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Multicolor photopolarimetric observation of 15-min variability in S5 0716+714

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We present the result of near-infrared and optical observations of the BL Lac object S5 0716+714 carried out by the KANATA telescope (Uemura et al. 2008 in these proceedings). S5 0716+714 has both a long term violent variability and a short-term variability. The shortest time-scale variability, so-called microvariability, provides a clue of the minimum size of the emitting region. Here, we report the detection of 15-min variability in S5 0716+714, which is one of the shortest time-scale in the optical and near-infrared variations observed in blazars. The detected microvariation had a small amplitude of 0.06±0.01 mag in V band and a blue color of $\Delta(V-J) = -0.03 \pm 0.01$. The microvariation has a feature of "bluer-when-brighter" that S5 0716+714 has in the variation time-scale of several hours. We furthermore obtained the temporal variation of polarization associated with the microvariation. We revealed that the microvariation had a specific polarization component whose polarization degree was higher than that of the overall trend. These results suggest that the microvariability originated from a small and local region where the magnetic field is aligned.

Workshop on Blazar Variability across the Electromagnetic Spectrum
April 22-25, 2008
Palaiseau, France

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PoS(BLAZARS2008)060

1. Introduction

Blazars exhibit variability on very short time-scales within one night, called intra-night variability or microvariability (e.g. [1]). A significant variability with a time-scale of minutes has recently been discovered in the gamma-ray region [2][3]. Such a short time-scale indicates that the size of the emitting region of the variation is smaller than the Schwarzschild radius R_{S} of the black hole in AGN if it has a typical black hole mass and a jet Doppler factor. In optical band, a 15-min microvariability has been observed [4] in Mrk 501. In their report, the amplitudes of the variation was about 0.05 mag in R band.

The spectral energy distribution (SED) of blazars can be described by synchrotron radiation and inverse-Compton scattering. In the optical band, the synchrotron radiation is dominant, hence, variations of polarization can be observed in blazars within one night (e.g. [5], [6]). In AO 0235+164, the polarizations were observed during the variations of a time-scale of hours [7]. According to their observation, the temporal variation of polarization parameters showed no correlation with the variation of the total flux.

S5 0716+714 is a BL Lac object in which microvariability is observed. The variability time-scale has been reported to be days and hours (e.g. [8]). Its optical emission is dominated by the synchrotron radiation, and shows featureless spectrum [9]. The redshift of S5 0716+714 is estimated to be $z = 0.31 \pm 0.08$ [10].

2. Observation

The observational material treated in this paper is mainly an intra-night time-series photopolarimetry of S5 0716+714 in V, J and K_{S} bands on 2007 Oct. 20 UT. This is a part of our ongoing optical and NIR monitoring of this blazar since 2007 Oct. For the observation, we used TRISPEC attached to the 1.5-m “KANATA” telescope in Higashi-Hiroshima Observatory. TRISPEC (Triple Range Imager and SPECtrograph) produces photopolarimetric data in one optical band and two NIR bands simultaneously [11].

The integration times in each exposure were 63, 55 and 28 sec for V-, J- and K_{S}-band images, respectively. Our one polarimetric data was derived from each set of the four exposures, while one photometric data was from each exposure. We adopted differential photometry with a comparison star taken in the same frame. Its position is R.A.=$07^{\mathrm{h}}21^{\mathrm{m}}52.3^{\mathrm{S}}$, Dec=$+71^{\circ}18'17.6''$, and the magnitudes are 12.48, 11.32 and 10.98 mag in V-, J-, and K_{S}-band, respectively [12][13].

For polarimetry, the instrumental polarization was found to be negligible ($< 0.1\%$) in V band from observation of unpolarized standard stars and we gave no correction for it.

3. Result

3.1 Photometric observation

When we observed the object, it was in a bright state in Oct. 2007. Figure 1 shows the light curves on that day when the object was the brightest in the period of our monitoring. The both V- and J-band flux gradually increased, and the object brightened by 0.12 ± 0.01 and 0.08 ± 0.01 mag during 3 hours in V and J bands, respectively. The $V - J$ color became bluer, associated with

PoS(BLAZARS2008)060

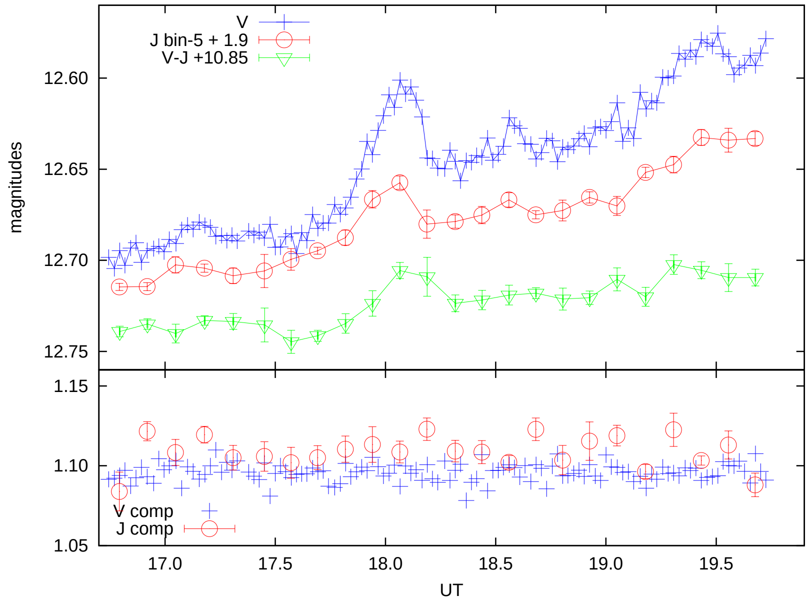

Figure 1: The top panel of the figure shows the light curves in V, J bands and $V-J$ color on 20 Oct. 2007. The time bin sizes are 63 and 280 sec in V and J bands, respectively. The bottom panel of the figure shows the differential magnitudes of the comparison star against the check star in V and J bands.

the overall brightening trend. The color at the end of the observation was 0.03±0.01 mag bluer than that at the start. In addition, there was a bump-like structure around 18.0 (UT). Both in V- and J-band light curves, its rising time was about 15-min, and its amplitudes is 0.06±0.01 and 0.03±0.01 mag, respectively. The K_S-band data has too large errors (∼0.1 mag) to be found a correlated bump. In this paper, we only treat the V- and J-band light curves. The time-scale $\Delta\tau$ is estimated as

$$\Delta\tau = \frac{1}{1+z}\frac{(\Delta F)}{dF/dt}, \tag{3.1}$$

where $1+z$ stands for a cosmological effect [14]. The time-scales of the bump were 970 and 620 sec at the rising and decaying time-scales in the observer frame. With $z = 0.31\pm0.08$, the rising and decaying time-scales in the object frame are calculated as 740±50 and 480±30 sec, respectively.

The changing of seeing and the unsuitable comparison star can cause a spurious variation [15][16]. In our current case, however, there is no correlation between the light curve and the temporal variation of the seeing size, and the difference of magnitude in the object and the comparison is < 1 mag in V band. Therefore, we conclude that the observed 15-min bump is a real one.

Also at the maximum of the 15-min bump, the object became blue, $\Delta(V-J) = -0.03\pm0.01$. Both the bump and the overall brightening trend exhibited a feature of "bluer-when-brighter" trend. In S5 0716+714, although the feature was observed in the internight variability which is in the time-scale of days, there was seldom seen the feature of bluer-when-brighter in a long term trend which the time-scale was tens of days [8][17]. In our detected microvariability (the 15-min bump), the feature of bluer-when-brighter was seen. It is indicated that microvariability of a time-scale of

PoS(BLAZARS2008)060

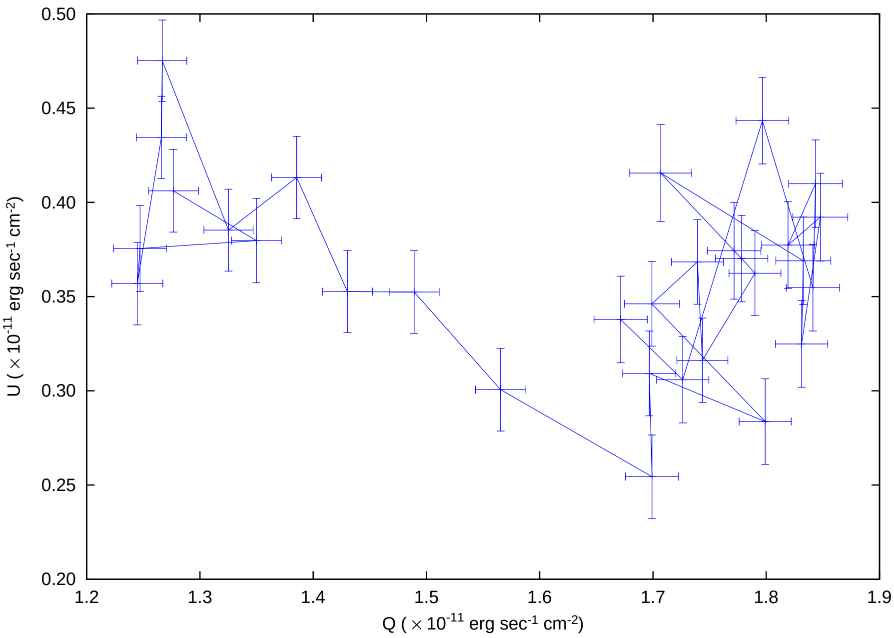

Figure 2: Stokes Q and U parameters in V band during observations on 20 Oct. 2007. The Stokes parameters have been rebinned to 252 sec. The unit of the Q and U is erg sec^{-1} cm^{-2}.

minutes has the same feature as the internight variability. Therefore it suggests that the mechanisms of the internight variability and the microvariability are same, while the long term variation has a different one.

3.2 Polarimetric observation

As can be seen in figure 2, the polarization parameters were varied during three hours. The temporal evolution of the Stokes parameters indicates the presence of a variation feature on the $Q-U$ plane associated with the bump. We calculated differential polarization vectors from the overall trend. We assumed that the polarization parameters had two components; the first component was $P_{\rm base}(t)$ associated with the overall brightening trend and the second one was $P_{\rm diff}(t)$ which is a deviation from $P_{\rm base}(t)$. They are written as,

$$P_{\rm obs}(t) = P_{\rm base}(t) + P_{\rm diff}(t) \tag{3.2}$$

$$P_{\rm base}(t) = (Q_{\rm base}(t), U_{\rm base}(t)). \tag{3.3}$$

In our analysis, $Q_{\rm base}(t)$ and $U_{\rm base}(t)$ are approximated as a linear function for simplicity, which is obtained by fitting the data ($t < 17.68$ and $18.27 < t$ in UT) excluded the bump as shown in figure 3. If the bump component has no specific polarization vector, the $P_{\rm diff}(t)$ should mainly be constructed by a random noise.

In figure 4, however, the polarized flux, $PF_{\rm diff}(t) = |P_{\rm diff}(t)|$, is correlated with the bump. The polarization angle, $PA_{\rm diff}(t) = arctan(P_{\rm diff}(t))$, is constant during the bump. Thus the bump had the intrinsic polarization vector whose polarization angle was constant. This result is insensitive to the data period used for the definition of the overall trend.

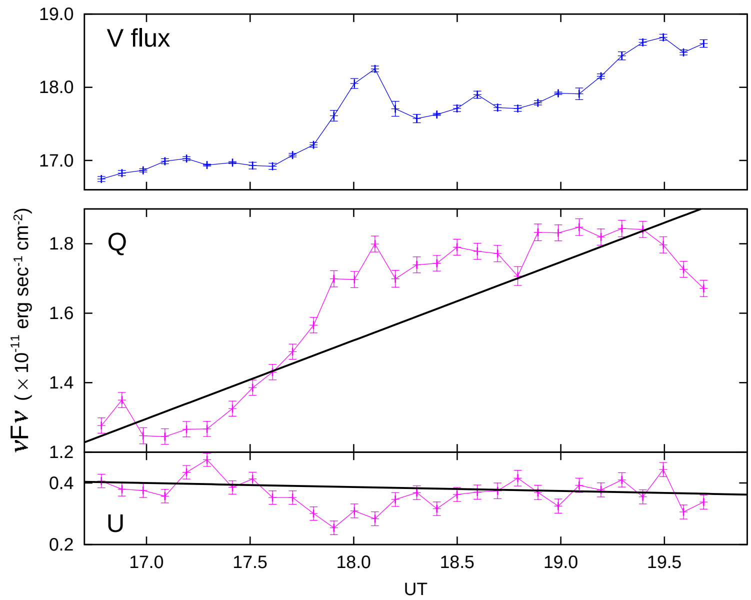

Figure 3: The top figure shows the flux light curve in V band. The middle and bottom figures show the Q and U curves in V band. Solid lines indicate the $P_{\rm base}(t)$, which is defined in the text. All units are erg sec^{-1} cm^{-2}.

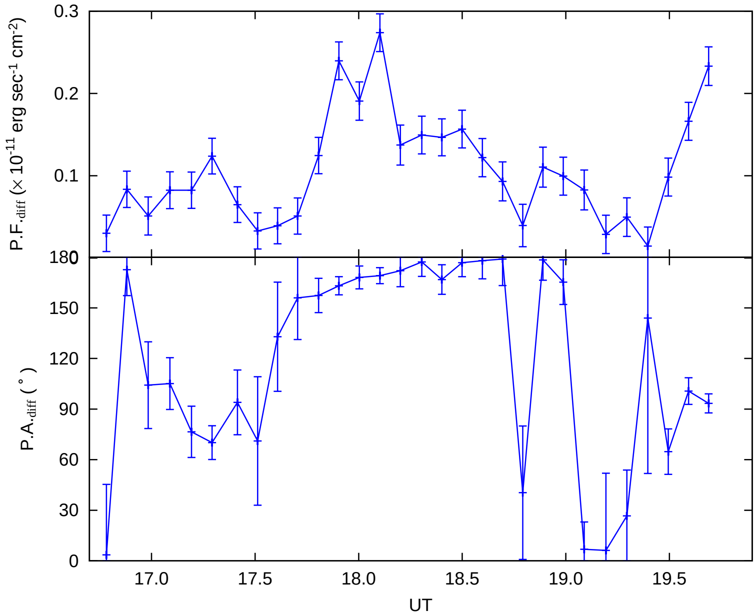

Figure 4: Time variation of the differential polarization vector from the overall brightening trend. The top figure shows the differential polarized flux $PF_{\rm diff}(t)$. At around 18 UT, there is a peak which is associated with the bump. The bottom figure shows the differential polarization angle (degree) $PA_{\rm diff}(t)$.

4. Discussion

The time-scale of the bump in the object frame were 740 and 480 sec because of the redshift $z = 0.31 \pm 0.08$. The size of the emitting region, R, can be estimated as a light-crossing time with the correction of the Doppler boosting, $R < \delta c \Delta\tau$ where c is light velocity.

We assume that the bump was caused from the whole optical emitting area in the jet at a certain distance apart from the black hole. We can expect that the emitting region is larger than R_S, except for a scenario with an extreme re-confinement of the jet [18]. If the object has the typical values of the Doppler factor $\delta \approx 10$ and the black hole mass $M = 10^9 M\odot$, we can estimate R_S. The calculated R_S is, however, larger than the size of the emitting region estimated from the light-crossing time of the bump; $R < (0.49 \pm 0.03) \cdot R_S$. In order to satisfy $R > R_S$, M should be

$$\frac{M}{\delta} < \frac{c^3 \Delta\tau}{2G}, \tag{4.1}$$

where G is the gravitational constant. The shortest variability time-scale 480 sec we observed is substituted to the equation (4.1), as a result, $\delta > (20 \pm 1) \times (M/10^9 M_\odot)$. The bump could, thus, originate from the whole area of the jet if S5 0716+714 has a relatively small black hole mass or a large Doppler factor. On the other hand, the optical emitting region in blazars is generally believed to be not so confined in R_S, but extended in sub-pc scale jets. If the emitting region is located at the sub-pc scale from the black hole, the black hole mass (or Doppler factor) would be extraordinary small (or large), in order to explain the bump by the variation of the whole emitting region.

An alternative idea is that the emission region of the microvariability should be a small and local area in the whole area of the jet.

The maximum value of the differential polarized flux is about $(2.7 \pm 0.5) \times 10^{-12}$ erg sec^{-1} cm^{-2}. Using the total flux at the bump peak, $I_{\rm bump} = (1.02 \pm 0.02) \times 10^{-11}$ erg sec^{-1} cm^{-2}, the polarization degree of the bump component $PD_{\rm bump}$ is calculated as,

$$PD_{\rm bump} = \frac{PF_{\rm diff}(t)_{\rm bump}}{I_{\rm bump}}. \tag{4.2}$$

Thus, the $PD_{\rm bump}$ is $27 \pm 5\%$. On the other hand, the polarization degree of the total flux at the bump peak is $9.8 \pm 0.5\%$. Hence, the differential polarization degree of the bump is much larger than that of the emission component of the overall brightening trend. The bump presumably originated from the local region where the magnetic field is more aligned than that in the emitting region of the overall brightening trend. On the basis of both variability time-scale and the polarization behavior, we suggest that the bump originated not from the whole optical emitting region of the jet, but from the local region where the magnetic field is aligned.

5. Conclusion

We discovered the 15-min microvariability in S5 0716+714. We performed multicolor photopolarimetric observations for the first time for such a short time-scale variation in blazars. Our findings are summarized as below; first, the object became blue during the bump. Second, the bump component has a specific polarization vector, which is distinct from the overall brightening trend.

PoS(BLAZARS2008)060

Our observations indicate that the microvariability is emitted from a small and local region in the whole emitting area in the jet. The emitting region of the blazar has still been argued. Multiband and polarimetric observations are the powerful tools to constrain the emitting region.

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