VERY LONG BASELINE ARRAY MULTI-FREQUENCY POLARIMETRIC IMAGING OF RADIO-LOUD BROAD ABSORPTION LINE QUASARS

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ABSTRACT

We conducted the first multi-frequency polarimetric imaging of four broad absorption line (BAL) quasars using the Very Long Baseline Array at milliarcsecond resolutions to investigate the inclination of the nonthermal jet and test the hypothesis that radio sources in BAL quasars are still young. Among these four sources, J0928+446, J1018+0530, and J1405+4056 show one-sided structures in parsec scales and polarized emission detected in the core. These characteristics are consistent with those of blazars. We set constraints on viewing angles to <66° for these jets in the framework of a Doppler beaming effect. J1159+0112 exhibits an unpolarized gigahertz-peaked spectrum component and several discrete blobs with steep spectra on both sides of the central component across ~1 kpc. These properties are consistent with those of young radio sources. We discuss the structures of jets and active galactic nucleus wind.

Key words: accretion, accretion disks – galaxies: active – quasars: absorption lines – radio continuum: galaxies – techniques: interferometric

1. INTRODUCTION

Quasars showing broad absorption troughs of resonance lines (e.g., Mg\textsc{ii}, C\textsc{iv}) in their rest ultraviolet spectra are called broad absorption line (BAL) quasars (e.g., Weymann et al. 1991). BAL quasars are classified into two categories, HiBAL and LoBAL quasars, depending on whether they show both high-ionization and low-ionization troughs or only low-ionization troughs. Ionized wind from an accretion disk of an active galactic nucleus (AGN) is the most plausible candidate for the origin of BAL to account for its high velocities (several thousand km s\textsuperscript{-1} to ~0.1c typically). For the quasar sample from the Sloan Digital Sky Survey Third Data Release (SDSS DR3; Abazajian et al. 2005), the fraction of BAL quasars is 26% (Trump et al. 2006), which is a key to understanding the origin of BAL quasars. To explain the fraction, two scenarios have been proposed: an orientation scheme and an evolution scheme.

In the orientation scheme, all quasars possess the AGN wind and whether BAL is observed or not can be attributed to the viewing angles to the sources. The AGN wind is produced by radiation pressure nearly parallel to the disk (Proga et al. 2000; Elvis 2000), based on support in spectropolarimetry at rest ultraviolet (Goodrich & Miller 1995; Cohen et al. 1995). In the model, BAL troughs can only be seen in quasars whose edge-on disk wind points toward the observer. In contrast, Zhou et al. (2006) found a number of radio-detected BAL quasars showing rapid radio-flux variation which indicates a Doppler beaming effect on pole-on viewd jets (Blandford & Konigl 1979; Urry & Padovani 1995). Moreover, widely distributed radio spectral indices (Becker et al. 2000; Montenegro-Montes et al. 2008b; Doi et al. 2009; Fine et al. 2011; DiPompeo et al. 2011; Bruni et al. 2012) also suggest that at least a portion of BAL quasars are blazar-type objects with flat-spectrum radio cores. The simple orientation scheme might not explain all BAL quasars.

The evolution scheme ascribes the ratio of BAL to non-BAL quasars to the duration of time when quasars possess the AGN wind (Becker et al. 2000). Most BAL quasars detected by the Faint Images of the Radio Sky at Twenty cm survey (FIRST survey; Becker et al. 1995) are point-like sources (Becker et al. 2000). The number of Fanaroff–Riley type-II (Fanaroff & Riley 1974) radio sources in BAL quasars is roughly 10 times less than that in all SDSS quasars (Gregg et al. 2006). In addition, Montenegro-Montes et al. (2008b) reported that a significant fraction of BAL quasars show radio spectra as found in gigahertz-peaked spectrum (GPS) or compact steep spectrum (CSS) radio sources that are candidates for young radio sources (Snellen et al. 2000; Conway 2002; Nagai et al. 2006). Quasars might show their BAL when they are young before they have large-scale jets. Thus, radio observation to measure the age of a source is an important approach for understanding BAL quasars in terms of the evolution scheme.

In contrast to the above argument, GPS/CSS sources as young radio sources are sometimes indistinguishable from blazars by radio observations with arcsecond-scale resolution. Usually, blazars have a flat or inverted spectrum up to high frequencies, while young radio sources have an optically thin steep spectrum in the gigahertz regime. However, blazars may show a convex spectrum similar to GPS/CSS sources during a flare (Torniainen et al. 2005, 2007). Thus, observations with limited frequency coverage cannot distinguish GPS/CSS sources from blazars. Even in these situations, blazars and young radio sources still display characteristics different from each other (Tinti et al. 2005; Orienti et al. 2007). Blazars appear as one-sided structures in milliarcsecond (mas) resolutions, long-term variability (Torniainen et al. 2005, 2007; Hovatta et al. 2007, 2008), and a high degree of polarization. On the other hand, young radio sources have lobes with sub-relativistic speeds, which appear as two-sided structures in mas resolution, little variability, and little polarization. To distinguish blazars and young radio sources, high-resolution direct imaging is important. Then, very long baseline interferometry (VLBI) is efficient to test the evolution scheme. In addition, VLBI is also one of the most direct ways to test the orientation scheme because radio structures on a mas scale include the information about the viewing angle.

There have been several studies of BAL quasars using VLBI (Jiang & Wang 2003; Montenegro-Montes et al. 2008a; Liu et al. 2008; Doi et al. 2009; Reynolds et al.
2009; Kunert-Bajraszewska et al. 2010; Bruni et al. 2010, 2013; Jiang & Wang 2003; Montenegro-Relativistic jet (Doi et al. 2009). Both one-sided and two-sided jet dio sources or Doppler-beamed sources having pole-on-viewed inverted-spectrum sources, which are interpreted as young ra-

presented in Section 5. We discuss the structures of parsec-

The multi-frequency polarimetric imaging was conducted at 1.7, 5, and 8 GHz bands using the VLBA on 2010 June 25 (project code BD137). The observation was carried out over 10 hr. Each source was observed at the three bands with 6–10 minutes scan at 3–4 different hour angles. This leads to the quasi-similar u–v coverages at each band. An aggregate bit rate of 128 Mbps was used; each band consisted of two 8 MHz wide, full polarization intermediate frequencies (IFs) centered at 1.663 and 1.671 GHz at 1.7 GHz band, 4.644 and 5.095 GHz at 5 GHz band, and 8.111 and 8.580 GHz at 8 GHz band. We integrated two IFs in each band to make Stokes I maps, while we produced the polarization map of each IF separately.

It is important to select a suitable setting for the IFs to determine n–π ambiguity (n = 0, ±1, ±2, · · · ) in polarization angle and to measure the Faraday rotation measure (RM). The upper limit of measurable RM is determined by $\pi/2 > (1 + z^2) |RM_{obs}|/|\Delta \theta|^2$, where $RM_{obs}$ and $\Delta \theta$ are the RM at the observer frame and the minimum separation of the square of observing wavelength, respectively. Then, we obtain the maximum measurable RM as ~10,000 rad m$^{-2}$ in the case of our setting. The maximum value in the rest frame becomes ~90,000 rad m$^{-2}$ for our sample sources at $z \sim 2$.

3. OBSERVATION

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4. DATA REDUCTION

4.1. A priori Calibration and Imaging Process

Data reduction was performed with a standard procedure using the Astronomical Image Processing System (AIPS; Greisen 2003) software developed at the National Radio Astronomy Observatory (NRAO). Amplitude calibration was performed using the measurements of system noise temperature during the observation and gains provided by each station. We also corrected the amplitude measurements of system noise temperature during the ob-

We selected a sample for the VLBA observation from 20 sources detected in the first systematic VLBI observation at 8.4 GHz (Doi et al. 2009) using the Optically ConncTed Array for VLBI Exploration project (OCTAVE; Kawaguchi 2008) operated by the Japanese VLBI Network (Fujisawa 2008). The OCTAVE sample consisted of SDSS-DR3 BAL quasars in Trump et al. (2006), which hosted radio counterparts in the FIRST survey with peak flux densities of more than 100 mJy. Then, we selected the target sources that have (1) flux density of more than 100 mJy in the OCTAVE observation, (2) expected polarized flux density$^5$ of more than 1 mJy, and (3) flat or inverted spectra$^6$ ($\alpha > -0.5$) in Doi et al. (2009). The sample is listed in Table 1.

Table 1

| Object SDSS Name | z | BAL Type | Af (km s$^{-1}$) | Br (km s$^{-1}$) | $s_{1.4 \text{GHz}}$ (mJy) | $s_{1.4 \text{GHz}}$ (mJy) | log $R_\ast$ | $L_{1.4 \text{GHz}}$ (erg s$^{-1}$ Hz$^{-1}$) | Ref. |
|-----------------|---|----------|----------------|-------------|----------------|----------------|------------|----------------|-----|
| J0928+4446      | 1.904 | Hi | 293 | 0 | 156 | 2.8 | 3.1 \times 10^{34} | a,b |
| J1018+0530      | 1.938 | Hi | 441 | 0 | 284 | 3.7 | 6.0 \times 10^{34} | a |
| J1159+0112      | 2.000 | Hi | 2887 | 0 | 267 | 2.6 | 5.9 \times 10^{34} | a,b,c,d |
| J1405+4056      | 1.993 | Hi | 780 | 0 | 206 | 3.3 | 4.7 \times 10^{34} | a |

Notes. Column 1: object name in this paper; Column 2: object name in the SDSS DR3; Column 3: redshift; Column 4: BAL classification. “Hi” denotes a HiBAL quasar; Column 5: absorption index; Column 6: balnicity index. Reference for Columns 2–6 is Trump et al. (2006); Columns 7–8: FIRST survey with peak flux densities of more than 100 mJy. Expected polarized flux density is defined as a product of degree of polarization provided by the NRAO VLA Sky Survey at 1.4 GHz (NVSS; Condon et al. 1998) and flux density obtained by the OCTA VE observation at 4 GHz.

References. (a) Trump et al. 2006; (b) Gibson et al. 2009; (c) Scaringi et al. 2009; (d) Briggs et al. 1984.
Figure 1. EVPA for polarization calibrator sources of J1310+3220 obtained by EVLA observation and OJ 287 obtained by our VLBA observation. We refer to EVPA of J1310+3220 (open squares) for that of OJ 287 (open triangles) and target sources. The reference value at 1.7 GHz is obtained by extrapolation of the value of 5 and 8 GHz (dotted line). EVPA of OJ 287 at 1.7 GHz is in excellent agreement with EVPA of OJ 287 extrapolated from 5 and 8 GHz (dot-dashed line).

ionospheric dispersive delay were corrected. Finally, bandpass calibration for both amplitude and phase was performed. All sources were detected on all baselines at all frequencies except for the 1.7 GHz band at Hancock station where system temperature was not obtained properly due to radio frequency interference.

Imaging processes were performed using the difmap software (Shepherd1997). We conducted self-calibration to derive the antenna-based amplitude corrections. The difmap does not solve for gain time variation for RR and LL visibilities separately. Hence, we constructed an RR or LL model by the difmap and then performed self-calibration for Stokes I by the AIPS, which corrects gain time variation for RR and LL visibilities separately (Aaron1997). The error on the absolute flux density scale was generally ∼5%.

4.2. Calibration of Polarization

We corrected RL and LR delay offsets using the bright polarized source, J0854+2006 (OJ 287), and corrected instrumental polarization (D-term) using the compact unpolarized source, J1407+2827 (OQ 208). After D-term was calibrated, we confirmed that OQ 208 had almost become unpolarized. We estimated the error on the absolute flux density scale for polarization was within 10% including residual D-term.

An unknown phase offset between L and R polarizations for a reference antenna was corrected using the observed electric vector position angle (EVPA) of J1310+3220 which was observed by EVLA at 5 and 8 GHz bands on 2010 July 15 and June 22, respectively, under the project named TPOL. Each band consists of two 128 MHz wide IFs centered at 4.896 and 5.024 GHz at 5 GHz band, 8.395 and 8.523 GHz at 8 GHz band. Using the data obtained by UMRAO,7 we confirmed that during

the months of June and July there was no significant variability in their total flux densities, degree of polarization, and EVPA. In addition, total and polarized flux density of J1310+3220 obtained by VLBA were similar to that obtained by EVLA. We derived the integrated EVPA for J1310+3220 at 1.7 GHz band by extrapolating from EVPA at 5 and 8 GHz bands because EVPA would be affected by RM. After the EVPA correction, EVPA of the other EVPA calibrator, OJ 287, at 1.7 GHz band was consistent with that extrapolated from EVPA at 5 and 8 GHz bands obtained using VLBA (Figure 1). Hence, our EVPA calibrations seemed to be performed well.

The errors of EVPA are the root sum square of flux density measurement errors and fitting error to derive RM for the calibrator source. Because polarimetry at low frequency is affected by ionospheric Faraday rotation, we checked the total electron content of the ionosphere during our observation; the typical variation of ionospheric RM within a scan was |RMobs| < 0.5 rad m⁻² and between scans was |RMobs| < 3 rad m⁻². These values are equivalent to ΔEVPA < 0.02 rad and ΔEVPA < 0.12 rad at a wavelength of 20 cm, which do not affect the estimation of the EVPA significantly even at 1.7 GHz band.

5. RESULTS

5.1. Morphology

Stokes I maps of the target sources at 1.663, 4.644, and 8.111 GHz are shown in Figures 2–5. Flux densities of each component were measured by fitting with a Gaussian model profile and the spectral indices were calculated for each component (Table 2).

J0928+4446. The radio structure in Figure 2 is consistent with that obtained by the VLBA Imaging and Polarimetry Survey (VIPS; Helmboldt et al. 2007) at 5 GHz. The spectral index of each component indicates (see Table 2) an inverted-spectrum
core (the component A) and steep spectrum one-side jets (the components B–D). Its morphology can be classified as a one-sided structure.

**J1018+0530.** The images at 5 and 8 GHz show an extended emission, which emerges at position angle (P.A.) of $\sim -170^\circ$ (Figure 3), while the source is unresolved at 1.7 GHz. The pc-scale radio structure is dominated by an inverted-spectrum core (Table 2). The extended emission found at 5 and 8 GHz is a jet. Its morphology can be classified as a one-sided structure.

**J1159+0112.** Table 2 indicates an inverted spectrum at the component A, which is a radio core. Additionally, images at 1.7 and 5 GHz show the linear alignment of several discrete components that extend $\sim 90$ mas toward the southeast and a significant counter feature $\sim 50$ mas northwest across $\sim 1$ kpc in total (Figure 4). The southeast components are consistent with the previous study by Montenegro-Montes et al. (2008a). They show steep spectra (Table 2) and thus morphology that can be classified as a two-sided structure. Although Montenegro-Montes et al. (2008a) also reported two symmetrical extensions close to the core located toward the northwest and the southeast, no such structure was detected by our observation. Instead, we found the components A1 and A2 both at 5 and 8 GHz.

The radio spectrum of J1159+0112 (Figure 6) can be represented by double-peaked spectra, peaked at a few hundred MHz and $\sim 10$ GHz; a steep spectrum and an inverted spectrum in the range of our VLBA observations. The gigahertz-peaked component originates in the radio core (the component A), while the steep spectrum components originate in the extended structure with several discrete blobs (the components B–E).

**J1405+4056.** The structure in Figure 5 is consistent with that obtained by the VIPS. Table 2 indicates that the radio structure consists of an inverted-spectrum core (the component A) and steep spectrum one-side jets (the components B and C). Its morphology can be classified as a one-sided structure.

### 5.2. Polarization

Figures 2–5 show polarization vectors overlaid on the Stokes $I$ maps. Polarized flux densities and degree of polarization at each component averaged within a band are listed in Table 3. Errors are the root sum square of calibration uncertainties of 10% and fitting error in the AIPS task IMFIT. EVPA at components whose polarized flux densities are detected is shown in Table 4.

Point-like polarized emissions in the radio core were detected for all the sources except for J1159+0112. Polarization of J1159+0112 was detected in the component D with a very high degree of polarization of 11.4% $\pm$ 1.7% at 1.7 GHz. This will be discussed in Section 6.4. For J1405+4056, no polarized emission at 1.663 and 1.671 GHz was detected at the core. Polarized emission at low frequencies could suffer from depolarization within a bandwidth and/or within a beamwidth. To make the source depolarized within an 8 MHz bandwidth at 1.7 GHz, RM more than 10,000 rad m$^{-2}$ in the observer-frame is needed. Such a high RM is reported in a BAL quasar, J1624+3758 (Bruni et al. 2012). Alternatively, even if RM is less than 10,000 rad m$^{-2}$, inhomogeneous spatial distribution of magnetic field and electron density could cause disordered EVPA distribution across the beam. Then, lower-frequency polarized emissions tend to be smeared out because of larger beam sizes. On the jet component of J1405+4056, we found a hint of polarized flux density only at 1.663 GHz (Figure 5) but the same polarization structure was not detected at the other frequencies including 1.671 GHz.
Figure 3. VLBA images of J1018+0530 observed on 2010 June 25 with superposed polarization vectors. Vector lengths are proportional to the polarized flux density (1 mas corresponds to 0.5 mJy beam$^{-1}$). (a) The 1.663 GHz Stokes $I$ map. The restoring beam is $12 \times 5.7$ mas at P.A. = 2.7, the contour levels are (1, 2, 4, 8, ...)$\times$1.1 mJy beam$^{-1}$, and the peak flux density is 344 mJy beam$^{-1}$. (b) The 4.644 GHz Stokes $I$ map. The restoring beam is $4.1 \times 1.7$ mas at P.A. = $-7.2$, the contour levels are (1, 2, 4, 8, ...)$\times$1.2 mJy beam$^{-1}$, and the peak flux density is 334 mJy beam$^{-1}$. (c) The 8.111 GHz Stokes $I$ map. The restoring beam is $2.4 \times 0.95$ mas at P.A. = $-8.0$, the contour levels are (1, 2, 4, 8, ...)$\times$1.2 mJy beam$^{-1}$, and the peak flux density is 339 mJy beam$^{-1}$.

Table 2
Flux Densities and Spectral Index of Each Component

| Object  | Component | Flux Density       | Spectral Index |
|---------|-----------|--------------------|----------------|
|         |           | 1.7 GHz (mJy)     | 4.9 GHz (mJy)  | 8.3 GHz (mJy) |
| J0928+4446 | A       | 164.9$\pm$8.2    | 206.7$\pm$10.3 | 258.3$\pm$12.9 | 0.26$\pm$0.05 |
|         | B       | 14.8$\pm$0.7     | 5.6$\pm$0.3    | 3.1$\pm$0.2   | $-0.96$\pm0.04 |
|         | C       | 6.1$\pm$0.3      | 0.7$\pm$0.0    | $<0.6$        | $-2.01$\pm0.09 |
|         | D       | 1.1$\pm$0.1      | $<0.8$         | $<0.6$        | ...            |
| J1018+0530 | Total   | 357.7$\pm$17.9   | 368.4$\pm$18.4 | 395.1$\pm$19.8 | 0.06$\pm$0.03 |
| J1159+0112 | A       | 41.9$\pm$2.1     | 99.9$\pm$5.0   | 135.6$\pm$6.8 | 0.74$\pm$0.06 |
|         | B       | 18.9$\pm$0.9     | 2.1$\pm$0.1    | $<0.8$        | $-2.07$\pm0.09 |
|         | C       | 29.1$\pm$1.5     | 7.5$\pm$0.4    | $<0.8$        | $-1.27$\pm0.09 |
|         | D       | 66.9$\pm$3.3     | 16.2$\pm$0.8   | $<0.8$        | $-1.33$\pm0.09 |
|         | E       | 11.9$\pm$0.6     | 0.9$\pm$0.0    | $<0.8$        | $-2.47$\pm0.09 |
| J1405+4056 | A       | 222.7$\pm$11.1   | 227.1$\pm$11.4 | 214.2$\pm$10.7 | $-0.02$\pm0.03 |
|         | B       | 18.8$\pm$0.9     | 11.7$\pm$0.6   | 1.5$\pm$0.1   | $-1.49$\pm0.58 |
|         | C       | 16.4$\pm$0.8     | 5.3$\pm$0.3    | 3.1$\pm$0.2   | $-1.04$\pm0.02 |

Table 3
Polarized Flux Densities and Degree of Polarization of Each Component

| Object  | Component | Polarized Flux Density | Degree of Polarization |
|---------|-----------|------------------------|------------------------|
|         |           | 1.7 GHz (mJy) | 4.9 GHz (mJy) | 8.3 GHz (mJy) | 1.7 GHz (%) | 4.9 GHz (%) | 8.3 GHz (%) |
| J0928+4446 | A       | 7.8$\pm$0.8   | 8.6$\pm$0.9   | 9.5$\pm$1.0   | 4.6$\pm$0.7 | 4.6$\pm$0.7 | 4.4$\pm$0.7 |
| J1018+0530 | Total   | 13.8$\pm$1.4  | 7.8$\pm$0.8   | 6.9$\pm$0.7   | 3.9$\pm$0.6 | 2.2$\pm$0.3 | 1.8$\pm$0.3 |
| J1159+0112 | D       | 7.6$\pm$0.8   | $<1.2$        | $<1.1$        | 11.4$\pm$1.7 | $<7.4$    | ...        |
| J1405+4056 | A       | $<0.9$        | 2.9$\pm$0.3   | 4.7$\pm$0.5   | $<0.3$        | 1.3$\pm$0.2 | 2.3$\pm$0.4 |
|         | C       | 2.3$\pm$0.3$^a$ | $<0.9$        | $<0.9$        | 13.7$\pm$2.7$^a$ | $<17.0$   | $<29.0$    |

Note. $^a$ Only detected at 1.663 GHz.

5.3. Faraday Rotation Measure

RM denotes the dependence of EVPA on wavelength. The result of RM fits is shown in Figure 7 and Table 4. When we fit the result, we assume no $n$-$\pi$ ambiguity in each band. The ambiguity between bands is determined to minimize the sum of the squares of the deviation. We obtained $|RM_{obs}|$ for the core region of J0928+4446 and J1018+0530 as $120 \pm 7$ rad m$^{-2}$ and $139 \pm 5$ rad m$^{-2}$, respectively. Then, $|RM_{rest}|$ is obtained as $1010 \pm 59$ rad m$^{-2}$ and $1200 \pm 43$ rad m$^{-2}$ for J0928+4446 and
Figure 4. VLBA images of J1159+0112 observed on 2010 June 25 with superposed polarization vectors. Vector lengths are proportional to the polarized flux density (1 mas corresponds to 0.5 mJy beam$^{-1}$). (a) The 1.663 GHz Stokes $I$ map. The restoring beam is 14 × 7.4 mas at P.A. = 0°08.0, the contour levels are (1, 2, 4, 8, ..., ) × 1.3 mJy beam$^{-1}$, and the peak flux density is 36.4 mJy beam$^{-1}$. (b) The 4.9 GHz image. The restoring beam is 4.7 × 1.7 mas at P.A. = −14°, the contour levels are (1, 2, 4, 8, ..., ) × 0.78 mJy beam$^{-1}$, and the peak flux density is 93.0 mJy beam$^{-1}$. (c) The 8.3 GHz image. The restoring beam is 2.4 × 0.95 mas at P.A. = −8°9, the contour levels are (1, 2, 4, 8, ...) × 0.76 mJy beam$^{-1}$, and the peak flux density is 122 mJy beam$^{-1}$.

Table 4 Electric Vector Position Angle and Faraday Rotation Measure of Each Component

| Object            | Component | 1.663 GHz (deg) | 1.671 GHz (deg) | 4.644 GHz (deg) | 5.095 GHz (deg) | 8.111 GHz (deg) | 8.580 GHz (deg) | Observed RM (rad m$^{-2}$) | Rest-frame RM (rad m$^{-2}$) |
|-------------------|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------------------------|-----------------------------|
| J0928+4446        | A         | 234 ± 9         | 237 ± 9         | 30 ± 3          | 39 ± 3          | 22 ± 2          | 21 ± 2          | 120 ± 7                 | 1012 ± 59                   |
| J1018+0530        | Total     | 339 ± 9         | 340 ± 9         | 107 ± 3         | 111 ± 3         | 96 ± 3          | 87 ± 3          | 139 ± 5                 | 1200 ± 43                   |
| J1159+0112        | D         | 152 ± 9         | 159 ± 9         | ...             | ...             | ...             | ...             | ...                     | ...                         |
| J1405+4056        | A         | ...             | ...             | 101 ± 4         | 114 ± 4         | 91 ± 5          | 94 ± 4          | ...                     | ...                         |
|                   | C         | 14 ± 10          | ...             | ...             | ...             | ...             | ...             | ...                     | ...                         |

J1018+0530, respectively. RM for J1159+0112 and J1405+4056 were not obtained because the detections of polarization only at one or two bands are inadequate to determine the $n$-$\pi$ ambiguity.

5.4. Flux Variability

We examined the flux variability. Between the FIRST survey and the NVSS, we found no significant variability on the basis of significance of variability by defining $\Delta S = |S_1 - S_2|$ and $\sigma_{\text{var}} = (\sigma_1^2 + \sigma_2^2)^{1/2}$, where $S_i$ and $\sigma_i$ are total flux density and its uncertainty of $i$th epoch data, respectively (Table 5). Errors were estimated to be 3% in total flux density (Condon et al. 1998). However, two-epoch observations are not enough to conclude that the sources are stable. J1405+4056 shows $\Delta S > 3\sigma_{\text{var}}$ at 5 GHz between the VIPS and our VLBA observation at 5 GHz; however, we cannot rule out possible effects due to a different $uv$-coverage at the short baselines. Thus, our verification of radio flux variability remains inconclusive.

6. DISCUSSION

6.1. Viewing Angle and Advancing Speed of Jets

Assuming an intrinsic symmetry of the jets, the apparent asymmetry of radio morphology with respect to the central engine results from a Doppler beaming effect. The ratio of flux
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Figure 5. VLBA images of J1405+4056 observed on 2010 June 25 with superposed polarization vectors. Vector lengths are proportional to the polarized flux density (1 mas corresponds to 0.5 mJy beam\(^{-1}\)). (a) The 1.663 GHz Stokes \(I\) map. The restoring beam is \(10 \times 5.4\) mas at P.A. = −11\(^\circ\), the contour levels are \((1, 2, 4, 8, \ldots) \times 0.69\) mJy beam\(^{-1}\), and the peak flux density is 220 mJy beam\(^{-1}\). (b) The 4.644 GHz Stokes \(I\) map. The restoring beam is \(3.5 \times 1.8\) mas at P.A. = −17\(^\circ\), the contour levels are \((1, 2, 4, 8, \ldots) \times 0.94\) mJy beam\(^{-1}\), and the peak flux density is 220 mJy beam\(^{-1}\). (c) The 8.111 GHz Stokes \(I\) map. The restoring beam is \(2.0 \times 1.0\) mas at P.A. = −15\(^\circ\), the contour levels are \((1, 2, 4, 8, \ldots) \times 0.89\) mJy beam\(^{-1}\), and the peak flux density is 192 mJy beam\(^{-1}\).

Figure 6. Radio spectrum of J1159+0112. Observations using VLA (filled circle; Condon et al. 1998; Becker et al. 1995; Montenegro-Montes et al. 2008b), flux density from the Texas survey (filled square at 365 MHz; Douglas et al. 1996), and our observation using VLBA are shown. A triangle means 3\(\sigma\) upper limit at 74 MHz (Cohen et al. 2007). Flux density obtained by our observation is decomposed into that of the radio core (open triangle; the component A) and jets (open circle; the components B–E). A power-law fit to the core flux density (dot-dashed), jet flux density (dashed), and sum of them (thick) are also illustrated. Although our observation was able to set a 3\(\sigma\) upper limit of 0.8 mJy for jet components at 8.3 GHz, it might be underestimated because the source could be resolved out.

6.2. Classification of Radio Sources

It is crucial to distinguish between blazars as pole-on viewed AGN and GPS radio sources as young radio sources for testing...

densities of an approaching to the receding components, \(R_F\), is related to intrinsic jet velocity, \(\beta\), and viewing angle, \(\theta\), by \(R_F = [(1 + \beta \cos \theta)/(1 - \beta \cos \theta)]^{3/2}\) (Blandford & Konigl 1979; Urry & Padovani 1995). In the cases that counter jets were not detected, we apply 3\(\sigma\) noise upper limits. We obtain \(\beta \cos \theta > 0.4\) for J0928+4446, J1018+0530, and J1405+4056, while \(\beta \cos \theta \sim 0.2\) for J1159+0112. As a result, the constraints on \(\beta\) and \(\theta\) are \(0.4 < \beta < 1\) and \(\theta < 66\,^\circ\) for J0928+4446, J1018+0530, and J1405+4056, while \(0.2 < \beta < 1\) and \(\theta < 77\,^\circ\) for J1159+0112 (Figure 9).

Alternatively, we can also obtain \(\beta \cos \theta\) based on a core–jet distance ratio of an approaching to the receding components, given by \(R_D = (1 + \beta \cos \theta)/(1 - \beta \cos \theta)\), which is applied to J1159+0112 with a two-sided structure. The apparent separation from the core (the component A) to a putative approaching component (the component D) is \(\sim 90\) mas and to the receding jet (the component E) is \(\sim 50\) mas. Then, we obtain \(\beta \cos \theta \sim 0.3\) (see Figure 9), which is nearly consistent with the result derived by the flux density ratio. We obtain \(0.3 < \beta < 1\) and \(\theta < 73\,^\circ\) for J1159+0112 (Figure 9).

In summary, we gave moderate constraints of \(\beta > 0.4\) for J0928+4446, J1018+0530, and J1405+4056 and of \(\beta > 0.3\) for J1159+0112 (Figure 9). This indicates that two kinds of outflows are present in BAL quasars in terms of the speed (cf. Doi et al. 2009); one is the relatively fast nonthermal jet and the other one is slower wind (\(\sim 0.1c\)). The model of an accretion disk generating both radiation-force-driven wind (e.g., Proga et al. 1998, 2000; Proga & Kallman 2004) and nonthermal jets with higher speeds (e.g., Ohsuga & Mineshige 2011) should be applied to explain radio-loud BAL quasars. On the other hand, our estimations do not set such tight constraints on the orientation.

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because polarization structures of the sources were simple, we derived RM using EVPA obtained by integrated flux densities of Stokes Q and U maps.

**Figure 7.** Fits of rotation measure for J0928+4446 (left) and J1018+0530 (right).

**Table 5**

| Object            | NVSS 1.4 GHz | FIRST 1.4 GHz | ΔS/σ_{\text{var}} 1.4 GHz | VIPS 5 GHz | Our VLBA 5 GHz | ΔS/σ_{\text{var}} 5 GHz |
|-------------------|--------------|---------------|----------------------------|-------------|----------------|------------------------|
| J0928+4446        | 170.2 ± 5.1  | 162.2 ± 4.9   | 1.1                        | 251.9 ± 12.6| 213.0 ± 10.7   | 2.3                    |
| J1018+0530        | 277.8 ± 8.3  | 296.6 ± 8.9   | 1.6                        | 368.4 ± 18.4| ···             | ···                    |
| J1159+0112        | 275.6 ± 8.3  | 268.5 ± 8.1   | 0.6                        | 126.6 ± 6.3 | ···             | ···                    |
| J1405+4056        | 205.9 ± 6.2  | 214.0 ± 6.4   | 0.9                        | 193.4 ± 9.7 | 244.1 ± 12.2   | 3.3                    |

**Figure 8.** Schematic picture of the geometric relationship between wind and jet on the basis of Elvis (2000). If we constrain our viewing angle, θ, a restriction is also imposed on inclination angle of the wind, θ_{\text{BAL}}. The scale size of each component in the picture is arbitrary.

6.3. Constraints on the AGN Wind

6.3.1. Geometry

The geometry of the AGN wind can be inferred from the viewing angle of the radio jet, which should be perpendicular to the innermost region of the accretion disk. The AGN wind cuts across the line of sight to the central engine and the pc-scale nonthermal jets (Figure 8). The lower end of the range of opening angle for the AGN wind, θ_{\text{BAL}}, should be less than the upper limit of the viewing angle, θ. This constraint will be an intriguing comparison with the theoretical models of an...
accretion disk because the AGN wind is thought to be lifted upward and accelerated to nearly edge-on from the disk by radiation force (Proga et al. 2000). A radio imaging study is one of the most direct ways to test the orientation scheme.

We have set a constraint on $\beta \cos \theta$ for our target sources, using the flux density ratio of an approaching to the receding components. We have also obtained $\beta \cos \theta$ using a core–jet distance ratio for J1159+0112 (Section 6.1). The results are $\beta_{\text{BAL}} < 66^\circ$ for J0928+4446, J1018+0530, and J1405+4056, and $\beta_{\text{BAL}} < 73^\circ$ for J1159+0112 (Figure 9). These estimations give only mild constraints. According to the model presented by Elvis (2000), the AGN wind bends outward to an opening angle of 60$^\circ$ with a divergence of 6$^\circ$ to give a covering factor of 10%. Although our finding of blazar-type BAL quasars strongly indicates pole-on-viewed AGN, the derived inclinations are not strong constraints on the orientation of the AGN wind in the framework of the orientation scheme. Stronger constraints can be obtained in a future observation because the capability of this method depends on an image dynamic range.

### 6.3.2. Column Density

RM is related to physical properties through our line of sight as

$$
\frac{\text{RM}}{1 \text{ m}^2 \text{ rad}} = 25 \left( \frac{B_1}{1 \text{ mG}} \right) \left( \frac{N}{10^{20} \text{ cm}^{-2}} \right),
$$

where $B_1$ and $N$ are strength of averaged magnetic field parallel to the line of sight and column density of thermal plasma, respectively. Since RM is an integral quantity toward polarized sources, the observed RM comprises the contribution from the AGN wind, foreground medium (mainly Galactic contribution), and magnetized plasma associated with a nonthermal jet (e.g., Asada et al. 2002). RM due to the foreground medium contributes $\sim 30$ rad $m^{-2}$ in the case of 45–70$^\circ$ in galactic latitude where our target sources range (Pushkarev 2001). As a result, we estimate RM due to the sources at $|\text{RM}_{\text{rest}}| \sim 1010 \pm 260$ rad $m^{-2}$ and $|\text{RM}_{\text{rest}}| \sim 1200 \pm 260$ rad $m^{-2}$ for J0928+4446 and J1018+0530, respectively. These RM are within the range of values for other radio sources (e.g., Inoue et al. 1995; Zavala & Taylor 2003). Although we cannot set constraints on the density of the AGN wind because the RM contains the contribution from the plasma associated with the jet, further studies with multi-frequency radio polarimetric observations can provide statistical estimates.

### 6.4. Interpretations of the Radio Morphology of J1159+0112

Among four sources presented in this paper, it is notable that J1159+0012 shows multiple components with the extension of more than 100 mas, which corresponds to the projected size of $\sim 1$ kpc. The bright central component with gigahertz-peaked spectrum can be interpreted as the core as often seen in the radio-loud quasars (Blandford & Konigl 1979). However, this source apparently exhibits emissions on both sides of the core while most quasars show a one-side jet structure in VLBI-resolution scale. The components B–D are relatively brighter than component E, suggesting that these components are the approaching jet components and the component E is the receding jet component. The detection of the counter jet implies that the relativistic beaming is not significant at least in the component E. The most likely explanation is that the counter jet is decelerated at the component E as a result of jet termination. Strong polarized emission (11.4% $\pm$ 1.7%) is seen at the component D, and this polarized flux density constitutes the majority of polarized flux density detected by the Very Large Array (VLA). Multi-frequency VLA and single dish observations derived the intrinsic EVPA of 24 $\pm$ 3$^\circ$ which took into account the Faraday rotation (Montenegro-Montes et al. 2008b). The resultant magnetic field direction is 114 $\pm$ 3$^\circ$, which is nearly perpendicular to the position angle of the approaching jet. Since the polarized flux density detected by our VLBA observations is almost equal to that by VLA, this magnetic field direction represents the one at the component D. Both strong polarized flux density and magnetic field perpendicular to the jet are consistent with this feature resulting from the compression of random magnetic field (Laing 1980), such as by shock. This evidence allows us to infer that the components D and E are hot spots produced by the jet termination by ISM (e.g., Dreher 1981; Tsien 1982). It is noted that most radio-loud quasars show two-sided structure at low frequencies (Bridle et al. 1994). Thus, the detection of the counter jet component in J1159+0012 is not surprising. The absence of a counterpart of the components B and C is also naturally explained if both approaching and receding jets are still relativistic before reaching the hot spots. One may think the lack of polarized emission from the component E is against the above scenario but, if the component E possesses a similar level of fractional polarization to the component D, the polarized flux density is only $\sim 1$ mJy, which is too diffuse to be detected by our observation. Besides, the counter jet component could be affected by rather significant Faraday depolarization. We need polarization observations with higher sensitivity, particularly at higher frequency, to confirm the polarized emission from the component E.

This source shows point-like structure on the arcsecond scale (e.g., FIRST survey; Becker et al. 1995). Two-sided structure with an angular size of about 200 mas, the same structure revealed by our observation, is seen on the image at 327 MHz by VLBA (Kanekar et al. 2009), whose total flux density is comparable to that measured by the Texas survey (Douglas et al. 1996) at 365 MHz. Therefore, most radio emission originates in the structure between the components D and E. Even if we assume a small viewing angle as usually inferred for the quasars, for instance 10$^\circ$, the total extent of these radio emissions is $\sim 5$ kpc. This source size is relatively compact as compared to the classical double radio galaxies. If we adopt the typical hot spot velocity in young radio sources (Conway 2002), the kinematic age of this source is $\sim 10^4$–$10^5$ yr.
The source might be the product of a recent episode of jet activity.

Another possible explanation for the core-dominated morphology is the change in Doppler factor and/or intrinsic jet power. One-sided structure represented by the components A1 and A2 both at 5 and 8 GHz (see Figure 4) in the core and two-sided morphology represented by the components D and E on a larger scale can be interpreted as the change in the jet angle to the line of sight. Such a change in jet angle can be attributed to the precession of the jet axis. One relevant observation is the BAL quasar J1048+3457. This source shows a distorted morphology, which is produced by the jet precession (Kunert-Bajraszewska et al. 2010). In contrast, even if the Doppler factor is constant with time, the brightness of the core (the component A) can also be explained by an increase in intrinsic luminosity of jets. The newly ejected component in the core represents that the source might now be in an active phase with an increase in the jet power. In this case, to form the much brighter core as compared to the extended emission, the activity should be intermittent. The activity of the core might cease after the components B–E were ejected. Then, the timescale of the intermittency should be longer than the decay time of the extended components B–E (e.g., Doi et al. 2013). However, the farthest (or the oldest) component is the brightest, and thus some ad hoc ingredients are needed to reconcile this with the intermittency.

7. CONCLUSION

Our VLBA polarimetric imaging for four radio-loud BAL quasars at 1.7, 5, and 8 GHz revealed the pc-scale radio structures of their nonthermal jets. J0928+4446, J1018+0530, and J1405+4056 show one-sided structures in pc scales and polarized emissions in their cores. Although radio flux variability is not confirmed in two-epoch observations, these characteristics are consistent with those of blazars. These three sources are presumably pole-on-viewed AGNs, although our observations with limited image qualities provided only mild constraints on viewing angles that are not sufficient to compete with the orientation scheme. On the other hand, J1159+0112 exhibits a two-sided structure across ~1 kpc and no significant polarization in its central component, which shows an inverted spectrum. These characteristics are consistent with those of young radio sources. The radio spectrum in the integrated flux density can be represented by a hybrid of a megahertz-peaked spectrum component and a gigahertz-peaked spectrum component. There are still several possible explanations for the gigahertz-peaked component and thus further study (e.g., testing the variability) is needed to uncover the nature of the source.

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