The Multimessenger Chakra of Blazar Jets
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The Microvariability and Wavelength Dependence of Polarization Vector of BL Lacertae in the Outburst 2020 to 2021

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Abstract. We performed photo-polarimetry observations for the blazar BL Lacertae (BL Lac) in 2020 to 2021, in which BL Lac showed historical outburst. As a result, we obtained microvariability with a timescale about five minutes and wavelength dependence of polarization degree and angle. These results indicate multiple emission regions and turbulent magnetic field structure.

Keywords. BL Lacertae, polarimetry

1. Introduction

Blazars are a type of active galactic nucleus (AGN) whose jet direction is parallel to our line of sight (Urry & Padovani 1995). The emission region and magnetic structure of the blazar jet are still under debate, and optical polarimetry is an important method for inferring the magnetic field structure of the jet. Some blazars show microvariability, which is the variation of the flux within a day. This phenomenon indicates that the emission region is compact and free from contamination by long-term variability. However, there are few observations of their polarimetry, which is useful for discussing the magnetic field in compact emission regions. BL Lacertae (BL Lac) is known as a low frequency synchrotron peaked (LSP) blazar (Abdo et al. 2010), and it has shown the microvariability several times (Miller et al. 1989; Matsumoto et al. 1999; Abeysekara et al. 2018). It showed the historic outburst since August 2020 in GeV and optical bands. We performed polarimetric observations for the flaring period of BL Lac, which is an ideal source for polarimetric studies of microvariability because it has a high polarization ($\geq 5\%$) and with a historically bright flux.

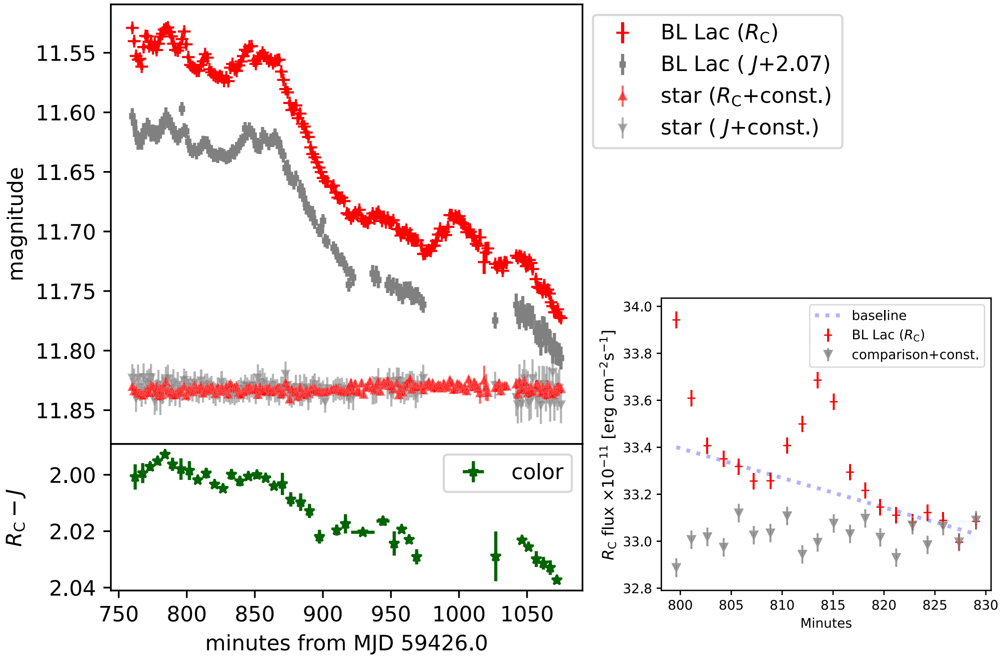

Figure 1. *Left panel*: time evolution of magnitude and color on July 31, 2021. Red crosses and gray squares in the top panel represent R_C- and J-band magnitudes, respectively. Red triangles and gray inverted-triangles indicate the comparison star. A part of the light curves in the J-band was removed due to saturation. Green stars in the bottom panel represent the R_C-J, calculated from the four-frame binned light curves. *Right panel*: light curve in the microvariability in the left panel. Red crosses and gray triangles represent the R_C band flux of BL Lac and the comparison star, respectively. The blue dashed line represents the baseline estimated by linear fitting.

2. Observations

We have performed polarimetric observations using the Hiroshima Optical and Near-InfraRed Camera (HONIR, Akitaya et al. 2014) installed on the 1.5 m Kanata telescope at the Higashi-Hiroshima Observatory, using R_C and J band filters for simultaneous observation. A fixed Wollaston prism and a rotating half-wave plate were used for polarimetry. The duration of the observations ranged from one to five hours per night and were performed over 14 nights during the bright period of BL Lac, from September 2020 to August 2021. The detailed observation and analysis method is based on Imazawa et al. (2022).

3. Results

We obtained light curves from 14 observations by considering the statistical error of 0.003–0.01 mag for the photometric data. We note that most of the days showed monotonic rise or decay with amplitudes of ∼0.1 mag in a few hours. The all light curves and polarization degree and angle variations are shown in Imazawa et al. (2022). In 2021 July 31, a microvariability of the flux with a timescale of a few minutes with an amplitude 0.01–0.02 mag was found. Figure 1 shows the time variation of magnitude and R_C - J color obtained on July 31, 2021. As shown in the bottom panel of Fig 1, the color variability follows the bluer-when-brighter (BWB) trend (Clements & Carini 2001). In addition to other days in this work, the BWB trend was also seen in previous studies, which utilized long term (Wierzcholska et al. 2015) and the short term (Gaur et al. 2015) observations. The differences of the PD and PA between R_C and J band values was

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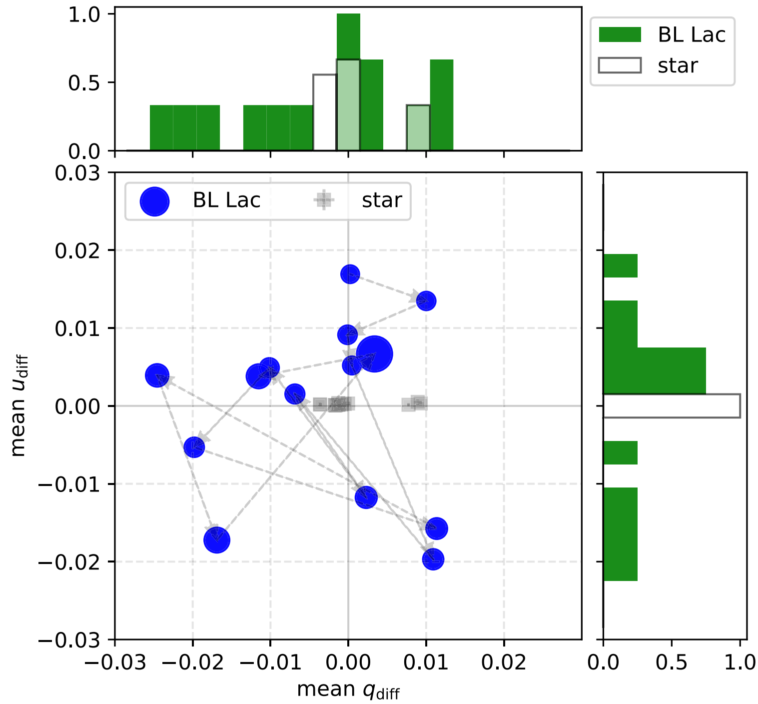

Figure 2. Scatter plot of differential q and u values between R_C and J (q_{diff} and u_{diff}) for each observation. Each data point shows the average value in each observation. Gray squares represent data of the comparison star and filled circles represent data of BL Lac. The circle size represents the flux value for each data point. Gray dashed arrows that connected each data point indicate time order. Normalized histograms on the horizontal and vertical axes represent projections along the q_{diff} and u_{diff} axis, respectively.

found. Nine nights showed higher PD in the optical band than the NIR band, while five nights showed higher PD in the NIR band than in the optical band.

4. Discussion

We found variations on timescale of the order of minutes. The timescale Δt can be estimated from the following equation:

$$\Delta t = \frac{1}{1+z}\frac{\Delta F}{dF/dt}, \tag{1}$$

where z is the redshift ($z = 0.069$, Miller & Hawley 1977) and ΔF is the peak of the flux from which the baseline component is subtracted ($\Delta F = 4.60 \times 10^{-12}$ erg cm^{-2} s^{-1}). As a result of timescale estimation using linear function fitting (details in Imazawa et al. (2022)), the rise and decay times are determined to be 340 ± 45 seconds and the decay time is 278 ± 37 seconds for 31 July 2021. We confirmed that the variability is significant because the variability parameter $C/\Gamma = 5.21$ after subtracting the baseline for this variability (Romero et al. 2002; Cellone et al. 2007). We assumed that the variability timescale is 5 minutes and the maximum size of the emission region R_{em} is estimated to be $R_{em} = (0.6 \pm 0.2) \times 10^{12}$ m.

We then discuss the Turbulent Extreme Multi-Zone (TEMZ) model, which explains the microvariability and wavelength dependence of the polarization (Marscher 2014; Marscher et al. 2017; Marscher & Jorstad 2021) by the separated multiple emission regions or 'cells' in the jet. In each cell, the energy spectrum of the electrons and the

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direction of the magnetic field are uniform. However, the energy spectrum of the electrons is different from cell to cell, and therefore the spectrum of emitted photons is also different from cell by cell. The polarized emissions from the cells cancel out with each other out due to the turbulent magnetic fields and the complicated nature of the Q and U components. Therefore, the PD from the cells is reduced depending on the number of cells. The spectral index α indicates a steep spectrum ($\alpha > 1$) and thus the number of high energy electrons should be small. Therefore, we can assume that most cells emit NIR photons while only a handful of cells emit optical photons. In this case, the PD in the NIR band should approach zero due to the large number of NIR-emitting cells, while the PD in the optical band should not be cancelled out as much due to the small number of optical-emitting cells. Remarkably, the difference in PA between the two bands can also be explained by this model (Marscher & Jorstad 2021). Therefore, the TEMZ model can better explain the high PD in the optical than in the NIR, but the reverse trend requires more complicated situations, such as the existence of accidentaty ordered magnetic field and bright cells in the NIR.

5. Summary

In this study we have performed simultaneous optical and NIR polarimetric observations for the for BL Lac during an outburst period between 2020 and 2021. The microvariability indicates the presence of compact emission regions and cannot be explained by the one-zone shock-in-jet model, but can be explained by the TEMZ model. We observed the wavelength differences of PD and PA. On several days the optical PD was higher than the NIR and vice versa. This behaviour cannot be explained by simple models, suggesting a more complicated situation such as a two-zone shock-in-jet model or an irregular TEMZ model.

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