Prominent polarized flares of the blazars
AO 0235+164 and PKS 1510–089

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Abstract. We report on multi-band photopolarimetric observations of the blazars AO 0235+164 and PKS 1510–089. These two blazars became in active states in 2008 and 2009, respectively. In these active states, prominent short-term flares were detected in both objects, having amplitudes of $>1$ mag within 10 days. The $V - J$ color became bluer when the objects were brighter in these flares. On the other hand, the color of PKS 1510–089 exhibited a trend that it became redder when it was brighter, except for its prominent flare. This feature can be explained by the strong contribution of thermal emission from an accretion disk. The degree of polarization increased at the flares, and reached $>25\%$ at the maxima in AO 0235+164 and PKS 1510–089. We compare these flares with other short-term flares which were detected by our monitoring of 44 blazars. Those two flares had one of the largest variation amplitudes in both flux and degree of polarization. Furthermore, we found a significant positive correlation between the amplitudes of the flux and degree of polarization in the flares. It indicates that the short-term flares originate from the region where the magnetic field is aligned.

1. Introduction

There are two components in the emission from blazars [3]. The low energy component from radio to optical or X-ray bands is attributed to synchrotron radiation emitted by relativistic electrons in jets. The high energy component is likely to be inverse-Compton scattering radiation. The synchrotron emission from blazars is occasionally highly polarized in the optical band [2]. Since the polarization gives us a way to probe magnetic field of a nonthermal radiation source, observations of temporal variations of the polarization are important for study of the structure of a blazar jet. However, the temporal behavior of the polarization is known to be complex. The polarization varies in an erratic manner in most blazars (e.g. [2]). On the other hand, systematic variations have also been reported in several blazars, for example, rotations of the polarization (e.g. [11]; [19]).

It has been suggested that the erratic behavior of polarization is due to the composition of several polarization components [10]. From the data of OJ 287 from 2005 to 2009, Villforth, et al. have reported that its observed polarization behavior could be explained by separating the jet emission into two components: an optical polarization core and chaotic jet emission [25]. Uemura, et al. have separated a long-term trend from observed temporal variations of polarization in blazars using a Bayesian approach [24].

AO 0235+164 is one of the most famous blazars, showing violent variability whose amplitude is larger than 1 mag (e.g. [16]). The object showed large amplitude outbursts in past.
outbursts repeated quasi-regularly with a periodicity of \(~5.7\) years [12]. The object shows high polarization in the optical band, and the polarization parameters vary violently. The highest degree of polarization (PD) has been reported to be 43.9% [7].

PKS 1510–089 is a radio-loud and highly polarized quasar. The object emits radiation from the radio to gamma-ray bands (e.g. [8]; [1]). The spectral energy distribution of the object has a bump structure over a synchrotron component in the ultraviolet (UV) band ([20]; [8]). The UV bump is thought to be thermal emission from an accretion disk. Polarization parameters of the object have also been varied. Marscher, et al. reported that the polarization rotated consecutively for \(50\pm10\) days [9].

In the above two blazars, we detected prominent short-term flares with a timescale of \(~10\) days, and found that they were associated with violent variations in polarization. We report their light curves, color and polarization variations, and discuss the characteristics in polarization variations of such short-term flares.

2. Observations

We performed monitoring of AO 0235+164 and PKS 1510–089 in the 2008–2009 seasons using TRISPEC attached to the Kanata 1.5-m telescope at Higashi-Hiroshima Observatory in Japan. TRISPEC has a CCD and two InSb arrays, which enable photopolarimetric observations in an optical and two NIR bands, simultaneously [26]. Unfortunately, the TRISPEC has a CCD and two InSb arrays, which enable photopolarimetric observations in an optical and two NIR bands, simultaneously [26]. Unfortunately, the TRISPEC was out of action. Thus, we obtained only \(V\) optical and two NIR bands, simultaneously [26].

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The integration time for an exposure depends on the sky condition and the brightness of the objects. Typical integration times were 120 and 108 sec in AO 0235+164, and 150 and 135 sec in PKS 1510–089 in the \(V\) and \(J\) bands, respectively.

All images were bias-subtracted and flat-fielded, and we performed an aperture photometry with a Java-based package. We performed a differential photometry with comparison stars taken in the same frames of AO 0235+164 and PKS 1510–089. The positions of the comparison stars are R.A.=02h38m32s.31, Dec.=-16°35′59″.7 and R.A.=15h12m53s.19, Dec.=-09°03′43″.6 (J2000.0), respectively. Their magnitudes are \(V=12.720, 13.282\) and \(J=11.221, 12.205\), respectively ([5]; [21]). The constancy of the comparison stars was checked by another set of polarization parameters was derived from each set of the four exposures.

We confirmed that the instrumental polarization was smaller than 0.1% in the \(V\) band using observations of unpolarized standard stars. We, thus, applied no correction for it. The zero point of the angle of polarization (PA) is corrected for in the equatorial coordinate system (measured from north to east) by observing the polarized stars, HD 19820 and HD 25443 [27].

3. Results

3.1. AO 0235+164

We had performed the photopolarimetric monitoring of AO 0235+164 from Aug. 12, 2008 to Feb. 18, 2009. Figure 1 shows the light curve of the object in the \(V\) band, \(V-J\) color variation, and temporal variations of the polarization parameters in the \(V\) band. We also show relative magnitude, C1-C2, between the comparison and the check stars. In the top panel of figure 1, the object showed the violent variability. The object had been active for 153 days from JD 2454696, in which it was brighter than \(V=18.0\). The peak flux of the object was \(V=15.067\pm0.004\) (JD 2454733). The faintest state of the object has been reported at \(V\sim20\) for 32 years from
Figure 1. Light curve of AO 0235+164 in the $V$ band, color variations of $V - J$, temporal variations of the PD and PA, % and degree. We also show the relative magnitude, C1-C2, between the comparison star (C1) and the check star (C2).

1975 to 2007 ([12]; [13]; [14]; [15]). Thus, the amplitude of the flux was about 5 mag from the faintest state. The light curve shows several short-term flares during the active state. We can see five flares labelled in figure 1 as “A” (from JD 2454720 to 2454742), “B” (from JD 2454747 to 2454758), “C” (from JD 2454785 to 2454801), “D” (from JD 2454803 to 2454815) and “E” (from JD 2454820 to 2454840).

The $V - J$ color was variable in our monitoring period, $\Delta (V - J) \sim 0.5$. In flares “A” and “B”, the color became bluer. Hence, the object showed a bluer-when-brighter trend in these bright flares. The color also became bluer in JD 2454696, at the onset of the active state when the object was brightened rapidly. On the other hand, no clear bluer-when-brighter trend was associated with flares “C”, “D” and “E”. In the faintest state in JD 2454879, the object was the reddest.

The PD showed variable, and distributed from 0 % to ~30 %. In JD 2454755, the PD was the highest, 34±2 %. The PD was well correlated with the flux in flares “A” and “B”. The peaks of the PD in flares “A” and “B” were higher than 25 %. However, the PD were not high during flares “C”, “D” and “E”, less than 16 %.

3.2. PKS 1510−089
We had also performed the photopolarimetric monitoring of PKS 1510−089 from Jan. 12 to Jul. 22 in 2009. Figure 2 shows the light curve of PKS 1510−089 in the $V$ band, $V - J$ color variation, and temporal variations of the polarization parameters in the $V$ band. The object has been brightened since JD 2454900, and a peak of the flux was once recorded in JD 2454928. After that, a prominent flare occurred around JD 2454960. We labelled this flare as “F” (from JD 2454954 to 2454966). In this flare, the peak of the flux reached about $V=13.6$ mag in
Figure 2. Light curve of PKS 1510–089 in the V band, color variations of V – J, temporal variations of the PD and PA, % and degree. The top panel shows the enlarged light curve and PD around flare “F”. We also show the relative magnitude, C3-C4, between the comparison star (C3) and the check star (C4).

JD 2454961, and the amplitude of the magnitude between the peak and the bottom of the flare in JD 2454954 was Δ V=2.5 mag. After the flare peak, the flux was fallen down to V=16.2 mag in JD 2454966. Thus, the flux varied by 10 times within 10 days. The flux again rose after this flare, and the flux reached another peak at about V=15.7 mag in JD 2454966.

The V – J color was about 2.1 in a faint state in JD 2454900. When the object became brighter, the V – J color got redder to 2.5. This “redder-when-brighter” trend was saturated at about V–J=2.5. On the other hand, the color during the flare “F” showed a bluer-when-brighter trend. The V – J color reached 1.9 in this flare.

Polarization parameters also varied in the whole observing period. The PA was distributed from 0 to 180°. The PD varied less than 10 % in a faint state from JD 2454844 to 2454911. The PD increased with the flux from JD 2454920, and reached 15 % at the maximum of a small flare in JD 2454928. In the rising phase of the flare “F”, the PD rapidly increased, and reached its peak about 36 % in JD 2454960, in which the flux was still in a rising phase (see the top panel of figure 2). Thus, the peak of the PD was 1 day earlier than that of the flux. In the decay
phase of the flux, the PD had already been low, about 13% in JD 2454962. After the flare, the PD did not vary more than 10%.

4. Discussion

We reported that there were positive correlations between the flux and PD in both AO 0235+164 and PKS 1510–089. Such correlations between the flux and PD have been reported in other blazars in past studies (e.g. [22]; [23]; [18]), although the polarization behaviors have generally been reported to be erratic (e.g. [2]). We propose that short-term flares on a timescale of 10 days in blazars are associated with increases in PD, with changes of the PA of each flare. If a small flare occurs, this flare is buried by other radiation component, for example the long-term component as mentioned above, and then, the PD is hardly changed. However, a large amplitude flare may not be buried like flares “A”, “B” and “F”. In this situation, the observed PD should increase during the large flare. In fact, the observed PD during the large flares “A”, “B” and “F” have been changed dramatically.

We investigated the correlation between amplitudes of the flux and PD during flares. We used the photopolarimetric data of 44 blazars which we obtained from 2008 to 2010 [6]. In this paper, we defined the flares and their amplitudes of the flux and PD as described below. First, we defined the peak of a flare as the observation point with the highest flux within ±10 days. Second, we can calculated the peak-to-valley amplitudes of the flux and PD in this 20 days period. Practically, the amplitude of the flux was calculated as $\Delta M = -(M_{\text{bri}} - M_{\text{fai}})$, where $M_{\text{bri}}$ and $M_{\text{fai}}$ are the brightest and faintest values of the $V$-band magnitude for the 20 days period. Similarly, the amplitude of PD is defined as $\Delta P = P_{\text{max}} - P_{\text{min}}$, where $P_{\text{max}}$ and $P_{\text{min}}$ are the maximum and minimum values of the PD for the 20 days period.

Figure 3 shows correlation between the amplitudes of the flux and PD of short-term flares selected with the above definition in the $V$ band. There is a positive correlation, and the correlation coefficient is $0.66^{+0.08}_{-0.10}$. The filled circle, triangle and square represent flares “A”, “B” and “F” of AO 0235+164 and PKS 1510–089, respectively. Those flares are one of the
largest flux- and polarization-amplitude flares in our sample (figure 3). On the other hand, the correlation is weak in small flares; there are flares having a relatively large amplitude of flux, but a small amplitude of the PD, and vice versa. This is naturally expected since polarization variations of small flares are readily buried by another variation component in our picture.

Sasada, et al., reported that a microvariation of S5 0716+714 had a specific polarization component, and suggested that the microvariation originated from a small and local region where the magnetic field was aligned [17]. Our result indicates that the short-term flares on timescales of 10 days also originate from regions where the magnetic field is aligned.

5. Conclusion
We performed photometric and polarimetric monitoring of the blazars AO 0235+164 and PKS 1510–089, and observed their flares. The large flares “A”, “B” and “F” exhibited the bluer-when-brighter trends. The $V-J$ color variation of PKS 1510–089 showed the redder-when-brighter trend, except for the period of flare “F”. There were positive correlations between the flux and PD in both objects. We studied the correlation between the amplitudes of the flux and PD of short flares in 44 blazars. We found that there was a significant positive correlation between them. We propose that the short-term flares on timescales of 10 days originate from a region where the magnetic field is aligned. Observed polarization variations are occasionally erratic probably because polarization variations of small flares are readily buried by another variations having different PAs and/or timescales.

References
[1] Abdo, A. A., et al. 2010b, ApJ, 721, 1425
[2] Angel, J. R. P. & Stockman, H. S. 1980, A&A, 18, 321
[3] Fossati, G., Maraschi, L., Celloti, A., Comastri, A. & Ghisellini, G. 1998, MNRAS, 299, 433
[4] Fukugita, M., Shimassaku, K. & Ichikawa, T. 1995, PASP, 107, 945
[5] González – Pérez, J. N., Kidger, M. R. & Martín – Luis, F. 2001, AJ, 122, 2055
[6] Ikejiri, Y., et al. 2011, astro-ph/1105.0255
[7] Impey, C. D., Brand, P. W. J. L. & Tapia, S. 1982, MNRAS, 198, 1
[8] Kataoka, J., et al. 2008, ApJ, 672, 787
[9] Marscher, A. P., et al. 2010, ApJ, 710, L126
[10] Moore, R. L., Angel, J. R. P., Duerr, R., Lebofsky, M. J., Wisniewski, W. Z., Rieke, G. H., Axon, D. J., Bailey, J., Hough, J. M. & McGraw, J. T. 1982, ApJ, 260, 415
[11] Qian, S. J., Quirrenbach, A., Wittel, A., Krichbaum, T. P., Hummel, C. A. & Zensus, J. A. 1991, A&A, 241, 15
[12] Raiteri, C. M., et al. 2001, A&A, 377, 396
[13] Raiteri, C. M., et al. 2005, A&A, 438, 39
[14] Raiteri, C. M., et al. 2006, A&A, 459, 731
[15] Raiteri, C. M., et al. 2008, A&A, 480, 339
[16] Rieke, G. H., Grasdalen, G. L., Kimman, T. D., Hintzen, P., Wills, B. J. & Wills, D. 1976, Nature, 260, 754
[17] Sasada, et al. 2008, PASJ, 60, L37
[18] Sasada, M., et al. 2010, PASJ, 62, 645
[19] Sillanpää, A., Takalo, L. O., Nilsson, K. & Kikuchi, S. 1993, Ap&SS, 206, 55
[20] Singh, K. P., Shrader, C. R. & George, I. M. 1997, ApJ, 491, 515
[21] Skrutskie, M. F., et al. 2006, AJ, 131, 1163
[22] Smith, P. S., Balonek, T. J., Heckert, P. A. & Elston, R. 1986, ApJ, 305, 484
[23] Tosti, G., et al. 1998, A&A, 339, 41
[24] Uemura, M., et al. 2010, PASJ, 62, 69
[25] Villforth, C., et al. 2010, MNRAS, 402, 208
[26] Watanabe, M., et al. 2005, PASP, 117, 870
[27] Wolff, M. J., Nordsieck, K. H. & Nook, M. A. 1996, AJ, 111, 856