation coefficient of 0.9348, which indicates a strong bluer-when-brighter trend. If the amplitude difference increases, the slope of the linear fit also increases.

2. Effect of time delay. As shown in the left panel of Figure 8, the two light curves are different in variation phase by 1/8π. The color–magnitude diagram is shown in the right panel. The numbers indicate the time sequence. The object evolves on the color–magnitude diagram along an elliptic orbit in the counterclockwise direction. The major axis of the ellipse is along the bluer-when-brighter line. When we change the phase difference from 1/8π to 1/4π, the slope of the major axis of the ellipse increases, and the ellipticity becomes smaller, but the counterclockwise evolution remains. Apart from two extreme examples of variability timescale of 15 minutes observed in S5 0716+714 (Sasada et al. 2008; Rani et al. 2010a), the variability timescales of the optical bands are longer than 1 hr on most occasions (Romero et al. 2002; Cellone et al. 2007). However, the observed time delay in the optical band is usually shorter than 10 minutes (e.g., Qian et al. 2000; Villata et al. 2000; Papadakis et al. 2003; Stalin et al. 2006). If π (the timescale) corresponds to one hour, then 1/4π equals 15 minutes, so there is no need to consider a longer time delay in our simulation. This loop path on the color–magnitude diagram has been predicted theoretically by Kirk et al. (1998). Some observational results at high energy were reported by several authors, as mentioned by Wu et al. (2007).

3. Effect of amplitude and time delay. The two light curves are different in both amplitude and phase. The amplitudes of the two light curves are 2.0 and 2.5, respectively, and the time delay is 1/8π. Such light curves are shown in the left panel of Figure 9. The right panel gives the relationship between color and magnitude. The diagram also shows as an ellipse in the counterclockwise direction. The major axis of the ellipse is also along the bluer-when-brighter line, and the ellipticity is larger than in Figure 8.

The simulations confirmed that both amplitude differences and time delay can result in the bluer-when-brighter phenomenon. In all three cases, the object tends to be bluer when brighter. The color changes more significantly as the difference in amplitude or phase increases. Moreover, the simulations provided a potential way to distinguish between the factors that lead to the bluer-when-brighter chromatism. If the object
evolves along a diagonal path on the color–magnitude diagram, the amplitude difference dominates the color change. If there is a loop path on the color–magnitude diagram, at least a time delay is involved. Of course, measurement accuracy is a key factor in the identification of a diagonal or a loop path on the color–magnitude diagram.

5. CONCLUSIONS

Based on the data from the OJ 94 monitoring project, we found that OJ 287 showed a bluer-when-brighter chromatism in its outburst period. Using data obtained from the 60/90 cm Schmidt Telescope of NAOC in 2005–2009, we found an even stronger chromatism. The amplitude of variation tends to decrease with frequency.

Our monitoring results proved that about 12 years after the outburst in 1994 and 1996, the object underwent a new outburst in 2005 and 2007 and showed a double-peaked structure. These results further support the binary black hole model of OJ 287. However, even with these new observational data, there are still some inconsistent estimates of the masses of the two black holes (e.g., Valtonen et al. 2008b; Fan et al. 2009). Monitoring of this object until the next major outburst may help to resolve these conflicts.

We ran some simulations and confirmed that both amplitude differences and time delay can result in the of bluer-when-brighter phenomenon. Moreover, the color measurement may be biased by some technical and artificial effects (J. H. Wu et al. 2011, in preparation). The relation of the color behavior to the central physics may be more complex than previously expected.

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Figure 9. Left: simulated light curves with different amplitudes and time delay. The amplitudes of the two light curves are 2.0 and 2.5, respectively, and the time delay is 1/8 π. Right: color–magnitude diagram. The numbers in the figure represent the time sequence.