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VLBI Detections of Parsec-Scale Nonthermal Jets in Radio-Loud Broad Absorption Line Quasars

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Abstract

We conducted radio detection observations at 8.4 GHz for 22 radio-loud broad absorption line (BAL) quasars, selected from the Sloan Digital Sky Survey Third Data Release, by a very-long-baseline interferometry (VLBI) technique. The VLBI instrument we used was developed by the Optically ConnecTed Array for VLBI Exploration project (OCTAVE), which is operated as a subarray of the Japanese VLBI Network. We aimed to select BAL quasars with nonthermal jets suitable for measuring their orientation angles and ages by subsequent detailed VLBI imaging studies to evaluate two controversial issues of whether BAL quasars are viewed nearly edge-on, and of whether BAL quasars are in a short-lived evolutionary phase of the quasar population. We detected 20 out of 22 sources using the OCTAVE baselines, implying brightness temperatures greater than 10^5 K, which presumably come from nonthermal jets. Hence, BAL outflows and nonthermal jets can be generated simultaneously in these central engines. We also found four inverted-spectrum sources, which are interpreted as Doppler-beamed, pole-on-viewed relativistic jet sources, or young radio sources: single edge-on geometry cannot describe all BAL quasars. We discuss the implications of the OCTAVE observations for investigations for the orientation and evolutionary stage of BAL quasars.

Key words: galaxies: active — galaxies: jets — quasars: absorption lines — radio continuum: galaxies — techniques: interferometric

1. Introduction

Broad absorption line (BAL) quasars are a subclass of active galactic nuclei (AGNs) with rest-frame ultra-violet spectra showing absorption troughs displaced blueward from the corresponding emission lines in the high-ionization transitions of C IV, Si IV, N V, and O IV, and occasionally in low-ionization transitions, e.g., Mg II and Al III (Weymann et al. 1991). The absorption troughs are broader than 2000 km s^{-1}, sometimes as broad as $\sim 0.1c$, and are presumably due to the intervening components of the outflow originating in the activity of central engines. The fact that the most luminous quasars showing BALs more frequently (Ganguly et al. 2007) is consistent with the strong radiation-pressure-driven outflows suggested by simulation-based studies for accretion phenomena (e.g., Proga et al. 2000; Ohsuga 2007). The observed maximum velocity of absorption as function of the luminosity has an upper envelope, which can be interpreted as the terminal velocity of a radiative-driven wind (Ganguly et al. 2007; Laor & Brandt 2002).

The intrinsic percentage of quasars with BALs is $\sim 20\%$ [e.g., Hewett & Foltz 2003; see also a recent result of $17\% \pm 1\%$ (statistical) $\pm 3\%$ (systematic) by Knigge et al. 2008]. This means that the BAL phenomenon takes one of the major roles in the activities of quasars. However, the principal parameter determining the finding of BAL features is still unknown. In the most widely accepted scenario, this percentage represents the covering factor of an outflowing BAL wind, which is preferentially equatorial, and the BAL features can be observed when the accretion disk is almost edge-on to the line of sight, based on spectropolarimetric measurements (Goodrich & Miller 1995; Cohen et al. 1995) and a theoretical disk wind model (Murray et al. 1995). However, some radio observations have provided a counterargument to this paradigm. Zhou et al. (2006) and Ghosh and Punsly (2007) found several BAL quasars with rapid radio variability that indicated very high brightness temperatures, which require Doppler beaming on jets with inclinations of less than 35°, i.e., a nearly face-on view of the accretion disk. Becker et al. (2000) found that about one-third of the radio-detected BAL quasars showed flat radio spectra ($\alpha > -0.5$, $S_\nu \propto \nu^\alpha$), preferring pole-on jets because this geometry tends to make radio sources core-dominated by significant Doppler effect only on nuclear jets. Also, in optical spectropolarimetry, Brotherton, De Breuck, and Schaefer (2006) found an electric vector nearly parallel to a large-scale jet axis, implying that BAL outflow is not equatorial in a Fanaroff–Riley Class II (FR II) radio galaxy as a BAL quasar. Thus, a pole-on outflow would be necessary for at least some of the known radio-emitting BAL quasars. These results support an alternative proposal that BALs are not closely related to inclinations, and may be associated with a relatively short-lived (possibly episodic) evolutionary phase with a large BAL wind-covering fraction (e.g., Briggs et al. 1984; Gregg et al. 2000). Gregg, Becker, and de Vries (2006) pointed out the rarity of FR II/BAL quasars and their observed anticorrelation between the balnicity index and radio loudness, and suggested that these properties can be explained naturally by an evolutionary scheme. Montenegro-Montes et al. (2008) indicated that many radio-emitting BAL quasars share several radio properties common to young radio sources, like Compact Steep Spectrum (CSS) or Gigahertz-Peaked Spectrum (GPS) sources. Thus, the 'inclination angle' and the 'evolutionary phase' are two of the most important aspects for understanding BAL quasars.

Very-long-baseline interferometry (VLBI) instruments in radio wavelengths provide exclusive and crucial opportunities to obtain spatial information about AGNs at milli-arcsecond (mas) scales by direct measurements, which should also be useful for investigating BAL quasars. The inclination can be resolved by determining the viewing angle of the jet axis, which is supposed to be perpendicular to the accretion disk. Using the framework of Doppler beaming effects, jet axes for many AGNs have been estimated by measurements of jet asymmetry (advancing speed, brightness, jet length, etc.) by VLBI imaging. Age as a radio source can also be estimated by measurements of its apparent linear size and expanding speed, or the age of relativistic electrons appearing on the synchrotron spectrum (e.g., Nagai et al. 2006 and references therein). VLBI observations for BAL quasars have recently begun to try to study such phenomena. Jiang and Wang (2003) observed three BAL quasars with the European VLBI Network (EVN) at 1.6 GHz, and suggested that the jet of J1556+3517 was possibly viewed from nearly pole-on because of a flat spectrum and unresolved core, while that of J1312+2319 may have been far from pole-on, because of the two-sided structure, and the inclination of J0957+2356 was unclear because of an unresolved steep-spectrum compact source. Liu et al. (2008) observed eight BAL quasar samples, including both LoBALs and HiBALs and both steep- and flat-spectrum sources, with the EVN+Multi-Element Radio Linked Interferometer Network (MERLIN) at 1.6 GHz. High brightness temperatures and linear polarization in their core components implied a synchrotron origin for the radio emission. No systematic difference was found in the radio morphology or polarization properties between their limited number of LoBAL/HiBAL or steep/flat-spectrum sources. Kunert-Bajraszewska and Marecki (2007) observed 1045+352 with the US Very Long Baseline Array (VLBA) at 1.7, 5, and 8.4 GHz, and found a complicated radio morphology and a projected linear size of only 2.1 kpc, which suggests it might be in an early stage, consistent with the evolutionary scenario. These investigations were still inconclusive because the detected jet structures, spatial resolutions, and frequency coverages were inadequate to definitively determine jet properties, and also because of still a small number of objects to conclude the natures of BAL quasars.

In this paper, we report on our VLBI observations of 22 BAL quasars at 8.4 GHz by direct measurements at the mas resolution, corresponding to the parsec scale at the distance to these sources. Our aim is to find BAL quasars that have jets suitable for determining their orientation angles and ages from jet properties for future detailed VLBI imaging studies. In section 2, we describe our selection processes, and present our observations and data-reduction procedures in section 3. We present the observational results in section 4, and discuss their implications in section 5. In section 6, we summarize the outcome of our investigation. Throughout this paper, a flat cosmology is assumed, with $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\mathrm{M} = 0.3$, and $\Omega_\Lambda = 0.7$ (Spergel et al. 2003).

2. Sample

The Sloan Digital Sky Survey (SDSS) Third Data Release (DR3: Abazajian et al. 2005) cataloged 46420 quasars (Schneider et al. 2005), including 4784 BAL quasars (Trump et al. 2006). In the catalog of the Very Large Array (VLA) 1.4-GHz Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey (Becker et al. 1995), we searched for radio counterparts with > 1 mJy located within $10''$ of these SDSS BAL quasars. This search radius was significantly large relative to the position uncertainties of the SDSS and FIRST ($\sim 1''$), in order to rescue even moderately resolved lobe-dominated radio sources. Of all the SDSS BAL quasars, 91.4% (4374/4784) were in the regions of the sky covered by the FIRST survey, and we found 492 radio sources

Table 1. Optically-selected, radio-flux-limited BAL quasar sample for OCTAVE observation.*

SDSS name (1)	FIRST name (2)	$r_{\rm FIRST}^{\rm SDSS}$ (arcsec) (3)	z (4)	l (pc mas^{-1}) (5)	BAL type (6)	$M_i^{\rm SDSS}$ (mag) (7)	$I_{\rm 1.4GHz}^{\rm FIRST}$ (mJy beam^{-1}) (8)	$S_{\rm 1.4GHz}^{\rm FIRST}$ (mJy) (9)	log $R*$ (10)
SDSS J004323.43−001552.4	FIRST J004323.8−001548	7.6	2.798	7.9	H	−27.94	103	115	2.7
SDSS J021728.62−005227.2	FIRST J021728.6−005226	0.3	2.463	8.1	H	−25.98	212	218	3.7
SDSS J075628.24+371455.6	FIRST J075628.2+371455	0.3	2.514	8.1	HL?	−26.10	239	247	3.7
SDSS J080016.09+402955.6	FIRST J080016.0+402955	0.5	2.021	8.4	Hi	−26.80	190	200	3.1
SDSS J081534.16+330528.9	FIRST J081534.1+330529	0.5	2.426	8.1	nH	−27.04	328	342	3.4
SDSS J092824.13+444604.7	FIRST J092824.1+444604	0.0	1.904	8.4	nHi	−27.16	156	162	2.8
SDSS J100515.98+480533.2	FIRST J100515.9+480533	0.2	2.372	8.2	Hi	−28.29	206	209	2.7
SDSS J101329.92+491840.9	FIRST J101329.9+491841	0.2	2.201	8.3	nHi	−26.86	267	269	3.3
SDSS J101827.85+053030.0	FIRST J101827.8+053029	0.2	1.938	8.4	Hi	−26.62	284	297	3.3
SDSS J102027.20+432056.2	FIRST J102027.2+432056	0.2	1.962	8.4	nHi	−26.74	108	110	2.9
SDSS J103038.38+085324.9	FIRST J103038.3+085324	0.6	1.750	8.5	nHi	−26.57	108	172	3.0
SDSS J104257.58+074850.5	FIRST J104257.5+074850	0.3	2.665	8.0	H	−27.32	374	382	3.5
SDSS J105726.62+032448.0	FIRST J105726.6+032448	0.5	2.832	7.3	H	−26.90	138	157	3.2
SDSS J110344.53+023209.9	FIRST J110344.5+023209	0.2	2.514	8.1	H	−27.63	163	166	2.9
SDSS J111914.32+600457.2	FIRST J111914.3+600457	0.1	2.646	8.0	nH	−28.97	186	192	2.5
SDSS J115944.82+011206.9	FIRST J115944.8+011206	0.2	2.000	8.4	Hi	−28.40	267	268	2.6
SDSS J122343.16+503753.4	FIRST J122343.1+503753	0.1	3.488	7.3	H	−29.21	222	229	2.7
SDSS J122836.92−030439.2	FIRST J122836.9−030438	0.7	1.801	8.4	nHi	−26.53	144	149	3.0
SDSS J140507.80+405657.8	FIRST J140507.7+405658	0.3	1.993	8.4	Hi	−26.31	206	214	3.3
SDSS J143243.29+410327.9	FIRST J143243.3+410328	0.4	1.970	8.4	nHi	−27.84	257	262	2.8
SDSS J151005.88+595853.3	FIRST J151005.4+595856	4.3	1.720	8.5	nHi	−27.05	182	307	3.1
SDSS J152821.65+531030.4	FIRST J152821.6+531030	0.4	2.822	7.8	H	−26.37	172	183	3.6

* Col. (1) SDSS source name; Col. (2) Radio counter part from FIRST; Col. (3) Difference between SDSS–FIRST positions; Col. (4) Redshift; Col. (5) Linear scale corresponding to 1 mas; Col. (6) BAL subtype, listed in Trump et al. (2006). The code "n" denotes a relatively narrow trough; "HL" denotes a HiBAL in which broad ($\geq 1000\,{\rm km\,s^{-1}}$) low-ionization absorption is also seen; "Hi" denotes a HiBAL-only object, in which broad low-ionization absorption is not seen even though Mg II is within the spectral coverage; and "H" denotes a HiBAL in which the Mg II region is not within the spectral coverage of SDSS or has a very low signal-to-noise ratio and so whether or not the object is a LoBAL as well as a HiBAL is unknown; Col. (7) i-band absolute magnitude listed in Trump et al. (2006) and calculated using a flat cosmology of $H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_{\rm M} = 0.27$, and $\Omega_\Lambda = 0.73$ (Spergel et al. 2003); Col. (8) 1.4 GHz peak intensity from FIRST data with a $\sim 5''$ resolution; Col. (9) 1.4 GHz flux density from FIRST data; Col. (10) Radio loudness, the ratio of radio-to-optical flux densities, $R* = f_{\rm 5GHz}/f_{2500\,\rm Å}$ (e.g., Stocke et al. 1992), which were calculated from z, $S_{\rm 1.4GHz}^{\rm FIRST}$, M_i, and the assumption of a radio spectral index of −0.5 and an optical spectral index of −0.5.

Table 2. Observing sessions.*

Date (Time) (1)	Telescopes (2)	Targets (3)	Flux reference (4)
2007 Nov 04 (14:00–16:30UT)	UYT	0756+371 0800+402 0815+330 0928+444 1005+480 1013+491 1020+432 1119+600	DA 193 (4.39 Jy)
2007 Dec 02 (05:40–12:00UT)	UYTK	0043−001 0217−005 1223+503 1405+405 1432+410 1510+595 1528+531	NRAO 512 (1.62 Jy)
2008 Feb 09 (19:00–20:30UT)	UYT	1018+053 1030+085 1042+074 1057+032 1103+023 1159+011 1228−030	OJ 287 (2.55 Jy)

* Col. (1) Observation date (and time); Col. (2) Telescopes used: "U" denotes Usuda 64 m, "Y" denotes Yamaguchi 32 m, "T" denotes Tsukuba 32 m, and "K" denotes Kashima 34 m; Col. (3) Truncated name of target source; Col. (4) Flux calibrator used for amplitude scaling.

corresponding to 11.2% of the SDSS BAL quasars. Most of them were unresolved at a spatial resolution of $\sim 5''$ of the FIRST, suggesting intrinsic sizes of less than $1''$ at the FIRST image sensitivity (see also Zhou et al. 2006). We selected out 23 sources with > 100 mJy. Except for three sources, these radio sources were found with separations of $< 1''$. FIRST J004323.8−001548 and FIRST J151005.4+595856 showed separation angles of $7''\!.6$ and $4''\!.3$ from their optical positions, respectively. The two sources had significantly resolved radio structures, which provide relatively large separations; FIRST J004323.8−001548 had already been identified as an FR II–BAL quasar by Gregg et al. (2006). FIRST J103434.4+592445 was found at $9''\!.9$ from SDSS J103433.49+592452.3; this was probably a misidentification because an another optical source, SDSS J103434.20+592445.8 (a candidate of gravitational lensing), was a much more likely source for the FIRST source. Hence, we have removed this source from the list. Finally, our optically-selected, radio-flux-limited sample for the present VLBI observations consists of 22 sources (table 1).

The redshift range is 1.72–3.488 with a median of ~ 2.2 for the 22 selected BAL quasars. The luminosity and angular distances are 17456 Mpc and 1705 Mpc at $z = 2.2$, respectively. An angular scale of 1 mas corresponds to a linear scale of 8.3 pc at $z = 2.2$ (see table 1 for individual sources). We determined radio loudness according to the definition of the ratio of radio-to-optical flux densities, $R* = f_{5\mathrm{GHz}}/f_{2500\mathrm{Å}}$ (e.g., Stocke et al. 1992), which was calculated from the redshift, z, the FIRST flux density, and the SDSS i-band absolute magnitude, assuming $\alpha = -0.5$ for the radio and optical spectral indices (see table 1). All of our samples were very radio-loud ($\log R* \geqq 2.5$; cf. the extensive study of radio-loudness for FIRST/SDSS sources by Ivezić et al. 2002). This definition may somewhat exaggerate the radio loudness of BAL quasars with substantial optical reddening. The largest extinction, $A_i = 0.22$ mag, was estimated from $E(B - V) = 0.114$ on SDSS J080016.09+402955.6 in the sample, and exaggerates the radio loudness by $\log \Delta R* \approx 0.1$. It is also useful to consider the rest-frame monochromatic radio luminosity, where $L_{5\mathrm{GHz}} > 10^{25}$ W Hz^{-1} distinguishes radio quasars (e.g., Miller et al. 1993). Our samples have $L_{5\mathrm{GHz}} \sim 10^{27}$–$10^{28}$ W Hz^{-1}, assuming $\alpha = -0.5$, and we diagnose them as radio-loud objects.

3. Observations and Data Analysis

We observed the selected 22 BAL quasars using an optical-fiber-linked real-time VLBI instrument constructed by the Optically ConnecTed Array for VLBI Exploration project (OCTAVE: Kawaguchi 2008) and operated as a subarray of the Japanese VLBI Network (JVN: Fujisawa 2008). OCTAVE connects six radio telescopes, the Usuda 64 m, Nobeyama 45 m, Kashima 34 m, Yamaguchi 32 m, Tsukuba 32 m, and Gifu 11 m, using optical fibers at 2.4 Gbps, and offers mJy-level fringe detection sensitivities. Its high baseline sensitivities are crucial for efficient exploration of the VLBI-detectability of a large number of weak radio populations, such as BAL quasars, in preparation for detailed imaging studies.

Observations were performed in three sessions (table 2) using the Usuda 64 m, Kashima 34 m, Yamaguchi 32 m, and Tsukuba 32 m telescopes, which had 8.4-GHz receiving systems in the OCTAVE array. Radio signals of left-hand circular polarization were received and amplified with cooled low-noise amplifiers (LNAs) on each antenna. An analog bandpass filter put through a bandwidth of 512 MHz (8192–8704 MHz), which was sampled into 2 bits (4 levels) at 1 Gsps using the ADS-1000 sampler. The sampled data were transmitted directly through optical fibers to dedicated real-time processing correlator units at the National Astronomical Observatory of Japan (NAOJ), Mitaka, Tokyo. The correlated data were converted into the Flexible Image Transport System (FITS) format for analysis using the Astronomical Image Processing System (AIPS: Greisen 2003) software. We were able to obtain all final results within one hour after the end of an observation.

The scan period for each target was 10 minutes, including an antenna slew, resulting in on-source integration of $\sim$8.0–9.5-minutes. One short scan on a flux calibrator, which is an almost perfectly point radio source in the OCTAVE baselines, was also performed during each session (see table 2). The flux densities of the flux calibrators were also measured using a single-dish mode on the Yamaguchi 32 m telescope within several days before or after the VLBI observations. The flux-calibrator scan determined antenna-gain ratios relative to each telescope and an absolute amplitude scaling factor at the time of the scan. System-noise temperatures were monitored at each antenna to correct the time variation of sensitivities. Such a method can achieve amplitude calibrations with a dispersion of $< 5\%$ for antenna-gain ratios and an uncertainty of $\sim 10\%$ for absolute flux scaling, according to past Japanese VLBI Network observations at 8.4 GHz (e.g., Doi et al. 2006, 2007). The visibility data, which had been fringe-fitted and bandpass-calibrated, were averaged over frequency.

We performed a non-imaging analysis for these calibrated data. We simply applied a model-fitting to the visibility amplitudes of each baseline with a structure model of a Gaussian profile. Free parameters of the Gaussian were the peak amplitude and the full width at half maximum (FWHM). OCTAVE had baselines in the range of 1.5–25 Mλ, resulting in a sensitivity to sources' FWHM sizes ranging from ~ 2 to 30–100 mas. Because all of the baselines are almost in the east–west direction, our one-scan snapshot for each target had sensitivity to the source's brightness profile roughly in one direction only. The calibration uncertainty was less than 5% in terms of the amplitude gains relative to each antenna, and baseline sensitivities of 0.4–1.4 mJy. To avoid amplitude biases due to low signal-to-noise ratios, we time-averaged the visibilities with time intervals sufficient to improve the signal-to-noise ratios to more than 10 in the cases of weak sources.

The results of the model-fitting are listed in table 3. The source sizes of targets detected in more than one baseline could be measured straightforwardly. For FIRST J004323.8−001548 and FIRST J080016.0+402955, we could not determine the source sizes, because no fringe was detected in any baseline. For FIRST J021728.6−005226 and FIRST J152821.6+531030, only the shortest baselines could detect fringes, which provided lower limits of the source sizes, and also provided upper limits with the possibly reliable assumption that their total flux densities were equivalent to their FIRST peak intensities. For FIRST J100515.9+480533, model-fitting cannot be done because its visibility profile was quite different from a simple Gaussian. Hence, we determined only an upper limit to its source size based on the detections with these baselines. For FIRST J111914.3+600457, no model-fitting could be applied because data from only one baseline were available, due to trouble with the third antenna at that time. We determined an upper limit to its source size in the same manner as in the case of FIRST J100515.9+480533.

4. Results

With the OCTAVE baselines, we detected 20 of the 22 FIRST/SDSS BAL quasars. Our OCTAVE observations provided baseline detection limits of brightness temperatures, $T_{\rm B}$, of 10^5–10^6 K for a $\sim$9-minute scan period. The brightness temperatures were calculated from

$$T_{\rm B} = 1.8 \times 10^9 (1+z) \frac{S_\nu}{\nu^2 \phi^2} \quad (1)$$

in kelvin, where z is the redshift, S_ν is the flux density in mJy at frequency ν in GHz, and ϕ in mas is the fitted FWHM of the source size (cf. Ulvestad et al. 2005). We derived the resolved sizes for 11 sources at mas scales ranging over 1.5–10 mas, implying that $T_{\rm B} = 10^{7.1}$–$10^{9.6}$ K. Five sources were unresolved ($\lesssim 2$ mas) with the OCTAVE baselines, implying $T_{\rm B} \gtrsim 10^8$ K. The sensitivity in the determination of the brightness temperature for each source depends on the projected baseline lengths, the signal-to-noise ratio, the uncertainty in the amplitude calibration, and any discrepancy between the two-dimensional intrinsic source profile and the one-dimensional fitting model (see section 3). For FIRST J100515.9+480533, the visibility profile cannot be represented by a simple Gaussian, which may suggest the existence of multiple components with comparable fluxes at the mas scale. A complicated structure was inferred in this BAL quasar.

We also show two-point spectral indices between the FIRST 1.4-GHz peak intensities and the maximum correlated flux densities of the OCTAVE at 8.4 GHz (table 3). We used the peak intensities rather than the total flux densities at 1.4 GHz to extract the emitting components as close to the nuclei as possible. The FIRST data were obtained with a $\sim 5''$-resolution, which is much larger than that of the OCTAVE; thus, the resolution effect could occur in deriving the spectral indices. Note that the derived spectral indices provide only lower limits, if any of the radio emitting components in a source lies outside a region within ~ 10 mas. For this reason, we can be confident of the detections of inverted spectra ($\alpha > 0$). On the other hand, we cannot determine whether steep spectra ($\alpha < 0$) were results of an intrinsic nature or a resolution effect. In the 22 targets, we found inverted spectra in four sources. Note that the derivations of the spectral indices could also be affected by the flux variability, as ~ 10 years elapsed between the FIRST and OCTAVE observations. We discuss this possibility later.

5. Discussion

5.1. *Coexistence of Nonthermal Jet and BAL Outflow*

We detected 20 radio sources using OCTAVE baselines, which assured brightness temperatures of greater than 10^5–10^6 K. Although the brightness temperature of a radio supernova at a very early stage could exceed $T_{\rm B} = 10^6$ K (e.g., Bietenholz et al. 2001), its expected flux density would be far from sufficient for fringe detection for such distant quasars in our sample (cf. Van Dyk et al. 1993). The brightness temperatures of stellar components of luminous starbursts are $\lesssim 10^5$ K (cf. Lonsdale et al. 1993), which are less than those of the detected radio counterparts of BAL quasars. Also, in terms of the radio luminosity, even the most radio-luminous starbursts show up to only $\sim 10^{24}$ W Hz^{-1} (e.g., Smith et al. 1998), in contrast to $\sim 10^{27}$–10^{28} W Hz^{-1} for our BAL quasar sample. Therefore, the OCTAVE-detected radio emissions cannot be accounted for by any stellar origin. We conclude that the OCTAVE-detected radio emissions of the BAL quasars originate in nonthermal jets from AGN activity, as in the cases of other AGN radio sources. VLBI observations previously conducted (Jiang & Wang 2003; Kunert-Bajraszewska & Marecki 2007; Liu et al. 2008) also support the existence of nonthermal jets in BAL quasars.

The fairly high VLBI-detection rate (20/22) is evidence that BAL outflows, which are inferred from broad troughs in UV spectra, can coexist with nonthermal jets in radio-loud BAL quasars. This indicates that the accretion disks of BAL quasars can generate radiation-pressure driven strong

Table 3. Results of OCTAVE observations for 22 BAL quasars.*

Source	$S_{8.4\mathrm{GHz}}^{\mathrm{cor}}$ (mJy)	B_{uv} (Mλ)	$S_{8.4\mathrm{GHz}}^{\mathrm{fit}}$ (mJy)	$\phi_{\mathrm{FWHM}}^{\mathrm{fit}}$ (mas)	$\phi_{\mathrm{FWHM}}^{\mathrm{fit}}$ (pc)	$\log(T_{\mathrm{B}})$ (K)	$I_{1.4\mathrm{GHz}}^{\mathrm{FIRST}}$ (mJy)	$\alpha(I_{1.4\mathrm{GHz}}^{\mathrm{FIRST}} - S_{8.4\mathrm{GHz}}^{\mathrm{cor-max}})$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0043−001†	<9.9	1.5	—	—	—	—	103	—
	<3.4	4.3						
	<4.6	5.8						
	<2.6	17.4						
	<5.5	21.5						
	<7.4	22.9						
0217−005‡	43	1.5	—	42–92	340–750	4.5–5.2	212	−0.9
	<3.4	4.4						
	<4.6	5.9						
	<2.6	18.7						
	<5.5	22.9						
	<7.4	24.3						
0756+371	140	3.0	139 ± 14	2.0 ± 0.6	16 ± 5	8.9	239	−0.3
	133	10.0						
	133	12.8						
0800+402†	<3.4	3.3	—	—	—	—	190	—
	<2.6	11.2						
	<5.5	14.2						
0815+330	30	2.8	31 ± 4	7.5 ± 0.7	61 ± 6	7.1	328	−1.3
	20	9.0						
	18	11.4						
0928+444	314	3.2	315 ± 32	1.5 ± 0.2	13 ± 2	9.6	156	+0.4
	311	9.6						
	305	12.7						
1005+480§	16	3.4	—	<51	<420	>5.0	206	−1.3
	21	10.3						
	20	13.6						
1013+491	90	3.4	97 ± 10	8.7 ± 0.1	72 ± 1	7.5	267	−0.6
	49	10.5						
	28	13.9						
1018+053	554	2.6	555 ± 56	2.2 ± 0.1	19 ± 1	9.5	284	+0.4
	530	10.5						
	520	12.8						
1020+432	196	3.1	234 ± 92	9.9 ± 2.4	83 ± 20	7.8	108	+0.3
	191	9.0						
	62	12.1						
1030+085	66	2.6	65 ± 8	3.0 ± 1.2	25 ± 10	8.3	108	−0.3
	56	11.2						
	59	13.5						
1042+074	131	2.6	133 ± 18	7.2 ± 0.5	58 ± 4	7.8	374	−0.6
	62	10.5						
	50	12.8						
1057+032	23	2.8	23 ± 3	5.8 ± 0.8	42 ± 6	7.2	138	−1.0
	15	11.2						
	15	13.8						
1103+023	71	2.8	72 ± 7	4.7 ± 0.3	38 ± 3	7.9	163	−0.5
	56	10.9						
	52	13.4						
1119+600‖	102	3.9	—	< 21	< 170	>5.5	186	−0.3
	—	—						
	—	—						

Table 3. (Continued)

Source (1)	$S^{\rm cor}_{\rm 8.4GHz}$ (mJy) (2)	B_{uv} (Mλ) (3)	$S^{\rm fit}_{\rm 8.4GHz}$ (mJy) (4)	$\phi^{\rm fit}_{\rm FWHM}$ (mas) (5)	$\phi^{\rm fit}_{\rm FWHM}$ (pc) (6)	$\log(T_{\rm B})$ (K) (7)	$I^{\rm FIRST}_{\rm 1.4GHz}$ (mJy) (8)	$\alpha(I^{\rm FIRST}_{\rm 1.4GHz} - S^{\rm cor-max}_{\rm 8.4GHz})$ (9)
1159+011	170	3.4	169 ± 17	< 0.7	< 6	> 9.9	267	−0.3
	168	13.3						
	170	16.5						
1223+503	102	3.5	105 ± 15	< 2.1	< 15	> 8.8	222	−0.4
	113	17.5						
	96	21.1						
1228−030	222	3.6	222 ± 22	< 2.0	< 17	> 9.2	144	+0.2
	224	13.9						
	224	17.4						
1405+405	179	2.8	182 ± 24	< 2.4	< 20	> 8.9	206	0.0
	193	15.6						
	170	18.4						
1432+410	45	2.9	46 ± 5	5.3 ± 0.1	45 ± 1	7.6	257	−1.0
	26	15.6						
	21	18.4						
1510+595	18	3.8	19 ± 3	< 2.5	< 21	> 7.9	182	−1.2
	20	18.1						
	17	21.9						
1528+531‡	12	3.6	—	7.9–51	62–400	5.0–6.6	172	−1.5
	< 2.6	17.4						
	< 5.5	21.0						

* Col. (1) Truncated name of target source; Col. (2) Correlated flux density; Col. (3) Projected baseline length; Col. (4) Fitted flux density of a Gaussian profile (see sections 3 and 4); Col. (5) Fitted FWHM size of a Gaussian profile; Col. (6) Fitted FWHM in pc; Col. (7) Brightness temperature calculated using equation (1); Col. (8) FIRST 1.4 GHz peak intensity, the same as in table 1; Col. (9) Spectral index between 1.4 and 8.4 GHz, calculated from the FIRST peak intensity and the maximum correlated flux density.

† Undetected at all baselines, indicating a 7σ upper limit of the shortest baseline.

‡ Detected only at the shortest baseline.

§ Complex visibility profile, cannot be fitted with a Gaussian.

‖ Only a single baseline observation.

outflows and magnetic-driven strong jets simultaneously. It is important to investigate the relationship between the properties of the BAL features and the radio emissions (cf. Ghosh & Punsly 2007) to understand accretion phenomena in quasars.

5.2. *Jet Properties of Observed BAL Quasars — Inverted-Spectrum Sources*

We found four inverted-spectrum ($\alpha > 0$) sources [column (9) in table 3]. Since optically-thin nonthermal synchrotron emissions should show a steep spectrum of $\alpha \leqq -0.5$, the observed inverted spectra should result from a lower-frequency absorption mechanism if a non-simultaneous spectral index is not affected by the flux variability. Absorbed components should dominate the total spectrum for an inverted spectrum to be observed, even using the FIRST beam width. Hence, an inverted spectrum suggests three possibilities: (1) a Doppler beaming effect on jets, (2) a young (compact) radio source, or (3) artificially made due to the flux variability, as follows.

Doppler boosting can apparently enhance only optically-thick nuclear components beyond extended jets that would have been decelerated and optically-thin; the nuclear components tend to be synchrotron self-absorbed because of high-brightness temperatures, and show an inverted spectrum at lower frequencies. An adequate Doppler beaming effect requires jets that are nearly aligned with our line-of-sight; this implies a face-on viewed accretion disk, which is inconsistent with the widely accepted scheme of equatorial BAL outflows. The presence of a Doppler beaming effect has already been inferred from the rapid flux variation between the NRAO VLA Sky Survey (NVSS: Condon et al. 1998) and the FIRST in several BAL quasars (Zhou et al. 2006; Ghosh & Punsly 2007). It is important to also confirm the Doppler beaming by VLBI imaging in the future.

Young radio sources can also make their spectra nuclear-dominated, because extended jets would not yet have been developed. Radio sources of ~ 100–1000 pc or less could show peaked spectra, resulting in inverted spectra possibly at ~ 1 GHz; the spectral-peak frequency is roughly determined by the linear size of the radio structure (e.g., Snellen et al. 2000). Explanations of the relation between the linear size and the spectral-peak frequency have been suggested using synchrotron self-absorption (O'Dea & Baum 1997) and free–free absorption (Bicknell et al. 1997). Montenegro-Montes et al. (2008) presented many radio sources of BAL quasars showing such peaked spectra. The ages could be determined from the linear size and the expanding speed of the radio structures; it is important to measure the expanding speed by a VLBI-imaging monitor in the future. For example, on a typical VLBI scale, an apparent expanding rate of 0.1 mas yr^{-1} and a linear size of a two-sided structure of 100 pc leads to an estimated age of 500 yr. This situation can be adapted to the evolutionary scenario of BAL quasars in a relatively short-lived phase (e.g., Briggs et al. 1984; Gregg et al. 2000; and see also Gregg et al. 2006).

Inverted spectra artificially-made due to a flux variability between the observations of the OCTAVE at 8.4 GHz and the VLA at 1.4 GHz (~ 10 yr) cannot be ruled out. BAL quasars of a significant fraction are in the radio band (Zhou et al. 2006; Ghosh & Punsly 2007). A flux variability of $> 10\%$ in 10 yr at 8.4 GHz for a 100-mJy source at $z = 2$ implies $T_{\mathrm{B}} > 10^{11.3}$ K, which would be above the inverse-Compton limit (Readhead 1994) and require a Doppler beaming effect. A flux variability of 10% corresponds to a change in the spectral index of only ~ 0.05. That means that even if the observed spectra had been artificially made, we reach the same conclusion that the four inverted-spectrum sources are possibly Doppler-boosted. As a result, we conclude that the inverted-spectrum sources are interpreted as being Doppler-beamed, pole-on-viewed relativistic jet sources or young radio sources, such as CSSs and GPSs; single edge-on geometry cannot descibe all BAL quasars.

We also checked the flux variation between NVSS and FIRST at 1.4 GHz for our BAL quasar sample. Using the same procedure as that of Ghosh and Punsly (2007), we found two sources, FIRST J075628.2+371455 and FIRST J122836.9−030438, with significant flux variations of $4.8\,\sigma$ and $3.2\,\sigma$; brightness temperatures were derived to be more than $10^{15.3}$ K and $10^{13.2}$ K, respectively. Both of the radio sources were very compact (2 mas or less) in the OCTAVE observations, and the latter showed an inverted spectral index ($\alpha = +2.0$). These situations are consistent with the presence of highly Doppler boosting in pole-on jets. It is important to also confirm them by VLBI imaging in the future.

5.3. Jet Properties of Observed BAL Quasars — Steep-Spectrum Sources

The majority of detected BAL quasars showed steep ($\alpha < 0$) radio spectra. It was unclear whether the weaker radio flux densities were observed at 8.4 GHz because extended structures were resolved out, or were due to intrinsically steep spectra on compact components. Hence, we do not discuss any further in detail the OCTAVE results. We have already stressed the importance of VLBI imaging observations for inverted-spectrum sources, and steep-spectrum sources are also needed to be VLBI-observed because they are the majority of BAL quasars, and are also compact in most cases (Becker et al. 2000). The correlated flux densities in the OCTAVE baselines were not much smaller than 10^{-1}-times the VLA peak intensities in most sources, despite the fact that the beam area of OCTAVE was $\sim 10^{-5}$-times that of VLA. This indicates that the radio-emitting origins considerably concentrated in parsec-scale components, which should be investigated using VLBI. As the evolutionary scenario, BAL quasars might associate with young radio sources (Briggs et al. 1984; Gregg et al. 2000, 2006), which should be optically-thin small radio lobes seen in compact steep spectrum (CSS: O'Dea 1998 for a review) objects. Many CSS sources have been revealed as young ($< 10^5$ yr) radio galaxies by VLBI-imaging studies (e.g., Murgia 2003; Nagai et al. 2006). VLBI-imaging studies may provide evidence supporting the evolutionary scenario for BAL quasars, if the steep-spectrum radio sources of BAL quasars are CSS objects (Kunert-Bajraszewska & Marecki 2007).

5.4. Implications of OCTAVE Observations

Our OCTAVE observations have many implications for studying BAL quasars. VLBI images of only four BAL quasars had been published before the OCTAVE observations (Jiang & Wang 2003; Kunert-Bajraszewska & Marecki 2007). Our OCTAVE observations have dramatically increased the number of VLBI-detected BAL quasars, and have established that this AGN subclass includes a non-trivial number of radio-loud objects that can be directly imaged at mas resolutions (corresponding to parsec scales) as well as objects in the other AGN classes. The orientation angle and the age as radio sources of BAL quasars should be determined from the jet properties in subsequent detailed VLBI imaging studies. OCTAVE strongly recommends that multi-epoch and multi-frequency (and polarimetric) VLBI observations should be performed for these sources. Multi-epoch imaging can measure the proper motion of jets or lobes to estimate the inclination or kinematic age. Multi-frequency imaging can measure the spectral-index profiles along approaching and receding jets or lobes, which can discriminate between Doppler-boosted self-absorbed jets and free–free absorbed jets obscured by a thermal plasma. BAL outflows could be free–free absorber along nonthermal jets; the projected one-dimensional profile of thermal BAL outflows could be studied in mas resolutions using VLBIs at multi-frequency by measuring opacity gradient along the jets. The free–free absorber could also cause Faraday rotation to the vector of polarization axis toward the jets, which is an another powerful tool to investigate the spatial profile of thermal BAL outflows. In multi-frequency VLBI observations, such processes should offer exclusive probes to the parsec-scale profile of BAL outflows. On the basis of the results of OCTAVE observations, we are observing some of the OCTAVE sample by multi-frequency VLBI imaging. It will be important to compare the results of inclination measurements based on the VLBIs and optical spectropolarimetry, and to investigate the relation among UV/optical spectra, pc-scale geometry, and ages.

6. Summary

Two of the most important questions for understanding BAL quasars are: (1) Are they viewed at nearly edge-on? (2) Are they in a short-lived evolutionary phase? Our OCTAVE observations have increased the number of VLBI-detected BAL quasars, which offers a better chance to determine their orientations and ages by subsequent VLBI-imaging studies to conclude the two pictures. We detected 20 out of the radio-brightest 22 sources selected from the counterparts of SDSS BAL quasars. We concluded that nonthermal pc-scale jets and thermal BAL outflows can coexist in these radio-loud BAL quasars simultaneously. BAL quasars have become targets of VLBIs to be revealed on the pc scale by direct imaging, as in the cases of other AGN classes. We also found four inverted-spectrum sources, which are interpreted as being Doppler-beamed, pole-on-viewed relativistic jet sources or young radio sources: single edge-on geometry cannot describe all BAL quasars.

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