MINUTE-SCALE RAPID VARIABILITY OF THE OPTICAL POLARIZATION IN THE NARROW-LINE SEYFERT 1 GALAXY PMN J0948+0022

RYOSUKE ITOH1, YASUYUKI T. TANAKA1, YASUSHI FUKAZAWA1, KOJI S. KAWABATA2, KENJI KAWAGUCHI1, YUKI MORITANI2, KATSUTOSHI TAKAKI1, ISSEI UEINO1, MAKOTO UEMURA2, HIROSHI AKITA2, MICHITOSHI YOSHIDA2, TAKASHI OHSUGI2, HIDEKAZU HANAYAMA3, TAKESHI MIYAI1, AND NOBUYUKI KAWAR4

1 Department of Physical Sciences, Hiroshima University, Higashi-Hiroshima, Hiroshima, Hiroshima 739-8526, Japan; itoh@hep01.hepl.hiroshima-u.ac.jp
2 Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
3 Ishigakijima Astronomical Observatory, National Astronomical Observatory of Japan, 1024-1 Arakawa, Ishigaki, Okinawa 907-0024, Japan
4 Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

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ABSTRACT

We report on optical photopolarimetric results of the radio-loud narrow-line Seyfert 1 (RL-NLSy1) galaxy PMN J0948+0022 on 2012 December to 2013 February triggered by flux enhancements in the near infrared and γ-ray bands. With the one-shot polarimetry of the Hiroshima One-shot Wide field Polarimeter installed on the Kanata Telescope, we detected very rapid variability in the polarized-flux (PF) light curve on MJD 56281 (2012 December 20). The rise and decay times were about 140 s and 180 s, respectively. The polarization degree (PD) reached 36% ± 3% at the peak of the short-duration pulse, while the polarization angle remained almost constant. In addition, temporal profiles of the total flux and PD showed highly variable but well correlated behavior and discrete correlation function analysis revealed that no significant time lag of more than 10 minutes was present. The high PD and minute-scale variability in PF provides clear evidence of synchrotron radiation from a very compact emission region of ~10^{14} cm size with a highly ordered magnetic field. Such micro-variability of polarization is also observed in several blazar jets, but its complex relation between total flux and PD is explained by a multi-zone model in several blazars. The implied single emission region in PMN J0948+0022 might reflect a difference of jets between RL-NLSy1s and blazars.

Key words: galaxies: active – galaxies: individual (PMN J0948+0022) – galaxies: jets – galaxies: Seyfert

Online-only material: color figures

1. INTRODUCTION

Narrow-line Seyfert 1 (NLSy1) galaxies are a class of active galactic nuclei (AGNs). It is widely recognized that NLSy1s possess a relatively light central black hole (BH) of ~10^6–10^9 M⊙ accreting at a very high rate near the Eddington limit (e.g., Yuan et al. 2008). Hence, an NLSy1 is considered to be a young AGN growing toward a super massive BH which is believed to have a mass of 10^9–10^10 M⊙. Thus, studying a class of NLSy1s provides us with knowledge about BH evolution. NLSy1s are usually radio-quiet and only 7% of NLSy1s are radio-loud (RL) objects (Zhou et al. 2003; Komossa et al. 2006). Owing to the high sensitivity of the Fermi Large Area Telescope instrument, γ-ray emission from some of these RL-NLSy1s are detected and the presence of a third class of AGNs with relativistic jets are confirmed from multi-wavelength observation (Abdo et al. 2009) following blazars and radio galaxies. These discoveries led to interesting questions on the unified model of AGNs, such as the development of the relativistic jet. Combined with the fact that their broadband spectra are quite similar to those of blazars, it is thought that at least these NLSy1s have powerful relativistic jets and that they are directed toward us. Finding evidence of blazar-like behavior in an RL-NLSy1 would help us to understand the evolution of relativistic jets.

Polarized radiation is evidence of the synchrotron origin of jet emissions. Therefore, optical polarimetric observations provide a strong tool to probe jet structures (e.g., Marscher et al. 2008; Abdo et al. 2010a). The radiation in the optical band is thought to be a superposition of synchrotron and disk emission from its spectral shape of the Fermi-detected NLSy1s which has enough multi-wavelength data. However, a timescale of micro-variability with photopolarimetric observation in an RL-NLSy1 has not yet been studied. It can provide an important and interesting tool to probe of the size and structure of the emission region in the jet and for distinguishing different models responsible for the variability. Several important and interesting results of micro-variability for blazars are reported (e.g., Miller & Noble 1996; Fossati et al. 2008).

PMN J0948+0022 (also known as 2FGL J0948.8+0020, R.A. = 09^h48^m32^s21, decl. = +00°22′25″55, J2000, z = 0.5846; Nolan et al. 2012; Beasley et al. 2002) is classified as an RL-NLSy1 and displays variable emission from radio to γ-ray bands, suggesting the presence of the relativistic jet (Zhou et al. 2003; Abdo et al. 2009). The optical polarization variability with a monthly timescale was detected in previous observations (Eggen et al. 2013). Additionally, a high polarization degree (PD) of 18.8% was also reported in 2009 April (Ikejiri et al. 2011). Micro-variability (timescale within a few hours) of the optical flux was also observed in PMN J0948+0022 in 2011 (Liu et al. 2012), and this result supports the fact that the object carries the relativistic jet with a small viewing angle. Hence, PMN J0948+0022 is a good target to study the difference of the relativistic jet between blazars and RL-NLSy1s.

Recently, PMN J0948+0022 showed an extreme activity in the near-infrared and GeV γ-ray bands in 2012 December (Carrasco et al. 2012; D’Ammando & Orienti 2013). In this Letter, we present results of high-temporal-density optical monitoring observations of PMN J0948+0022 just after the 2012 December 18 (MJD 56279) near-infrared flare.
2. OBSERVATION

We performed the $g'$-, $V$-, and $R_C$-band photometric observations of PMN J0948+0022 from 2012 December 20 to 2013 February 20, using the Hiroshima One-shot Wide field Polarimeter (HOWPol) installed on the 1.5 m Kanata Telescope located at the Higashi-Hiroshima Observatory, Japan (Kawabata et al. 2008) and the Multicolor Imaging Telescopes for Survey and Monstrous Explosions (MITSuME) installed on the 1.05 m Murikabushi Telescope located on Ishigaki island, Japan. Reductions of optical data were performed under the standard procedure of CCD photometry. We performed the aperture photometry using APHOT packaged in PYRAF, and the differential photometry with a comparison star taken in the same frame of PMN J0948+0022. The position of the comparison star is R.A. = $09^h49^m00^s.4$, decl. = +00° 22′ 35″.1 (J2000) and its magnitudes are $g'$ = 18.288 mag, $V$ = 17.429 mag, and $R_C$ = 16.849 mag (Adelman-McCarthy et al. 2007). We confirmed a systematical flux difference of the comparison star between the two instruments and standard deviations of flux are ~0.02 mag in the $V$ band and ~0.02 mag in the $R_C$ band. These values were added to the photometric errors of PMN J0948+0022 in each observation. We corrected the data for the Galactic extinction of $A_V = 0.305$ mag, $A_V = 0.253$ mag, and $A_{R_C} = 0.206$ mag (NED database; Schlafly & Finkbeiner 2011).

We also performed temporally high-density photopolarimetric observations of PMN J0948+0022 with HOWPol on six nights. In order to study a relation between the optical flux and the micro-variability, we performed high-density photopolarimetric observations in several flux levels. The double-Wollaston prism installed on HOWPol allowed us to obtain both the Stokes $Q$ and $U$ parameters in only a single exposure. Therefore, short-interval (100–310 s) photopolarimetric observations were available. A detailed photopolarimetric observation log is given in Table 1. The bad quality frames (cloudy sky, suffering from cosmic ray, and so on) are excluded from our analysis. Polarimetry with HOWPol suffers from large instrumental polarization ($\Delta PD \sim 4\%$) caused by the reflection of the incident light on the tertiary mirror of the telescope. The instrumental polarization was modeled as a function of the declination of the object and the hour angle at the observation, and we subtracted it from the observed value. The polarization angle (PA) is defined in the standard manner as measured from north to east. The PA was calibrated with two polarized stars, HD 183143 and HD 204827 (Schulz & Lenzen 1983). Because the PA has an ambiguity of $\pm 180^\circ \times n$ (where $n$ is an integer), we selected $n$ which gives the least angle difference from the previous data, assuming that the PA would change smoothly. We confirmed that the error of PD in the instrumental polarization correction is smaller than 0.5% and the error of PA is smaller than $2^\circ$ from observations of unpolarized and polarized stars. The typical standard deviations of the Stokes parameters of the comparison star during the observation were $\Delta Q \sim 0.02$ and $\Delta U \sim 0.02$, which corresponds to $\Delta PD \sim 3\%$. These values were added to the polarimetric errors of PMN J0948+0022 in each observation.

3. RESULTS

Figure 1 shows a long-term history of the $R_C$-band flux and spectral index from 2012 December 20 (MJD 56281) to 2013 February 20 (MJD 56356). A local two-point spectral index $\alpha$ is defined between two brightness measurements $F_1$ and $F_2$ at frequencies $\nu_1$ and $\nu_2$, respectively, as $\alpha = \ln(F_1/F_2)/\ln(\nu_1/\nu_2)$. We use the mean wavelengths of the filters, 658.8 nm for the $R_C$ band, 550.5 nm for the $V$ band, and 485.8 nm for the $g'$ band. A detailed photopolarimetric observation log is given in Table 1.

Table 1: Log of High-density Photopolarimetric Observations Using HOWPol

| MJD   | Start and End Time (UT) | Interval | $N_{\text{obs}}$ |
|-------|-------------------------|----------|-----------------|
| 56281 | 18.04–20.94             | 160 s    | 51              |
| 56283 | 17.17–20.69             | 220 s    | 26              |
| 56284 | 17.76–20.18             | 260 s    | 22              |
| 56295 | 16.59–18.86             | 310 s    | 14              |
| 56342 | 17.74–19.21             | 100 s    | 16              |
| 56343 | 13.11–15.88             | 160 s    | 18              |

Note. $^a$ CCD read out time (10 s) is included.

Figure 1. Long-term history of the optical flux and spectral index taken by HOWPol and MITSuME. The upper panel shows a light curve in the $R_C$ band. The lower panel shows a history of spectral index. The dashed lines indicate the dates when high-density photopolarimetric observations were performed.

\textsuperscript{5} PYRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA (http://www.stsci.edu/institute/software_hardware/pyraf).

\textsuperscript{6} http://ned.ipac.caltech.edu/
Figure 2. Intra-night light curve of PMN J0948+0022 from MJD 56281 to 56284. From top to bottom, the histories of the total flux in the \(R_C\) band, the polarization degree (PD), and the polarization angle (PA) are shown.

(A color version of this figure is available in the online journal.)

Figure 3. Intra-night light curve of PMN J0948+0022 from MJD 56295 to 56343. The figure is laid out in the same way as in Figure 2.

(A color version of this figure is available in the online journal.)

\(g'\) band. We calculate the spectral index with the \(R_C\)- and the \(V\)-band data except the data on MJD 56282, on which the spectral index is calculated with the \(R_C\)- and the \(g'\)-band data. The error bars include both statistical and systematic errors. Large variation has been detected in the \(R_C\)-band flux and the amplitude of the total flux reaches a factor of four. On the other hand, the variation of the spectral index is relatively small and there is no clear correlation between the optical flux and the spectral index.

Figures 2 and 3 show results of temporally high-density monitoring of PMN J0948+0022 and Figure 4 shows an enlarged view of temporal variation of the polarized flux (PF) and PA on MJD 56281. Light curves of \(R_C\)-band polarized flux are calculated by \(PF = F_{R_C} \times PD/100\), where PD and \(F_{R_C}\) are...
The discrete correlation function (DCF; Edelson & Krolik 1988) variation pattern of PD is quite similar to that of the total flux. The object brightened by a factor of two in the total flux and by a factor of six in the PF around 19.6 UT within a few hours. The variation pattern of PD is quite similar to that of the total flux. The discrete correlation function (DCF; Edelson & Krolik 1988) shows a good correlation (DCF value of 0.92) with no significant time lag; an upper limit of lag is 0.5 minutes. A rapid and violent outburst of the PF around 19.6 UT (Abdo et al. 2010b): The light curve on MJD 56281 has some structures. It seems that there are two flaring components that have different variability timescales. We tried a light curve fitting with the following function to reproduce the time profile of outburst around 19.6 UT (Abdo et al. 2010b):

\[ PF(t) = PF_C + PF_{\text{long}} \left( e^{\frac{t - T_{\text{long}}}{\tau_{\text{long}}}} + e^{\frac{t - T_{\text{long}}}{\tau_{\text{long}}}} \right)^{-1} + PF_{\text{short}} \left( e^{\frac{t - T_{\text{short}}}{\tau_{\text{short}}}} + e^{\frac{t - T_{\text{short}}}{\tau_{\text{short}}}} \right)^{-1}, \]  

where \( PF_C \) represents an assumed constant level underlying the outburst, \( PF_{\text{long}} \) and \( PF_{\text{short}} \) measure the amplitude of the flares, \( T_{\text{long}} \) and \( T_{\text{short}} \) describe the approximate time of the peak, \( \tau_{\text{long}} \) and \( \tau_{\text{short}} \) measure the rise time, and \( T_{d\text{long}} \) and \( T_{d\text{short}} \) measure the decay time. The suffixes indicate the long-term and the short-term components. We obtained \( T_{\text{long}} = 16 \pm 3 \) minutes and \( T_{d\text{long}} = 39 \pm 4 \) minutes for the long-term component and \( T_{\text{short}} = 2.4 \pm 1.5 \) minutes and \( T_{d\text{short}} = 3.0 \pm 1.6 \) minutes for the short-term component. The characteristic flare duration can be estimated as \( T_r + T_d \). The variability timescale is significantly different between the two flares. In contrast, PA maintains its value during the outburst around 19.6 UT with an average value of \( 15^\circ \pm 1^\circ \). We also obtained the upper limit of \( PF_C < 0.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \).

Except for MJD 56281, there is no significant micro-variability of the total flux and PD while the daily light curve indicates significant variability from MJD 56283 to 56284. Data on MJD 56283, 56284, and 56295 show a low PD value of \( \sim 5^\circ \). It seems that there is micro-variability of PAs during these periods, but it could be due to low statistics. In MJD 56342 and 56343, a relatively increased total flux was observed with no significant micro-variability. During these periods, the total flux is constant but higher than that of MJD 56281. There is also no significant micro-variability of PAs on MJD 56342 and 56343, but a gradual increase of PA is implied. PD is also higher than that on MJD 56283 and 56284. The average of PAs is \( 36^\circ \pm 3^\circ \) and \( 51^\circ \pm 2^\circ \) in MJD 56342 and 56343, respectively, and these are slightly different from that on MJD 56281 (PA is \( 15^\circ \pm 1^\circ \)).

4. DISCUSSION

With the one-shot photopolarimetry of HOWPol, we obtained the highly variable light curve of PF on MJD 56281. In particular, the light curve in the later night of the same day (around 19–21 UT) consisted of two major pulses whose variability timescales (rise and decay times) are of the order of minutes and hours. No significant time lags between the flux and PD would indicate that the short-duration pulse occurred in the shock-compressed region with a highly ordered magnetic field. This minute-scale variability suggests a very compact emission region of the order of \( R \sim c \delta t_{\text{var}} = 1 \times 10^{13} \delta /10 \text{ s} \) cm, where \( R \) is the typical size of the emission region, \( c \) is the speed of light, \( \delta \) is beaming factor, and \( t_{\text{var}} \) is the observed variability timescale. In addition, the very high PD of up to \( \sim 36^\circ \) observed during the short-duration pulse requires a highly ordered magnetic field inside the very compact emission region.

NLSy1s are generally believed to have relatively smaller central BH mass compared to typical blazars (see Section 1). If we assume that the variability timescale is determined by the activity of the central BH, its lower limit is the light crossing time of BH horizon \( t_{\text{hc}} \sim r_s/c \sim 3.2 \times 10^2 (M/10^7 M_\odot) \) s, where \( r_s \) is the Schwarzschild radius and \( M \) is the mass of central BH. This is in good agreement with the observed timescale, which may indicate that the central BH mass of PMN J0948+0022 is indeed small, as was estimated by Yuan et al. (2008) under the conical structure assumption. On the other hand, however, larger BH mass cannot be ruled out if the conical assumption is
not held and the emission region size is estimated to be larger by the Doppler factor than the observed timescale. We finally note that such a minute-scale variability has recently also been detected by Paliya et al. (2013), and hence it is robust that PMN J0948+0022 shows this kind of rapid variability in the optical band.

High spatial resolution radio images toward the core of PMN J0948+0022 taken with VLBI revealed the presence of a parsec-scale jet and the jet is directed at $\sim 30^\circ$ (Doi et al. 2006). Since the magnetic field direction is usually assumed to be perpendicular to the PA, the observed optical PA of $\sim 15^\circ$ implies that the magnetic field direction at the emission site is roughly transverse to the jet direction. This reminds us of a well-known internal shock scenario (Hughes & Miller 1991) to explain the outburst. If this is the case, relativistic shells emitted from central BH intermittently with an interval of $c\delta t$ collide at $r \sim r_g (\Gamma/10)^2 \approx 1.5 \times 10^{16}$ cm and internal transverse shock is generated there. The compression of the magnetic field by the transverse shock would generate a highly ordered magnetic field inferred from the observed high PD. The variability timescale for hour-scale suggests a size of the emission region of $R \sim c\delta t_{\text{var}} = 1 \times 10^{15} (\delta/10) (\text{var}/3300 \text{ s})$, which is consistent with the standard conical jet assumption ($R \sim v\theta$) of the opening angle of $\theta \approx 1/\Gamma$. We speculate that the transverse shock generated a relatively compact emission region of $R \sim 10^{15}$ cm with a highly ordered magnetic field.

If the minute-scale pulse is indeed radiated by a very compact blob that is different from the larger emission region responsible for the underlying hour-scale pulse, a sudden change of PA may also occur because the magnetic field direction inside the very compact blob does not need to be the same as that of the larger emission region. Of course, there are some possibilities that explain the constant PA with the superposition of two emission regions, such as the scenario with accidental coincidence of magnetic vectors in two emission regions. We propose other possibilities to explain the mechanism of variability of flux and polarization other than the scenario postulating two emission regions. Among them, in the model with a single emission region from which internal shocks arise, colliding relativistic shells in the jet can also interpret the change of variability timescale due to the increasing size of the emission region, as reported in Böttcher & Dermer (2010). The authors predicted a temporally asymmetric light curve and our results support this scenario. Our results of constant PA around 19.6 UT indicate that the outburst may have originated in a single emission region and the change of variability timescale was caused by the propagation of an emission region in the jet.

Similar short timescale (from a few minutes to a few hours) variabilities of polarization are reported from blazar jets, such as AO 0235+164, S5 0716+714, and CTA 102 (Hagen-Thorn et al. 2008; Sasada et al. 2008; Itoh et al. 2013). However, it should be noted that these blazars do not always show the correlation between total flux and PD in the micro-variability. In addition, simultaneous short-term photopolarimetric observations have been performed in several blazars (Andruchow et al. 2003; Cellone et al. 2007; Andruchow et al. 2011), and only a few blazars show the correlation between the total flux and PD. In some blazars, the multi-zone model which has several emission regions is applied to explain these random correlations between the total flux and PD in micro-variability (e.g., Uemura et al. 2010; Rafie et al. 2012). On the other hand, our results indicate the model with a single emission region in the jet of PMN J0948+0022, as mentioned above. This assumption might reflect a difference in the formation rate of blobs between NLSy1s and blazars. Namely, a pure synchrotron radiation from the intermittent emergence of a single blob can be seen in RL-NLSy1 jets. The low values of PD in quiescent states and no significant underlying component in MJD 56281 (PF$C < 0.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$) support this scenario. Of course, there is only one short-term photopolarimetric observation of PMN J0948+0022, thus more photopolarimetric observations of RL-NLSy1s in the short time variability will be needed to study the relation between RL-NLSy1 jets and blazar jets.

We also found that the total flux increased by a factor of $\sim 2$ on MJD 56342, 61 days after the first observation (see also Figure 1). Motivated by this brightening, we conducted a continuous polarimetric observation over the subsequent two nights. As shown in Figures 2 and 3, temporal profiles of the total flux, PD, and PA did not show significant variation during the exposures, but we note that PD increased somewhat from $< 10\%$ to $\sim 15\%$ compared to the previous observations on MJD 56283, 56284, and 56295. These results can be understood in terms of the large-scale emission region of $R \gtrsim c\delta t_{\text{var}} = 3 \times 10^{15} (\delta/10) (\text{var}/10^3 \text{ s})$ cm, by substituting the variability timescale greater than $10^3$ s. In addition, PDs on MJD 56342 are lower than that on MJD 56281. No significant micro-variability except the data on MJD 56281 indicates that there are various timescales of variability. In general, the size of the emission region is related to the location of the emission region in the jet. The differences between emission regions give a weak correlation between the total flux and PD on long-term variability.

In conclusion, we performed optical polarimetric observation of RL-NLSy1 PMN J0948+0022 using Kanata/HOWPol and Murikabushi/MITSuME on 2012 December to 2013 February after the near-infrared and $\gamma$-ray flux enhancements. We find (1) highly variable total and PFs but almost constant PA, (2) minute-scale variability in the light curve of PF, (3) a very high maximum PD of $\sim 36\%$, and (4) that PA is grossly directed to the parsec-scale jet. The high and dramatic change of PD indicates that synchrotron emission in a highly ordered magnetic field is responsible for the optical emission. The observed variability timescale of minutes is in good agreement with the light crossing time of the Schwarzshild radius of the central BH under the assumption of $M_{\text{BH}} \sim 10^{6.5} M_\odot$. We note that the transverse shock inside a jet (known as “shock-in-jet” model) is consistent with the jet-directed PA and that the compression of the magnetic field by the shock can generate a highly ordered magnetic field. We also considered models of two radiation region scenarios as well as that of a single emission region scenario. Our results of a constant PA around 19.6 UT indicate that the outburst may have originated in a single emission region while many other blazars have been explained with the multi-zone model. It may also reflect a difference between the jets of NLSy1s and blazars if our assumptions are correct. We also searched the relation between the appearance of micro-variability and the flux state, but did not find a clear correlation. This result indicates that the mechanism of flux variability is different between the long-term (from a few days to a few weeks) and the short-term components (intra-night).

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REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJL, 707, L142
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, Natur, 463, 919
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJ, 722, 520
Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2007, ApJS, 172, 634
Andruchow, I., Cellone, S. A., Romero, G. E., Dominici, T. P., & Abraham, Z. 2003, A&A, 409, 857
Andruchow, I., Combi, J. A., Muñoz-Arjonilla, A. J., et al. 2011, A&A, 531, A38
Beasley, A. J., Gordon, D., Peck, A. B., et al. 2002, ApJS, 141, 13
Böttcher, M., & Dermer, C. D. 2010, ApJ, 711, 445
Carrasco, L., Recillas, E., Miramón, J., Porras, A., & Carraminana, A. 2012, ATel, 4659, 1
Cellone, S. A., Romero, G. E., Combi, J. A., & Martí, J. 2007, MNRAS, 381, L60
D’Ammando, F., & Orienti, M. 2013, ATel, 4694, 1
Doi, A., Nagai, H., Asada, K., et al. 2006, PASJ, 58, 829
Edelson, R. A., & Krolik, J. H. 1988, ApJ, 333, 646
Eggen, J. R., Miller, H. R., & Maune, J. D. 2013, ApJ, 773, 85
Fossati, G., Buckley, J. H., Bond, I. H., et al. 2008, ApJ, 677, 906
Hagen-Thorn, V. A., Larionov, V. M., Jorstad, S. G., et al. 2008, ApJ, 672, 40
Hughes, P. A., & Miller, L. 1991, in Introduction: Synchrotron and Inverse-Compton Radiation, ed. P. A. Hughes (Cambridge: Cambridge Univ. Press), 1
Ikejiri, Y., Uemura, M., Sasada, M., et al. 2011, PASJ, 63, 639
Itoh, R., Fukazawa, Y., Tanaka, Y. T., et al. 2013, ApJL, 768, L24
Kawabata, K. S., Nagae, O., Chiyonobu, S., et al. 2008, Proc. SPIE, 7014, 70144L
Komossa, S., Voges, W., Xu, D., et al. 2006, AJ, 132, 531
Liu, H., Wang, J., Mao, Y., & Wei, J. 2010, ApJL, 715, L113
Marscher, A. P., Jorstad, S. G., D’Arcangelo, F. D., et al. 2008, Natur, 452, 966
Miller, H. R., & Noble, J. C. 1996, in ASP Conf. Ser. 110, Blazar Continuum Variability, ed. H. R. Miller, J. R. Webb, & J. C. Noble (San Francisco, CA: ASP), 17
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Paliya, V. S., Stalin, C. S., Kumar, B., et al. 2013, MNRAS, 428, 2450
Rafle, H., Webb, J. R., & Bhatta, G. 2012, JSARA, 7, 33
Sasada, M., Uemura, M., Arai, A., et al. 2008, PASJ, 60, L37
Schalicky, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Schulz, A., & Lenzen, R. 1983, A&A, 121, 158
Uemura, M., Kawabata, K. S., Sasada, M., et al. 2010, PASJ, 62, 69
Yuan, W., Zhou, H. Y., Komossa, S., et al. 2008, ApJ, 685, 801
Zhou, H.-Y., Wang, T.-G., Dong, X.-B., Zhou, Y.-Y., & Li, C. 2003, ApJ, 584, 147