POSSIBLE DETECTION OF APPARENT SUPERLUMINAL INWARD MOTION IN MARKARIAN 421 AFTER THE GIANT X-RAY FLARE IN 2010 FEBRUARY

K. Niinuma1, M. Kino2, H. Nagai3, N. Isobe4, K. E. Gabanyi5,10, K. Hada6, S. Koyama7, K. Asada8, T. Oyama2, and K. Fujisawa9

1 Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi 753-8511, Japan; ninuma@yamaguchi-u.ac.jp
2 Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan
3 ALMA-J Project, National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan
4 Institute of Space and Astronautics, Japan Aerospace Exploration Agency, Yoshinodai, Chuo, Sagamihara 252-5210, Japan
5 Hungarian Academy of Sciences, Research Group for Physical Geodesy and Geodynamics, FOMI Satellite Geodetic Observatory Budapest, 1522 Budapest, Hungary
6 INAF Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy
7 Department of Astronomy, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8654, Japan
8 Academia Sinica Institute of Astronomy and Astrophysics, Taipei 10617, Taiwan
9 Research Institute for Time Studies, Yamaguchi University, Yamaguchi 753-8511, Japan

ABSTRACT

We report on the very long baseline interferometry (VLBI) follow-up observations using the Japanese VLBI Network array at 22 GHz for the largest X-ray flare of TeV blazar Mrk 421 that occurred in 2010 mid-February. The total of five epochs of observations were performed at intervals of about 20 days between 2010 March 7 and May 31. No newborn component associated with the flare was seen directly in the total intensity images obtained by our multi-epoch VLBI observations. However, one jet component located at ∼1 mas northwest from the core was able to be identified, and its proper motion can be measured as −1.66 ± 0.46 mas yr−1, which corresponds to an apparent velocity of −3.48 ± 0.97c. Here, this negative velocity indicates that the jet component was apparently moving toward the core. As the most plausible explanation, we discuss that the apparent negative velocity was possibly caused by the ejection of a new component, which could not be resolved with our observations. In this case, the obtained Doppler factor of the new component is around 10−20, which is consistent with the ones typically estimated by model fittings of spectral energy distribution for this source.

Key words: BL Lacertae objects: individual (Mrk 421) – techniques: interferometric

1. INTRODUCTION

Blazars are a sub-class of radio-loud active galactic nuclei with relativistic jets pointing almost along the line of sight. The spectral energy distributions (SEDs) of blazars are dominated by non-thermal, strongly Doppler-boosted, and variable radiation produced at the innermost part of the jets. The SED and the multi-frequency correlations of blazars have been intensively studied in the past through dedicated multi-frequency campaign observations (e.g., Abdo et al. 2011 and references therein).

One of the most important pieces for understanding relativistic jet formation is to obtain the direct image of a region radiating high-energy emission. However, it is difficult to obtain these images for the following reasons: (1) Many of the radio observations have been done by single-dish telescopes (e.g., Raiteri et al. 2009; Villata et al. 2009), and their spatial resolution is much larger than the relevant size. (2) Recent progress of very long baseline interferometry (VLBI) observations indicates possible correlations between newborn VLBI components and high-energy emissions by the Monitoring Of Jets In Active galaxies with VLBI Experiment (MOJAVE) project (e.g., Lister et al. 2009c; Kovalev et al. 2009). It is, however, difficult to confirm the correlation between a newborn VLBI component and X-ray and/or the very high energy (VHE) γ-ray flares when several flares occur during a single monitoring span, which is typically a few months for each source. Therefore, to confirm the fact mentioned above, examining the behavior at the root of the jet by conducting a dense monitor using VLBI soon after (< a few weeks) the giant X-ray and/or VHE γ-ray flare can be a complementary approach.

Mrk 421 is one of the best sources for studying the most compact regions in blazars, because of its proximity (z = 0.031, 131 Mpc). With respect to the kinematics of the parsec-scale jets in Mrk 421, very slow and/or almost stationary components, which can be monitored by long-term observations with VLBI, have been studied by Piner et al. (2010). However, no dense monitoring has yet been conducted to study the behavior near the core of Mrk 421 right after the giant flares (see Section 2).

Throughout this paper, we adopt the cosmological parameters of H0 = 71 km s−1 Mpc−1, Ωm = 0.27, and ΩΛ = 0.73 (Komatsu et al. 2009). Using these parameters, 1 mas corresponds to a linear distance of 0.64 pc, and a proper motion of 1 mas yr−1 corresponds to an apparent velocity of 2.1c at the distance of Mrk 421.

The organization of this paper is as follows: In Section 2, we summarize past giant flares of Mrk 421 and their follow-up observations using VLBI. In Sections 3–5, we describe our observations, data analysis, and the results obtained from model fitting the data. In Section 6, we compare our result with the one derived from the MOJAVE program to identify the position of the jet component, and in Section 7, we discuss the astrophysical implications derived from our result.

2. REVIEW OF GIANT VHE γ-RAY AND X-RAY FLARES

As mentioned in Section 1, systematic VLBI monitoring within ~100 days for investigating the behavior near the core
after the occurrence of a giant flare has not been done yet. In this section, we briefly review the previous giant flares of Mrk 421 at the VHE and/or X-ray band and the follow-up observations with VLBI for the flares.

### 2.1. Previous Flares

Since the first discovery of VHE $\gamma$-ray emission from Mrk 421 was reported by Punch et al. (1992), large X-ray or VHE $\gamma$-ray flares of Mrk 421 have occasionally been reported. Gaidos et al. (1996) succeeded in detecting the VHE $\gamma$-ray flares from Mrk 421 within a few years after the discovery of VHE emission of Mrk 421. An extremely high state of Mrk 421 at VHE band, which last from 2001 January to March, was reported by Krennrich et al. (2002). Recently, multi-epoch observations have also been performed for such large flares of Mrk 421 (Błażejowski et al. 2005; Lichti et al. 2008; Donnarumma et al. 2009). Among those, especially the second and fourth ones were also clearly detected with the energy range of Swift/BAT (15–50 keV). In the fourth one, the flux reached $164 \pm 17$ mCrab on a 6 hr average, which is the largest one at X-ray band among those ever reported. Especially for the largest X-ray flare, the detection of very bright VHE $\gamma$-ray emission ($\sim 10$ Crab) was also reported (Ong 2010).

### 3. Observations and Data Reduction

Anticipating the detection of a newly born component associated with the largest X-ray flare, we started follow-up observations with the Japanese VLBI network (JVN; Doi et al. 2006) within a month after the 2010 February flare. JVN includes VLBI Exploration of Radio Astrometry (VERA; Kobayashi et al. 2003) and is spread across the Japanese islands. Our first JVN observation of Mrk 421 took place on 2010 March 7. It was followed by another four epochs distributed by regular intervals of $\sim 20$ days. The last observation was conducted on 2010 May 31. All these observations were performed at 22 GHz. Unfortunately, the data we could analyze are only from VERA antennas because the other antennas mainly suffered from recording trouble.

The data from four telescopes (“VERA Mizusawa,” “VERA Iriki,” “VERA Ogasawara,” and “VERA Ishigaki-jima”; baseline ranging over 1000–2300 km) that were recorded with a bandwidth of 256 MHz using 2-bit samples and left-circular polarization were used for data reduction. The on-source time of Mrk 421 in each epoch is approximately 5.5 hr, and the range of elevation at which we carried out observations for Mrk 421 is $35^\circ \leq El \leq 88^\circ$ during the first epoch and $10^\circ \leq El \leq 82^\circ$ at the fifth epoch. The elevation dependence of the aperture efficiency of each VERA antenna is almost flat at $El \geq 25^\circ$. The synthesized beam size in our observations is typically a major axis of 1.2 mas and a minor axis of 0.8 mas with a position angle of $\sim 50^\circ$ measured from north through east. The correlation was carried out on the Mitaka FX correlator (Chikada et al. 1991).

In the last epoch, May 31, fringes to the “VERA Mizusawa” antenna could not be detected due to system troubles. This means
that the maximum baseline length was lacking. Therefore, we only had data from three antennas in this epoch. Since the synthesized beam size is 1.5 times larger than in the other four epochs, we decided to exclude this observation from further analysis. Also, at the second epoch, April 1, Mrk 421 was not detected in more than half of an observing time at the baseline including at the VERA Iriki station because of bad weather.

For the correlated data, we performed the standard VLBI calibration and fringe-fitting procedure using the NRAO Astronomical Image Processing System (AIPS) software package. The flux calibration done by the AIPS task APCAL typically achieved an accuracy of 10%, for VERA at 22 GHz (Nagai et al. 2010). The calibrated visibilities were then exported to carry out an imaging procedure using the Caltech Difmap package. After the time averaging of visibility data in 30 s bins, we carried out the iteration of CLEAN and self-calibration procedures in Difmap. During this iteration process, the solution interval of an amplitude self-calibration was shortened from intervals as long as the whole observational time down to 15 minutes.

4. MODELFIT

The total intensity images of Mrk 421 are shown in Figure 1. The direction of the outflow is consistent with those reported in other studies (Lico et al. 2012; Piner et al. 1999, 2010; Piner & Edwards 2005). Following Piner et al. (2010), we have carried out the elliptical and the circular Gaussian model fitting to the self-calibrated visibility data in the (u−v)-plane using the task modelfit in the Difmap at all epochs. To avoid the unrealistic changes in Gaussian sizes between adjacent epochs, we found that the elliptical Gaussian model for the core and the circular one for the jet component named JC1 are an appropriate combination. Model parameters are given in Table 2. The 1σ errors or 1σ upper limits of each parameter were derived from the model-fit procedure. The parameter we focused on is varied around the best-fit value by confirming a change in the χ² value. The position angle of the core components is around −30°, which coincides with that between the core and JC1 (about −40° except for the second epoch). From our model fit, the model components for the core were resolved toward the jet axis at all epochs. Regarding the direction perpendicular to the position angle of the core component, one is resolved at only the third epoch, and others are unresolved. When we fixed the axial ratios of the core components as the value obtained at the third epoch, a slight difference between the major axis of the core component and the jet axis generates a negligibly small fitting error of 0.02 mas at maximum. Therefore, JC1 is sufficiently distinguished from the core at all epochs, because of the size of its major axis.
motion of $\mu_{\text{arc}} = -1.66 \pm 0.46 \text{mas yr}^{-1}$, which corresponds to an apparent velocity of $v_{\mu_{\text{arc}}}$ = $-3.48 \pm 0.97c$ at the distance of Mrk 421. This negative velocity implies apparent inward motion of JC1. To measure the apparent velocity of JC1, although we have to estimate not only thermal but systematic errors as the uncertainty on the position of JC1 relative to the core at each epoch, it is quite difficult to estimate the latter quantitatively due to its nonlinearity. Therefore, following Homan et al. (2001) and Piner et al. (2010), we set the positional uncertainty on the data points that were uniformly rescaled so that the reduced $\chi^2$ is unity. Also, as seen in Figure 2, if we exclude the last epoch from the fit, the result obtained would only be half of the value mentioned above. Here, we applied the first-order fit to the motion of JC1. Based on our results, the significance of the detected superluminal motion of JC1 in Mrk 421 is $3.57\sigma$.

On the other hand, though the 10% flux errors mentioned in Section 3 are slightly large relative to the core flux change, which can be seen in Table 2, it appears that the core flux in the last epoch is higher than in the previous epochs. Additionally, the other flux data, which were compiled by the F-GAMMA program\(^{13}\) (Angelakis et al. 2010), also show almost the same trend of increasing flux as our result. Although the scale of flux variability was not large, there is a possibility that a delayed increase in radio flux was seen. When the flare occurs in the blazars, it has often been reported in radio observations at low frequency because of the opacity effect (e.g., Orienti et al. 2011). These support the possibility of structural changes occurring in the core region, such as the emergence of a new component. The

\(^{13}\) http://www3.mpifr-bonn.mpg.de/div/vlbi/fgamma/results.html

![Figure 2](image-url)

**Figure 2.** JC1 positions and weighted linear fit to JC1 positions (dashed line). The position uncertainties of each data point are uniformly rescaled so that the proper motion of $\mu_{\text{arc}} = -1.66 \pm 0.46 \text{mas yr}^{-1}$.

5. RESULTS

The position of JC1 relative to the core is plotted as a function of time in Figures 2 and 3. As a result of the least-squares fit to the displacements of the position of JC1 relative to the core during 66 days (from March 7 to May 12) under the assumption of linear motion of JC1, we obtained a proper

![Figure 3](image-url)

**Figure 3.** VLBI images of Mrk 421 produced by restoring model-fit components. The epoch and the scale of 1 mas for our images are indicated on the top of each image as year “YYYY.YY” and in the bottom of the panel of the first epoch, respectively. The interval of each image is proportional to the date when each observation was made. The filled squares represent the position of JC1 relative to the core, and the solid and the dashed lines show the trajectory of the core and of JC1, respectively. The decrease in the separation between the core and JC1 is shown by these two lines. The beam size of this figure is the same as Figure 1 and is shown in the bottom-left corner of the panel of the first epoch. Contours begin at 3 mJy beam$^{-1}$ and increase in $-1$ and $2\theta$ steps.

| Epoch          | Component | Maj (mas) | Axial Ratio | P.A. (deg) | Flux Density (mJy) | Distance from the Core R (mas) | Distance from the Core $\theta$ (deg) |
|----------------|-----------|-----------|-------------|------------|-------------------|-------------------------------|--------------------------------------|
| 2010 Mar 7     | Core      | 0.23 ± 0.02 | <0.27       | -24.0 ± 4.5 | 263.7             | ...                           | ...                                  |
| 2010 Apr 1     | Core      | 0.65 ± 0.01 | 1.0         | ...        | 17.9              | 1.28 ± 0.05                  | -37.6 ± 1.5                         |
| 2010 Apr 25    | Core      | 0.29±0.03   | <0.35       | -36.7±11.5 | 261.5             | ...                           | ...                                  |
| 2010 May 12    | Core      | 0.51±0.35   | 1.0         | ...        | 9.1               | 1.26 ± 0.17                  | -60.4 ± 7.5                         |
|                | JC1       | 0.26 ± 0.02 | <0.27       | -34.0 ± 4.7 | 288.5             | 1.14 ± 0.04                  | -38.3 ± 1.4                         |
|                | JC1       | 0.57 ± 0.11 | 1.0         | ...        | 14.3              | 0.97 ± 0.06                  | -41.5 ± 2.7                         |
fittings were done without JC1 data, and each error bar was calculated in the same way as in Figure 2. For MC3a and MC4a, each positional error is set to the same value as MC3 and MC4, respectively, because each component was not detected at other epochs. In this fit, the components showed the following proper motion: for MC1 0.08 ± 0.12 mas yr\(^{-1}\), for MC2 1.22 ± 0.24 mas yr\(^{-1}\), for MC3 0.34 ± 0.10 mas yr\(^{-1}\), and for MC4 0.25 ± 0.05 mas yr\(^{-1}\), which correspond to 0.17 ± 0.25 c, 2.56 ± 0.50 c, 0.71 ± 0.21 c, and 0.53 ± 0.11 c, respectively. MC1, MC3, and MC4 showed the sub-luminal speeds, which are consistent with the results shown in previous works (e.g., Piner et al. 2010). In these five epochs, MC2 showed superluminal motion. Recently, Lico et al. (2012) also performed VLBA observations of Mrk 421 every month in 2011. In their 15 GHz observations, four jet components are also detected, and their angular distance from the core was consistent with MC1, MC2, MC3, and MC4.

7. DISCUSSION

To examine the behavior inside the sub-pc region of Mrk 421, we conducted multi-epoch VLBI observations anticipating a superluminal component that is ejected from the core region after a large flare. Instead of detecting a newly emerging component on the VLBI images, we detected the apparent superluminal inward motion of the jet component JC1. Such motions of jet components have been reported by previous MOJAVE project studies, in which Lister et al. (2009b) discussed the detection probability of superluminal inward motions among all observations to be approximately 2%. We consider our detection of the inward motion of JC1 in Mrk 421 to be similar to the one rarely seen in the MOJAVE samples.

There is also a possibility that the positional fluctuations of the jet component close to the core showed its unusual motion in a short span (Edwards & Piner 2002); however, the motion of JC1 showed systematic inward motion at a superluminal speed rather than its positional fluctuations. Therefore, here we discuss several possible ideas suggested in Kellermann et al. (2004) for explaining an apparent superluminal inward motion of JC1. Among them, it is clear that the free–free absorption effect of disk, torus, and ambient cold plasma (the case discussed in Kamen et al. 2001) seems less likely. Another possibility they indicated is a highly curved jet. Although such extreme bending has been reported in a small number of sources (see, e.g., Savolainen et al. 2006), previous higher resolution studies for Mrk 421 indeed do not show any evidence for extreme bending within a parsec of the jet. The possibility of the bobbling of the core component with a short time span is also considerable. However, it seems that JC1 moved in closer to the core systematically through the first to the last epochs. Therefore, below, we focus on the following scenario proposed by Kellerman: a newly born component (JC0) on 2010 February 16, when the largest X-ray flare occurred, was in the core but was not resolved by our beam, and it made the centroid of the core shift toward the jet motion. Also, as seen in Figure 5, the motions of JC1 and MC3 seem discontinuous between the third and the fourth epoch of JVN observations (April 25 and May 12, respectively) and in the third epoch of MOJAVE observations (July 12). It is, however, possible to explain this motion as JC1 (or MC3) getting back on the track confirmed by previous studies, because the newborn component associated with the giant flare, which shifted the centroid of the core, faded within approximately 0.2 years. Therefore, basically, we have
Figure 5. Angular distances of each component detected with our observations and MOJAVE, relative to the core. The dashed and the solid arrows indicate the date when the large X-ray flares occurred. Also, each solid line shows the results of the linear fit to each component without JC1.

Table 3
Model Fit Parameters at Each Epoch: VLBA 15 GHz (MOJAVE)

| Epoch          | Component | Maj (mas) | Axial Ratio | P.A. (deg) | Flux Density (mJy) | $R$ (mas) | $\theta$ (deg) |
|----------------|-----------|-----------|-------------|------------|--------------------|------------|----------------|
| 2009 Dec 17    | Core      | 0.10      | 0.439       | −23.6      | 225.8              | ...        | ...            |
|                | MC4       | 0.24      | 1.0         | ...        | 23.3               | 0.38       | −31.7          |
|                | MC3       | 0.37      | 1.0         | ...        | 16.0               | 0.95       | −35.1          |
|                | MC2       | 0.63      | 1.0         | ...        | 8.3                | 1.60       | −32.9          |
|                | MC1       | 1.27      | 1.0         | ...        | 9.5                | 4.04       | −32.5          |
| 2010 Feb 11    | Core      | 0.10      | 0.00        | −73.1      | 279.2              | ...        | ...            |
|                | MC4       | 0.24      | 1.0         | ...        | 40.9               | 0.39       | −41.2          |
|                | MC3       | 0.42      | 1.0         | ...        | 14.9               | 1.17       | −35.6          |
|                | MC2       | 0.97      | 1.0         | ...        | 10.5               | 2.12       | −33.5          |
|                | MC1       | 1.16      | 1.0         | ...        | 8.0                | 4.09       | −33.7          |
| 2010 Jul 12    | Core      | 0.11      | 0.73        | −52.5      | 250.9              | ...        | ...            |
|                | MC4       | 0.38      | 1.0         | ...        | 35.4               | 0.46       | −42.4          |
|                | MC3a      | 0.16      | 1.0         | ...        | 11.3               | 0.96       | −50.0          |
|                | MC3       | 0.52      | 1.0         | ...        | 23.0               | 1.31       | −37.6          |
|                | MC2       | 0.46      | 1.0         | ...        | 3.6                | 2.32       | −29.4          |
|                | MC1       | 1.40      | 1.0         | ...        | 9.9                | 4.22       | −31.6          |
| 2010 Oct 15    | Core      | 0.14      | 0.54        | −30.5      | 265.2              | ...        | ...            |
|                | MC4       | 0.29      | 1.0         | ...        | 22.7               | 0.56       | −39.1          |
|                | MC3       | 0.46      | 1.0         | ...        | 17.6               | 1.26       | −37.6          |
|                | MC2       | 1.15      | 1.0         | ...        | 8.9                | 2.58       | −37.7          |
|                | MC1       | 0.58      | 1.0         | ...        | 4.6                | 4.00       | −29.6          |
| 2010 Nov 29    | Core      | 0.11      | 0.73        | −51.9      | 248.4              | ...        | ...            |
|                | MC4a      | 0.27      | 1.0         | ...        | 56.6               | 0.25       | −26.3          |
|                | MC4       | 0.23      | 1.0         | ...        | 17.3               | 0.67       | −39.5          |
|                | MC3       | 0.59      | 1.0         | ...        | 16.3               | 1.38       | −40.2          |
|                | MC2       | 1.04      | 1.0         | ...        | 4.3                | 3.08       | −42.9          |
|                | MC1       | 1.13      | 1.0         | ...        | 9.6                | 4.23       | −30.8          |

considered that the motion and the position of JC1 detected by our observations were consistent with previous studies.

Lastly, we discuss the Doppler factor and the Lorentz factor of JC0 under the assumption mentioned above. The apparent velocity of $v_{app} = -3.48 \pm 0.97c$ derived from the linear fit to the positions of JC1 relative to the core is the relative velocity. Therefore, assuming that JC1 did not move or its apparent velocity is sufficiently slow, we can consider that the JC0 moved
toward JC1 with the apparent velocity of $v_{\text{app}} \sim 3.48 \pm 0.97c$. In Figure 6, we show the bulk Lorentz factor ($\Gamma_0$) and the Doppler factor ($\delta_0$) of JC0 calculated by setting a range of $2.51c \leq v_{\text{app}} \leq 4.45c$ and $1^\circ \leq \theta \leq 5^\circ$, respectively. Here we use the equations of $\Gamma_0 = 1/\sqrt{1-\beta_0^2} = 1/\Gamma_0(1-\beta_0 \cos \theta)$, (where, $\beta_0 = v_{\text{app}}/c = \beta_0/(\sqrt{1+\beta_0^2 \sin^2(\theta+\phi)})$, $\beta_0 = v_{\text{app}}/c = \cos^{-1}(1/(1+\beta_0^2))$). As a result of these calculations, $\delta_0 = 11.03^{+1.26}_{-1.52}$ and $\Gamma_0 = 6.11^{+0.88}_{-0.97}$ are obtained for the median value of $\theta = 3^\circ$.

We consider that these values are reasonable, because our result does not require extreme values for the jet parameters and the Doppler factor $\delta_0$ is almost consistent with the typical value of $\sim 10$ derived from the broadband (optical to TeV $\gamma$-ray) SED fit (e.g., Kino et al. 2002; Blażejowski et al. 2005; Donnarumma et al. 2009; Abdou et al. 2011).

8. CONCLUSION

For the giant X-ray flare of Mrk 421 that occurred on 2010 February 16, we carried out the multi-epoch VLBI observations at intervals of $\sim 20$ days using the JVN array soon after the giant flare. Although no newborn component can be seen directly in the total intensity images obtained by our quick follow-up observations, the jet component JC1 located at $\sim 1$ mas northwest from the core showed its apparent inward motion at an apparent speed of $3.48 \pm 0.97c$. As the most plausible explanation, we discuss that the inward motion of JC1 at a superluminal speed was possibly caused by the ejection of a new component JC0, which could not be resolved with our observations. In this case, the obtained Doppler factor of JC0 is around $10-20$, which is consistent with the ones typically estimated by model fittings of SED for this source.

To confirm our result, we must carry out a quick follow-up or sufficiently dense monitoring for such a large flare with a phase-referencing VLBI technique. By doing this, there is a possibility of identifying the actual motion of all components, including the core region after the large flare. Also, a polarization observation such as that by Piner & Edwards (2005) or Marscher et al. (2008) is also an effective means of identifying whether a VLBI component is produced by the flare and investigating its motion right after the flare occurs.

We are grateful to the anonymous referee, whose suggestions improved our paper substantially. We are grateful to all JVN members for their assistance in observations. We also thank K. Akiyama for very useful comments for the data reduction. The JVN project is led by the National Astronomical Observatory of Japan, which is a branch of the National Institutes of Natural Sciences, Hokkaido University, The University of Tsukuba, Ibaraki University, Gifu University, Osaka Prefecture University, Yamaguchi University, and Kagoshima University, in cooperation with the Geographical Survey Institute, the Japan Aerospace Exploration Agency, and the National Institute of Information and Communications Technology. This research has made use of data from the MOJAVE database that is maintained by the MOJAVE team (Lister et al. 2009a). K.N. acknowledges financial support from Grant-in-Aid for Young Scientists (B) (No. 22740130) from the Japan Society for the Promotion of Science (JSPS). This work is partially supported by Grant-in-Aid for Scientific Research KAKENHI 24540240 (M.K.) from JSPS. K.E.G. was supported by the Hungarian Scientific Research Fund (OTKA, grant No. K72515).

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, ApJ, 736, 131
Angelakis, E., Fuhrmann, L., Nestoras, I., et al. 2010, arXiv:1006.5610
Blażejowski, M., Blaylock, G., Bond, I. H., et al. 2005, ApJ, 630, 130
Chikada, Y., Kawaguchi, N., Inoue, M., et al. 1991, in Frontiers of VLBI, ed. H. Hirabayashi et al. (Tokyo: Universal Academy press), 79
D’Ammando, F., Perri, M., Tramacere, A., et al. 2009, ATel, 2295, 1
Doi, A., Fujisawa, K., Harada, K., et al. 2006, in Proc. 8th European VLBI Network Symposium, ed. A. Marecki et al., (PoS(EVN071), http://pos.sissa.it/archive/conferences/036/index.pdf
Donnarumma, I., Vittorini, V., Vercellone, S., et al. 2009, ApJ, 691, L13
Edwards, P. G., & Piner, B. G. 2002, ApJ, 579, L67
Gaidos, J. A., Akerlof, C. W., Biller, S., et al. 1996, Nature, 383, 319
Homan, D. C., Ojha, R., & Wardle, J. F. C. 2001, ApJ, 549, 840
Isobe, N., Sugimori, K., Kawai, N., et al. 2010, PASJ, 62, L55
Kobayashi, H., Sasao, T., Kawaguchi, N., et al. 2003, in ASP Conf. Ser. 306, New Technologies in VLBI, ed. Y. C. Minh (San Francisco, CA: ASP), 367
Kotera, M., Dunkley, J., Nolta, M. R., et al. 2009, ApJS, 180, 330
Kovalev, Y. Y., Aller, H. D., Aller, M. F., et al. 2009, ApJ, 696, L17
Krennrich, F., Bond, I. H., Bradbury, S. M., et al. 2002, Nature, 389, L9
Krimm, H. A., Barthelmy, S. D., Baumgartner, W., et al. 2008, ATel, 1449, 1
Kobayashi, H., Sasao, T., Kawaguchi, N., et al. 2003, in ASP Conf. Ser. 306, New Technologies in VLBI, ed. Y. C. Minh (San Francisco, CA: ASP), 367
Komatsu, E., Dunkley, J., Nolta, M. R., et al. 2009, ApJS, 180, 330
Kovalev, Y. Y., Aller, H. D., Aller, M. F., et al. 2009, ApJ, 696, L17
Krennrich, F., Bond, I. H., Bradbury, S. M., et al. 2002, ApJ, 575, L9
Krimm, H. A., Barthelmy, S. D., Baumgartner, W., et al. 2008, ATel, 1449, 1
Lichti, G. G., Bottacini, E., Ajello, M., et al. 2008, A&A, 486, 721
Lichti, G. G., Paltani, S., Mowlavi, N., et al. 2006, ATel, 848, 1
Lico, R., Girolitti, M., Orienti, M., et al. 2012, A&A, 545, A117
Lister, M. L., Aller, H. D., Aller, M. F., et al. 2009a, AJ, 137, 3718
Lister, M. L., Cohen, M. H., Homan, D. C., et al. 2009b, AJ, 138, 1874
Lister, M. L., Homan, D. C., Kadler, M., et al. 2009c, ApJ, 696, L22
Marscher, A. P., Jorstad, S. G., D’Arcangelo, F. D., et al. 2008, Nature, 452, 966
Matsuo, K., Kawasaki, K., Ueno, S., et al. 2009, PASJ, 61, 999
Nagai, H., Suzuki, K., Asada, K., et al. 2010, PASJ, 62, L11
Ong, R. A. 2010, ATel, 2443, 1
Orienti, M., Venturi, T., Dallacasa, D., et al. 2011, MNRAS, 417, 359
Piner, B. G., & Edwards, P. G. 2005, ApJ, 622, 168
Piner, B. G., Pant, N., & Edwards, G. P. 2010, ApJ, 723, 1150
Piner, B. G., Unwin, S. C., Wehrle, A. E., et al. 1999, ApJ, 525, 176
Punch, M., Akerlof, C. W., Gawley, M. F., et al. 1992, Nature, 358, 477
Raiteri, C. M., Villata, M., Capetti, A., et al. 2009a, A&A, 507, 769
Savolainen, T., Wikl, K., Vaajalaa, E., et al. 2006, ApJ, 647, 172
Schubnell, M. 1997, in AIP Conf. Proc. 410, The Fourth Compton Symposium, (Melville, NY: AIP), 1386
Villata, M., Raiteri, C. M., Larionov, V. M., et al. 2009, A&A, 501, 455