The compact structure of radio-loud broad absorption line quasars

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Accepted 2008 August 14. Received 2008 August 14; in original form 2008 April 28

ABSTRACT
We present the results of EVN+MERLIN very long baseline interferometry (VLBI) polarization observations of eight broad absorption line (BAL) quasars at 1.6 GHz, including four low-ionization BAL quasars (LoBALs) and four high-ionization BAL quasars (HiBALs) with either steep or flat spectra on Very Large Array (VLA) scales. Only one steep-spectrum source, J1122+3124, shows two-sided structure on the scale of 2 kpc. The other four steep-spectrum sources and three flat-spectrum sources display either an unresolved image or a core–jet structure on scales of less than 300 pc. In all cases, the marginally resolved core is the dominant radio component. Linear polarization in the cores has been detected in the range of a few to 10 per cent. Polarization, together with high brightness temperatures (from 2×109 to 5×1010 K), suggests a synchrotron origin for the radio emission. There is no apparent difference in the radio morphologies or polarization between low-ionization and high-ionization BAL quasi-stellar objects (QSOs) or between flat- and steep-spectrum sources. We discuss the orientation of BAL QSOs with both flat and steep spectra, and consider a possible evolutionary scenario for BAL QSOs. In this scenario, BAL QSOs are probably a young population of radio sources that are compact steep spectrum or GHz peaked radio source analogues at the low end of radio power.

Key words: galaxies: active – galaxies: jets – quasars: absorption lines – quasars: general.

1 INTRODUCTION
About 10–20 per cent of optically selected quasars exhibit broad absorption line (BAL) troughs up to ~0.1c blueward of their corresponding emission lines (Weymann et al. 1991; Tolea, Krolik & Tsvetanov 2002; Weymann 2002; Hewett & Foltz 2003; Reichard et al. 2003; Knigge et al. 2008). These BALs are produced via resonant scattering in partially ionized outflows. BAL quasars can be further divided into high- and low-ionization subclasses (HiBALs and LoBALs). HiBAL quasars are those objects which show BALs only in highly ionized species such as C iv and N v, while LoBAL quasars also show BALs in Mg ii or Al iii. Two different scenarios have been proposed to explain the BAL phenomena. In the first scenario, the BAL region (BALR) is present with a small covering factor in every quasi-stellar object (QSO). The different appearance of BAL and non-BAL QSOs is solely due to different lines of sight. In a BAL QSO, our line of sight intercepts the BALR while it does not in non-BAL QSOs. In this scenario, the fraction of BAL QSOs is interpreted as the covering factor of BALRs. This paradigm has also been generalized to interpret the dichotomy of LoBAL and HiBAL as an orientation effect, in which a low-ionization outflow covers a small fraction of sky with the BAL outflow. This scenario is consistent with a number of statistical properties, such as the similarity between the ultraviolet continuum and emission line spectra for both types of QSOs (e.g. Weymann et al. 1991), their similar millimetre and far-infrared luminosities (e.g. Willott, Rawlings & Grimes 2003), as well as their similar large-scale environments (Shen et al. 2008). In the second scenario, BALs exist only in a relative short phase of QSO activity, which is very likely in their early phase of evolution, at least for LoBAL QSOs (Briggs, Turnshek & Wolfe 1984). Support for the latter scenario includes the excess fraction of LoBAL quasars among infrared selected quasars (Boroson & Meyers 1992), and a special locus in black hole mass versus accretion rate space (Boroson 2002).

In the first scenario, the BALR is probably located in a preferred direction with respect to the system’s symmetry axis, for example in the equatorial or polar direction. Higher polarization in the optical continuum in comparison to non-BAL QSOs suggests that BAL QSOs are seen nearly edge-on (Cohen et al. 1995; Goodrich & Miller 1995; Hines & Wills 1995; Wang, Wang & Wang 2005). Equatorial outflows are also preferred from theoretical considerations for radiatively accelerated winds from an accretion disc or evaporated gas from a putative dusty torus (Punsly 2006).

However, there are indications for both polar and equatorial outflows in radio-loud BAL QSOs. It is generally believed that the radio jet is aligned with the symmetry axis of the accretion disc. Thus, it
can be taken as an indicator of the system inclination. According to the unification scheme of radio quasars, a radio-loud quasar would show a flat radio spectrum and a core-dominated morphology when viewed along the radio jet, due to relativistic boosting of the optically thick core. It would appear as a steep-spectrum radio source with double-lobed morphology when viewed sideways (e.g. Urry & Padovani 1995). Thus, the radio morphology and spectrum can serve as a surrogate for the inclination of the system: in an equatorial outflow model a radio-loud BAL QSO would appear as a steep-spectrum radio source with double-lobed radio morphology, while the opposite situation will be observed in a polar-outflow model. Becker et al. (2000) found that BAL QSOs in the FIRST Bright Quasar Survey (FBQS) display both steep and flat radio spectra (see also Menou et al. 2001), indicating both polar and equatorial outflows. Other studies suggest a similar result. On the one hand, nearly a dozen double-lobed Fanaroff–Riley type II (FR II) quasars were found, mostly from the Sloan Digital Sky Survey (SDSS) and FIRST samples (Wills, Brandt & Loar 1999; Gregg et al. 2000; Brotherton et al. 2002; Gregg, Becker & de Vries 2006; Zhou et al. 2006). On the other hand, evidence for polar outflows has also been found in a small number of radio variable BAL QSOs (Zhou et al. 2006; Ghosh & Punsly 2007), in which the radio variability suggests that the radio jet is beamed towards the observer. The presence of both polar and equatorial outflows can be better interpreted in the context of an evolutionary scenario, rather than the geometrical unification scheme.

Further studies of radio-loud BAL QSOs are necessary in order to fully understand the geometry of outflows in their population. Note that most radio-loud BAL QSOs with steep radio spectra show compact structures on VLA scales, different from classical radio-loud quasars on which the unification scheme is based. Thus, it is not clear whether the radio spectrum can be used as an indicator for inclination or not. Powerful FR II radio BAL QSOs are extremely rare among radio-loud BAL QSOs, and most radio BAL QSOs are only moderately strong in the radio. Morphological studies of these radio intermediate BAL quasars can reveal representative properties of the majority radio population of BAL QSOs. Currently, less than a handful of such BAL QSOs have been studied at sufficiently high angular resolution and they have revealed a complex situation.

In previous European VLBI Network (EVN) observations, Jiang & Wang (2003) observed three BAL quasars, at L band using the phase reference technique. Among these three sources, only one (J1312+2319) has compact two-sided structure, and the other two are still unresolved. The jet orientation might be near the line of sight if the compact component is the jet base in these two unresolved sources. In this case the orientation model may be problematic, at least for these three sources.

In this paper, we report our EVN+MERLIN observations at 1.6 GHz of eight BAL quasars, including equal numbers of HiBAL and LoBAL quasars, and then give some discussion of the results. Section 2 presents the observations as well as data reduction and the results are described in Section 3. The discussion is contained in Section 4, and in Section 5 we give the conclusions. Throughout the paper, we adopt the spectral index convention $f_\nu \propto \nu^{-1}$ and a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$. All values of luminosity used in this paper are calculated with our adopted cosmological parameters.

2 OBSERVATION AND DATA REDUCTION

Our BAL quasars are comparatively bright sources ($\sim 10$ mJy), which have been selected from the Becker et al. (2000) BAL quasar sample. EVN+MERLIN phase-reference polarimetric continuum observations were made for eight BAL quasars at L band on 2005 June 22. The observations were divided into two runs, each lasting 12 h. In order to compare the radio morphology of either low- and high-ionization or steep- and flat-spectrum BAL quasars, our sample included four LoBAL quasars and four HiBAL quasars with both steep and flat spectra on VLA scales. The left/right-circular polarization signals were recorded in eight baseband channels with a total bandwidth of $32 \text{ MHz}$ and two-bit sampling. The angular distances of the phase referencing sources to the target sources are less than 3'. The scan time for each source was about $1.5$ h, and the estimated thermal noise in the total intensity images was no more than $0.1 \text{ mJy beam}^{-1}$. We used OQ208/J1407+284 and J0927+3902 as the D-term calibrators for the 1st and 2nd runs, respectively, and 3C286/J1331+305 as the electric vector polarization angle (EVPA) calibrator for both runs. The EVN data were correlated at the Joint Institute for VLBI in European (JIVE) in Dwingeloo. Pipeline results were used for the phase referencing. Since the flux densities of all BAL quasars in our sample except J1603+3002 are lower than $20 \text{ mJy}$ on VLA scales, we used non-phase referencing results of J1603+3002 (about $54 \text{ mJy}$, which is strong enough to detect with normal fringe fitting) to compare with the results from phase referencing. The results are in good agreement, suggesting that the phase referencing observations of the other sources should also be reliable. The initial amplitude calibration and the fringe fitting were performed using the National Radio Astronomy Observatory (NRAO) Astronomical Image Processing System (AIPS). The imaging and self-calibration were carried out in the DIFMAP package (Shepherd, Pearson & Taylor 1994) and these self-calibrations allowed us to improve the signal-to-noise ratio in the images. The estimated uncertainty of the amplitude calibration is about 10 per cent. The detailed information for these observations is listed in Tables 1 and 2, including total flux densities from both EVN and MERLIN, positions shifts, fractional polarization, EVPA as well as uncertainty for polarization. Moreover, making use of the phase-reference technique, we were able to obtain positions from the VLBI data which are more accurate than those obtained from the VLA. Table 3 lists all the position information for target BAL sources and phase-reference sources. The position of the phase tracking centre for BAL sources is shown in Columns (2) and (3), while the name and position of the phase-reference sources are denoted in Columns (4)–(6), respectively. In our sample, J1044+3656 has the largest shift away from its phase tracking centre, about $225 \text{ mas}$ east and $225 \text{ mas}$ south. Although these shifts might affect the signal-to-noise ratio, the EVN flux densities of our sources are similar to those observed at the VLA, suggesting that their influence is too small to be important. The accurate positions of the BAL quasars calculated from the shifts away from the phase tracking centres are listed in the last two columns in Table 3. The $3\sigma$ uncertainty in these positions, which mainly depends on both the angular resolution of the EVN at 18 cm and the signal-to-noise ratio, is $\sim 15$ mas.

3 SOURCES AND RESULTS

3.1 J0724+4159

J0724+4159 is a LoBAL quasar. The radio source associated with this quasar is unresolved in the VLA observation at 20 cm. Its flux density is $7.9 \text{ mJy}$ in FIRST. J0724+4159 has a spectral index between 20 and $3.6 \text{ cm}$ of $\alpha = 0.0$. The radio loudness is $\log R = 1.6$ (Becker et al. 2000). The naturally weighted image with the
Table 1. Sources observed with EVN+MERLIN at 18 cm. The source name (in J2000) and Greenwich Sidereal Time (GST) range are shown in Columns (1) and (2). The VLA spectral index and VLA flux density at 20 cm are listed in Columns (3) and (4), while the EVN and MERLIN flux density at 18 cm are shown in Columns (5) and (6), respectively. The last column is the classification of BAL quasars.

| Name(s)          | GST range (Europe) | $\alpha$ ($\nu^5$) | VLA (mJy at 20 cm) | EVN (mJy at 18 cm) | MERLIN (mJy at 18 cm) | Note   |
|------------------|--------------------|-------------------|-------------------|-------------------|----------------------|--------|
| J0724 + 4159     | 22:00–14:00        | 0.0               | 7.9 (B)           | 7.2               | 8.0                  | LoBAL  |
| J0728 + 4026     | 22:00–14:00        | −1.1              | 18.0 (A)          | 16.1              | 17.6                 | LoBAL  |
| J1044 + 3656     | 02:00–18:00        | −0.5              | 15.6 (A)          | 16.4              | 18.5                 | LoBAL  |
| J1122 + 3124     | 03:00–17:00        | −0.6              | 12.9 (B)          | 8.3               | 10.2                 | LoBAL  |
| J1150 + 2819     | 04:00–17:00        | −1.2              | 14.2 (B)          | 12.6              | 12.3                 | HiBAL  |
| J1413 + 4212     | 05:00–21:00        | −0.2              | 18.7 (B)          | 17.1              | 18.1                 | HiBAL  |
| J1603 + 3002     | 08:00–21:00        | −0.6              | 54.2 (A)          | 52.1              | 52.6                 | HiBAL  |
| J1655 + 3945     | 08:00–23:00        | −0.2              | 10.2 (A)          | 12.1              | 10.6                 | HiBAL  |

Table 2. EVN+MERLIN observational details of BAL quasars at 18 cm.

| Source name | Position | Position | $m$ | $\sigma_m$ | EVPA | $\sigma_{EVPA}$ |
|-------------|----------|----------|-----|------------|------|-----------------|
| J0724 + 4159 | (−129, 228) | (−150, 210) | 11  | 3.9 | 113.8 | 11.6 |
| J0728 + 4026 | (−126, 224) | (−120, 210) | 4.7  | 1.5  | 131.9 | 34.7 |
| J1044 + 3656 | (225, −225) | (210, −240) | 3.2  | 1.3  | 125.9 | 32.9 |
| J1122 + 3124 | (−123, −200) | (−120, −210) | 3.0  | 1.3  | 81.9  | 7.7  |
| J1150 + 2819 | (45, −58) | (30, −60) | 3.1  | 1.3  | 5.8  | 30.0 |
| J1413 + 4212 | (−158, −5) | (−180, 0) | 3.3  | 1.3  | 85.5  | 32.9 |
| J1603 + 3002 | (−104, −171) | (−120, −180) | 1.3  | 0.3  | 126.4 | 34.7 |
| J1655 + 3945 | (18, −66) | (30, −60) | 4.1  | 1.4  | 49.2  | 26.6 |

Table 3. The VLBI positions of 11 BAL quasars, including three previously observed BAL quasars.

| Source | RA (hh mm ss) (J2000) | Dec. (° ') (J2000) | Reference RA (J2000) | Reference Dec. (J2000) | RA (hh mm ss) (J2000) | Dec. (° ') (J2000) |
|--------|-----------------------|--------------------|----------------------|-----------------------|-----------------------|---------------------|
| J0724 + 4159 | 07 24 18.4920 | +41 59 14.400 | J0730 + 4049 | 07 30 51.3466 | +40 49 50.827 | 07 24 18.4834 | +41 59 14.628 |
| J0728 + 4026 | 07 28 31.6610 | +40 26 15.850 | J0730 + 4049 | 07 30 51.3466 | +40 49 50.827 | 07 28 31.6526 | +40 26 16.074 |
| J1044 + 3656 | 10 44 59.5910 | +36 56 05.390 | J1050 + 3340 | 10 50 58.1230 | +34 30 10.941 | 10 44 59.6060 | +36 56 05.165 |
| J1122 + 3124 | 11 22 20.4620 | +31 24 41.200 | J1130 + 3031 | 11 30 42.4292 | +30 31 35.388 | 11 22 20.4538 | +31 24 41.000 |
| J1150 + 2819 | 11 50 23.7000 | +28 19 07.500 | J1147 + 2635 | 11 47 59.7639 | +26 35 42.333 | 11 50 23.5730 | +28 19 07.442 |
| J1413 + 4212 | 14 13 34.0400 | +42 12 01.760 | J1405 + 4056 | 14 05 07.7954 | +40 56 57.831 | 14 13 34.395 | +42 12 01.755 |
| J1603 + 3002 | 16 03 54.1620 | +30 02 08.880 | J1605 + 3001 | 16 05 33.0480 | +30 01 29.702 | 16 03 54.155 | +30 02 08.709 |
| J1655 + 3945 | 16 55 43.2350 | +39 45 19.940 | J1652 + 3902 | 16 52 58.5096 | +39 02 49.823 | 16 55 43.262 | +39 45 19.874 |
| J0957 + 2356* | 09 57 07.3670 | +23 56 25.320 | J0956 + 2515 | 09 56 49.8754 | +25 15 16.050 | 09 57 07.312 | +23 56 25.379 |
| J1312 + 2319* | 13 12 13.5600 | +23 19 58.510 | J1321 + 2216 | 13 21 11.2014 | +22 16 12.092 | 13 12 13.575 | +23 19 58.572 |
| J1556 + 3517* | 15 56 37.7200 | +35 17 57.620 | J1602 + 3326 | 16 02 07.2635 | +33 26 53.071 | 15 56 33.776 | +35 17 57.389 |

Column (1): IAU name of BAL quasar in J2000, * denotes previously observed source; Column (2): RA measured by VLA in J2000; Column (3): Dec. measured by VLA in J2000; Column (4): IAU name of phase-reference source in J2000; Column (5): RA for phase-reference source; Column (6): Dec. for phase-reference source; Column (7): RA remeasured for BAL quasar by our EVN observation in J2000; Column (8): Dec. remeasured for BAL quasar by our EVN observation in J2000.

3.2 J0728+4026

J0728+4026 was discovered as a LoBAL quasar. It is a point source with 18 mJy with the VLA at 18 cm (A-configuration). The flux density with the VLA A-configuration at 3.6 cm is 2.7 mJy. These non-simultaneous data suggest a steep spectral index $\alpha = −1.1$. Its radio loudness is log $R = 0.37$ (Becker et al. 2000). The naturally weighted image with the EVN in Fig. 1(b) shows a core–jet structure. The flux density in the core–jet structure is 16.1 mJy in
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Figure 1. EVN images of LoBAL quasars at 1.6 GHz. (a) The restoring beam is $12.2 \times 4.3$ mas at position angle (PA) $= 3.3^\circ$, the contour levels are $(1, 2, 4, 8, 16) \times 0.383 \text{ mJy beam}^{-1}$, and the peak flux density is $7.0 \text{ mJy beam}^{-1}$. (b) The restoring beam is $11.8 \times 4.8$ mas at PA $= 1.3^\circ$, the contour levels are $(1, 2, 4, 8, 16) \times 0.443 \text{ mJy beam}^{-1}$, and the peak flux density is $11.2 \text{ mJy beam}^{-1}$. (c) The restoring beam is $10.9 \times 4.6$ mas at PA $= 14.8^\circ$, the contour levels are $(1, 2, 4, 8, 16) \times 0.343 \text{ mJy beam}^{-1}$, and the peak flux density is $10.8 \text{ mJy beam}^{-1}$. (d) The restoring beam is $17.4 \times 5.9$ mas at PA $= 12.6^\circ$, the contour levels are $(-1, 1, 2, 4, 8, 16) \times 0.240 \text{ mJy beam}^{-1}$, and the peak flux density is $6.71 \text{ mJy beam}^{-1}$.

the EVN observation, which accounts for about 92 per cent of the total flux density of 17.3 mJy detected by MERLIN. The core–jet structure has a degree of polarization of about 4.7 per cent.

3.3 J1044+3656

J1044+3656 is a LoBAL quasar. The VLA observation in A-configuration at 20 cm suggests that this source is unresolved with a flux density of about 15.6 mJy. The spectral index between 20 and 3.6 cm is $\alpha = -0.5$. The radio loudness is $\log R = 1.29$ (Becker et al. 2000). The naturally weighted image with the EVN [Fig. 1(c)] displays a core–jet structure at 18 cm with a total flux density of 16.4 mJy. MERLIN detected a flux density of about 18.5 mJy. There might be some weak structures resolved out in the EVN image. The difference in the flux density between the VLA and MERLIN images is probably due to source variation. J1044+3656 shows a fractional polarization of about 3.2 per cent in the central component. The two different directions of the electric vector in the compact region in the EVN map may come from two different components, one being the core and another the jet.
component. The jet component might be only just separated from the core, its direction of electric vector following the jet direction.

3.4 J1122+3124

J1122+3124 is a LoBAL quasar. The spectral index between 20 and 3.6 cm obtained by the VLA in D-configuration is \( \alpha = -0.6 \). The estimated radio loudness is \( \log R = 1.52 \) (Becker et al. 2000). The naturally weighted image of the source with the EVN [Fig. 1(d)] shows a central component with two-sided structure at 18 cm, which is nearly aligned with the central component. The southern component is located 150 mas away from the central component, while a weak northern component lies 87 mas away. About 90 per cent of the flux density is present in the central component. In order to confirm the two-sided structure, we combined EVN and MERLIN data with different weights (see Fig. 2). It seems that the northern component has more extended structure. The flux densities of the clean components in the EVN and MERLIN images are 8.3 and 10.2 mJy, respectively. The extended northern emission was probably resolved at EVN resolution. The source may vary. The flux density measured by the VLA is 12.9 mJy in B-configuration at 20 cm, and another two measurements at the same frequency with the VLA are 10.9 and 10.0 mJy in D-configuration (Becker et al. 2000).

The naturally weighted EVN image shows about 3.0 per cent fractional polarization in the central component, but it is not detected in the two-sided lobes because of their weak intensity. The fractional polarization with MERLIN is about 2.7 per cent, which is consistent with the EVN result.

3.5 J1150+2819

J1150+2819 is a HiBAL quasar. The VLA observation at 20 cm shows an unresolved image with a flux density of about 14.2 mJy. The spectral index between 20 and 3.6 cm is \( \alpha = -1.2 \). The estimated radio loudness is \( \log R = 1.43 \) (Becker et al. 2000). The naturally weighted image with the EVN [Fig. 3(a)] still displays unresolved structure at 18 cm. The clean components sum to 12.6 mJy in the EVN measurement, and 12.3 mJy with MERLIN. J1150+2819 shows a fractional polarization of about 3.1 per cent in the central component.

3.6 J1413+4212

J1413+4212 is a HiBAL quasar. It is a point source with 18.7 mJy in the FIRST catalogue. The flux density measured with the VLA at 3.6 cm in the D-configuration is 11.3 mJy. This gives a flat spectral index \( \alpha = -0.2 \). The radio loudness is \( \log R = 1.68 \) (Becker et al. 2000). The naturally weighted image with the EVN [Fig. 3(b)] displays a short core–jet structure at 18 cm with 17.1 mJy. The MERLIN array measures about 18.1 mJy in clean components. The central component has 3.3 per cent fractional polarization.

3.7 J1603+3002

J1603+3002 is a HiBAL quasar. It is the most luminous source in these observations. It has a radio loudness \( \log R = 2.04 \) (Becker et al. 2000). The flux densities at 20 and 3.6 cm detected by the VLA in A-configuration are 54.2 and 18.1 mJy, respectively, which suggests a spectral index of \( \alpha = -0.6 \). The total flux density is about 52.1 mJy in the EVN image [see Fig. 3(c)]. The MERLIN image shows an unresolved structure with 52.6 mJy flux density. The fractional polarization of the EVN image is about 1.3 per cent.

3.8 J1655+3945

J1655+3945 is a HiBAL quasar. The VLA observation at 20 cm shows an unresolved image. The flux density of J1655+3945 in the FIRST catalogue is 10.2 mJy. The spectral index between 20 and 3.6 cm is \( \alpha = -0.2 \). Its radio loudness is \( \log R = 1.41 \) (Becker et al. 2000). The naturally weighted EVN image depicts a resolved structure elongated to the south-west with a total of 12.1 mJy [Fig. 3(d)]. In the central component the fractional polarization is about 4.1 per cent.

4 DISCUSSION

The origin of the radio emission from these radio intermediate quasars is not fully understood. Based on the high brightness temperature inferred from radio variability, Zhou et al. (2006) suggested that the emission comes from relativistic jets for a small subsample of radio-loud BAL QSOs, while Blundell & Kuncic (2007) argued that the emission is produced by free–free emission from outflows in radio-weak QSOs. The brightness temperature in the source rest frame for the strongest components of these BAL quasars, based on the results of model fitting, ranges from \( 2.0 \times 10^8 \) to \( 5.2 \times 10^{10} \) K. The high brightness temperature and moderate polarization degree suggest that the radio is synchrotron emission from the jet.
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Figure 3. EVN images of HiBAL quasars at 1.6 GHz. (a) The restoring beam is $18.1 \times 4.4$ mas at PA $= 2.5^\circ$, the contour levels are $(1, 2, 4, 8, 16, 32) \times 0.432$ mJy beam$^{-1}$, and the peak flux density is $11.7$ mJy beam$^{-1}$. (b) The restoring beam is $9.5 \times 4.2$ mas at PA $= 3.6^\circ$, the contour levels are $(1, 2, 4, 8, 16, 32) \times 0.362$ mJy beam$^{-1}$, and the peak flux density is $12.7$ mJy beam$^{-1}$. (c) The restoring beam is $13.0 \times 4.0$ mas at PA $= 11.2^\circ$, the contour levels are $(1, 2, 4, 8, 16, 32) \times 0.669$ mJy beam$^{-1}$, and the peak flux density is $37.1$ mJy beam$^{-1}$. (d) The restoring beam is $9.0 \times 4.2$ mas at PA $= 9.1^\circ$, the contour levels are $(1, 2, 4, 8, 16) \times 0.313$ mJy beam$^{-1}$, and the peak flux density is $8.84$ mJy beam$^{-1}$.

Including the two-sided structure source J1122+3124, all BAL quasars that we observed with EVN+MERLIN at 18 cm exhibit a compact structure with a projected size of less than 2 kpc. In addition to J1122+3124, the total flux densities of the other seven compact sources measured with EVN at 18 cm are very close to the flux densities measured by both our simultaneous MERLIN and previous VLA observations at 20 cm. Therefore, if there is any low brightness extended structure in these object, it must be weak. Assuming that the 3.6 cm radio emission of these BAL quasars measured with the VLA comes from the compact component and they are non-variable, their radio spectra can be calculated by using VLA measurements between 20 and 3.6 cm. Five are steep-spectrum radio sources, and the rest are flat-spectrum sources. Combined with our previous observations of another three compact BAL quasars (see Section 1) (Jiang & Wang 2003), there are seven steep-spectrum BAL quasars and four flat-spectrum sources. In these 11 compact BAL quasars observed with the EVN (or EVN+MERLIN) array, there is no significant difference between HiBAL and LoBAL quasars in their...
radio morphology and polarization. Similarly, there is no apparent difference in radio properties between flat- and steep-spectrum BAL quasars.

Among the seven steep-spectrum sources, five (J0728+4026, J1044+3656, J1150+2819, J1603+3002 and J0957+2356) show only compact cores or core–jet structures. In these cases, there is no good indicator for the symmetry axis of the system, and the inclination might be distributed over a large range of values. However, although their sizes are much smaller than the typical values for compact steep spectrum (CSS) sources (~15 kpc), it is likely that these BAL quasars could be related to CSS sources (e.g. Kunert-Bajraszewska & Marecki 2006; Montenegro-Montes et al. 2008). The remaining two steep-spectrum sources, J1122+3124 and J1312+2319, exhibit two-sided structure. According to the unification scheme, the orientation of their jets is far from the line of sight. The sizes of the radio sources are less than 2 kpc, the same as the typical size of a compact symmetric object (CSO). However, their central components account for more than 80 per cent of the total flux density, which is significantly different from the structure of CSOs or FR II quasars, which have weak cores at low frequencies in general. Given the weakness of the lobes in both objects at 18 cm, it is plausible that their cores also have steep spectra. Therefore, these two sources are similar to other steep-spectrum radio BAL quasars except for the detection of weak extended lobes. The compact, steep-spectrum central component in these two BAL quasars suggests a link to the CSS sources.

The four flat-spectrum sources, J0724+4159, J1413+4212, J1556+3517 and J1655+3945, show core-dominated or marginal core–jet structures in the EVN/MERLIN maps. There are two possible interpretations for this. If their compact component is relativistically beamed emission from the base of the jet, the jet in these BAL quasars is near the line of sight. Their flat spectra are consistent with this interpretation. The degree of polarization of a few to 10 per cent is also typical for such sources. On the other hand, the flat, compact core might be related to the GHz peaked sources (GPSs) (e.g. Benn et al. 2005). Note that with an $\alpha = 0$ between 3.6 and 20 cm for J0724+4159, the peak frequency is likely to be around a few GHz in the observer’s rest frame. For the other three, with spectral indexes of $\alpha = 0.1$ and 0.2 between 3.6 and 20 cm, the turnover frequency is also likely to be in the GHz range although further observations are needed to confirm this.

Our results suggest that the simple unification of BAL and non-BAL quasars by orientation is problematic. All the BAL quasars in our sample have compact radio morphology, including two-sided structure sources. If these BAL quasars are intrinsically small sources with relativistic jets, they can be observed either pole-on or edge-on. This scenario is not consistent with the current popular disc-wind models. Based on their radio spectrum and morphology, the steep-spectrum BAL quasars could be classified as CSS, while the flat-spectrum BAL quasars might be GPSs (Becker et al. 2000; Gregg et al. 2000; Montenegro-Montes et al. 2008). Both CSS and GPS sources are generally thought to represent the early stage in quasar lifetimes (O’Dea 1998). Due to their low luminosity, these BAL quasars might be located at the low end of radio power. Meanwhile, as for those radio luminous BAL quasars, a significant anti-correlation between radio loudness and the strength of the BAL features is exhibited in a total of eleven FR II-BAL quasars (Gregg, Becker & Vries 2006) so far. The rarity of the FR II-BAL quasars indicates that the period of FR II type combined BAL features is very short (Gregg et al. 2006). This suggests an evolutionary picture in which FR II-BAL sources are frustrated by the obscuring BAL shroud until the quasars can boil away enough of the material through radiation pressure. Meanwhile, comparing the black hole mass and accretion rate between two small samples of BAL and non-BAL quasars, Yuan & Willis (2003) suggest that BAL quasars have a more plentiful fuel supply than non-BAL quasars, which might be related to the young age of this kind of source. In addition, by using optical information from released SDSS data, we derived black hole masses for seven BAL quasars in our sample within the range $9.3 \times 10^8$ to $4.5 \times 10^9 M_\odot$ (see detailed information in Table 4). Despite the limited numbers in the sample, the comparatively low black hole masses of these BAL quasars might also be connected to their stage in the evolutionary sequence.

### 5 CONCLUSIONS

We present the results of EVN plus MERLIN polarization observations of eight BAL quasars at 1.6 GHz, including four LoBALs and four HiBALs with either steep or flat spectra on VLA scales. The main conclusions are summarized as follows.

(i) Only one steep-spectrum source, J1122+3124, shows two-sided structure on the scale of 2 kpc. The other four steep-spectrum sources and three flat-spectrum sources display either an unresolved image or a core–jet structure on scales of less than 300 pc, well within the galaxy size. In all cases, the marginally resolved core is the dominant radio component. Making use of the phase-reference

### Table 4. Optical line information from SDSS released data and black hole mass for sources in our sample.

| Sources name | Redshift | $f_{\lambda,3000}$ $(10^{-17}$ erg s$^{-1}$ Å$^{-1}$ cm$^{-2}$) | FWHM (km s$^{-1}$) | Lines | $M_{BH}$ $10^8 M_\odot$ |
|--------------|----------|-------------------------------------------------|-----------------|------|-------------------|
| J0724+4159  | 1.551    | 85                                              | 2428            | Mg II| 0.26              |
| J1044+3656  | 0.702    | 201                                             | 4197            | H$\beta$| 3.98             |
| J1122+3124  | 1.453    | 124                                             | 2518            | Mg II| 0.34              |
| J1150+2819  | 3.124    | 323                                             | 2069            | C$\alpha$| 0.59             |
| J1413+4212  | 2.817    | 225                                             | 6161            | C$\alpha$| 4.47             |
| J1603+3002  | 2.030    | 95                                              | 1619            | Mg II| 0.11              |
| J1655+3945  | 1.753    | 80                                              | 1529            | Mg II| 0.09              |

Column (1): object name; Column (2): redshift; Column (3): flux density at 3000 Å in units of $10^{-17}$ erg s$^{-1}$ Å$^{-1}$ cm$^{-2}$; Column (4): full width at half-maximum (FWHM) of broad line in units of km s$^{-1}$; (5): line used for FWHM; Column (6): black hole mass in units of $10^8 M_\odot$. See Kaspi et al. (2005) and Jarvis & McLure (2002) for the detailed method of the black hole mass calculation.
technique, celestial positions are derived from our observations which are more accurate than those from the VLA.

(ii) Linear polarization has been detected in the core in the range of a few to 10 per cent. Polarization, together with high brightness temperatures (from $2 \times 10^9$ to $5 \times 10^{10}$ K), suggests a synchrotron origin for the radio emission. There is no apparent difference in the radio morphologies or polarization between low-ionization and high-ionization BAL quasars or between flat- and steep-spectrum sources.

(iii) We considered compact steep-spectrum or GHz peaked radio sources at the low end of radio power as the most likely explanation for these radio BAL QSOs. Therefore, they are probably a population of young radio sources.

ACKNOWLEDGMENTS

We are grateful to I. W. A. Browne and X. W. Cao for helpful suggestions and discussions. We thank the anonymous referee for insightful comments and constructive suggestions. We also thank Richard Porcas for helpful proofreading that improved the presentation of this work. The work is supported by the NSFC under grants 10373019 and 10333020. TGW acknowledges financial support from NSFC 10573015. The European VLBI Network is a joint facility of European, Chinese, and other radio astronomy institutes funded by their national research councils. MERLIN is operated as a National Facility by the University of Manchester at Jodrell Bank Observatory on behalf of the UK Particle Physics & Astronomy Research Council. This research has made use of the NASA IPAC Extragalactic Data base (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This paper has made use of data from the SDSS. Funding for the creation and the distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the participating institutions, the National Aeronautics and Space Administration, the National Science Foundation, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society.

REFERENCES

Becker R. H., White R. L., Gregg M. D., Brotherton M. S., Laurent-Muehleisen S. A., Arav N., 2000, ApJ, 538, 72
Benn C. R., Carballo R., Holt J., Vigotti M., González-Serrano J. I., Mack K.-H., Perley R. A., 2005, MNRAS, 360, 1455
Blundell K. M., Kuncic Z., 2007, ApJ, 668, 103
Boroson T. A., 2002, ApJ, 565, 78
Boroson T. A., Meyers K. A., 1992, ApJ, 397, 442
Briggs F. H., Turnshek D. A., Wolfe A. M., 1984, ApJ, 287, 549
Brotherton M. S., Croom S. M., De Breuck C., Becker R. H., Gregg M. D., 2002, AJ, 124, 2575
Cohen M. H., Ogle P. M., Tran H. D., Vermeulen R. C., Miller J. S., Goodrich R. W., Martel A. R., 1995, ApJ, 448, L77
Ghosh K. K., Punsly B., 2007, ApJ, 661, 139
Gregg M. D., Becker R. H., Brotherton M. S., Laurent-Muehleisen S. A., Lacy M., White R. L., 2000, ApJ, 544, 142
Gregg M. D., Becker R. H., de Vries W., 2006, ApJ, 641, 210
Goodrich R. W., Miller B. J., 1995, ApJ, 448, L73
Hewett P. C., Foltz C. B., 2003, AJ, 125, 1784
Hines D. H., Wills B. J., 1995, ApJ, 448, L69
Jarvis M. J., McLure R. J., 2002, MNRAS, 336, L38
Jiang D. R., Wang T. G., 2003, A&A, 397, L13
Kaspi S., Maoz D., Netzer H., Peterson B. M., Vestergaard M., Jannuzi B. T., 2005, ApJ, 629, 61
Knegge C., Scaringi S., Goad M. R., Cottis C. E., 2008, MNRAS, 386, 1426
Kunert-Bajraszewska M., Marecki A., 2006, preprint (astro-ph/0612490v1)
Menou K. et al., 2001, ApJ, 561, 645
Montenegro-Montes F. M., Mack K.-H., Vigotti M., Benn C. R., Carballo R., González-Serrano J. I., Holt J., Jiménez-Luján F., 2008, MNRAS, 388, 1853
O’Dea C. P., 1998, PASP, 110, 493
Punsly B., 2006, ApJ, 647, 886
Reichard T. A. et al., 2003, AJ, 125, 1711
Shen Y., Strauss M. A., Hall P. B., Schneider D. P., York D. G., Bahcall N. A., 2008, ApJ, 677, 858
Shepherd M. C., Pearson T. J., Taylor G. B., 1994, BAAS, 26, 987
Tolea A., Krolik J. H., Tsvetanov Z., 2002, ApJ, 578, L31
Urry C. M., Padovani P., 1995, PASP, 107, 803
Wang H. Y., Wang T. G., Wang J. X., 2005, ApJ, 634, 149
Weymann R. J., 2002, in Crenshaw D. M., Kraemer S. B., George I. M., eds, ASP Conf. Ser. Vol. 255, Mass outflow in Active Galactic Nuclei: New Perspective. Astron. Soc. Pac., San Francisco, p. 329
Weymann R. J., Morris S. L., Foltz C. B., Hewett P. C., 1991, ApJ, 373, 23
Willott C. J., Rawlings S., Grimes J. A., 2003, ApJ, 598, 909
Wills B. J., Brandt W. N., Loar A., 1999, ApJ, 520, L91
Yuan M. J., Wills B. J., 2003, ApJ, 593, L11
Zhou H. Y., Wang T. G., Wang H. Y., Wang J. X., Yuan W. M., Lu Y., 2006, ApJ, 639, 716

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