A VLBI survey of compact Broad Absorption Lines (BAL) quasars with BALnicity Index BI=0

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ABSTRACT

We present high-resolution observations, using both the European VLBI Network (EVN) at 1.7 GHz, and the Very Long Baseline Array (VLBA) at 5 and 8.4 GHz to image radio structures of 14 compact sources classified as broad absorption line (BAL) quasars based on the absorption index (AI). All source but one were resolved, with the majority showing core-jet morphology typical for radio-loud quasars. We discuss in details the most interesting cases. The high radio luminosities and small linear sizes of the observed objects indicate they are strong young AGNs. Nevertheless, the distribution of the radio-loudness parameter, log R, of a larger sample of AI quasars shows that the objects observed by us constitute the most luminous, small subgroup of AI population. Additionally we report that for the radio-loudness parameter, the distribution of AI quasars and those selected by using the traditional balnicity index (BI) – BI quasars differ significantly. Strong absorption is connected with the lower log R, and thus probably with larger viewing angles. Since, the AI quasars have on average larger log R, the orientation can cause that we see them less absorbed. However, we suggest that the orientation is not the only parameter that affects the detected absorption. The fact that the strong absorption is associated with the weak radio emission is equally important and worth exploring.

Key words: galaxies: active-galaxies: evolution, quasars: absorption lines

1 INTRODUCTION

Broad absorption line quasars have been observed for over two decades. They spectra have blue-shifted absorption troughs. This features are usually linked with the outflow of highly ionized plasma. The velocities of outflow can reach up to 0.3 c (Hewett & Foltz 2003). Noteworthy is that, in general absorption, can have various origin (Reichard et al. 2003), from structures closely bonded by gravity to central engine, followed by host galaxy environment and matter which lies in the line of sight between observer and AGN. Therefore, it is extremely difficult to exclude one form of absorption from another and draw unambiguous threshold. To tackle this issue, Weymann et al. (1991) proposed the balnicity index (BI), which accounts only for troughs 2000 km/s wide and blue-shifted more than 3000 km/s, from structures closely bonded by gravity to central engine, followed by host galaxy environment and matter which lies in the line of sight between observer and AGN. Therefore, it is extremely difficult to exclude one form of absorption from another and draw unambiguous threshold. To tackle this issue, Weymann et al. (1991) proposed the balnicity index (BI), which accounts only for troughs 2000 km/s wide and blue-shifted more than 3000 km/s, to quantify the true broad absorption. However, BI is too restrictive since it excludes large number of quasars with significant absorption lines troughs or the so-called mini-BALs with BI=0. Hence, Hall et al. (2002) suggested a more relaxed definition, the absorption index (AI), which includes troughs no smaller than 1000 km/s. The fraction of broad absorption line quasars (BALQSOs) among the whole quasar population varies from 15 % to 26 % depending on the definition used (Hewett & Foltz 2003, Trump et al. 2006, Dai et al. 2008, Maddox et al. 2008, Shankar et al. 2008, Knigge et al. 2008, Gibson et al. 2009).

Recently, the radio, optical and X-ray studies of traditional BI quasars and absorption line (AI) quasars showed that they might be two independent classes of objects (Knigge et al. 2008, Streblyanska et al. 2010). However, this do not necessarily means that the classical BALs and much weaker and narrower absorption lines must be produced in different line-forming regions. Theoretical model of Elvis (2000) unifies the broad and narrow absorption features, suggesting they are formed in the same disc wind but the orientation of the source with respect to the observer changes their appearance or can even prevent us from detection of these lines. Discovery of the existence of radio-loud BALQSOs gave us another opportunity to study the BAL phenomenon. The radio emission is an additional tool to understand their orientation and age by the VLBI imaging (detection of radio jets and their direction plus size determination), through the radio-loudness parameter distribution and variability study.

It has been suggested (Becker et al. 2000) that, because of their small sizes, most of the radio-loud BALQSOs belong to the class of compact radio sources, namely compact steep spectrum (CSS) objects and gigahertz peaked spectrum (GPS) objects. Currently, there are only few surveys focused on radio imaging of compact radio-loud BALQSOs using global interferometric arrays as well as local-interferometry technique (Jiang & Wang 2003, Kunert-
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We carefully prepared our sample based on final release of the FIRST survey (White et al. 1997) and A catalogue of Broad Absorption Line Quasars from the Sloan Digital Sky Survey Third Data Release made by Trump et al. (2006) The selection process required several stages and resulted in pinpointing genuine unresolved radio objects. In the first step we have matched the optical positions of BALQSOs from the Trump et al. (2006) catalogue to FIRST coordinates in a radius of 10 arcseconds. Primary we excluded sources with radio emission less than 2 mJy and/or side lobe probability more than 0.1, as the likelihood of false detection was the highest in this case. At this stage our sample counted 350 sources. Afterwards we have excluded from the sample objects with additional radio counterparts within 60 arcseconds of SDSS position as those possessing large scale structures which constituted < 12% of the above number. This approach allowed us to avoid ambiguity in identification of the radio core, which is important in the statistical studies. We recall here that Trump et al. (2006) quantify the sources as BALQSOs using absorption index (AI), so their final catalogue contains also sources with the traditional balnicity index BI=0. As has been already discussed in Sec.1 the AI (AI>0 and BI=0) and BI (AI=0 and BI>0) quasars differ significantly in many properties and thus we treat them also as separate

1 Our observations were made in 2008, therefore, we could use only data available from Trump et al. (2006) as no additional catalogue existed back then.

Table 1. Radio-loud AI quasars observed with VLBA and EVN.

| RA(J2000) | Dec(J2000) | z | AI | $S_{1.4\,GHz}$ | $\log L_{1.4\,GHz}$ | $S_{8.4\,GHz}$ | $S_{1.4\,GHz}$ | $\alpha_{1.4\,GHz}$ | $\alpha_{8.4\,GHz}$ | $R_L$ |
|-----------|------------|---|----|----------------|-----------------|----------|-----------|-------------|-------------|-------|
| h m s     | °′″       |   | mJy| (mJy)         | (W Hz$^{-1}$)   | mJy      | (mJy)     |             |             |       |
| (1)       | (2)       | (3) | (4) | (5)            | (6)            | (7)      | (8)        | (9)          | (10)         | (11)  |
| 02 17 28.614 | 00 52 26.88 | 2.46 | 791 | 217 | 28.01 | 104 | – | 0.59 | – | 3.44 |
| 07 56 28.260 | 37 14 55.80 | 2.51 | 841 | 233 | 28.08 | 236 | 136 | 0.04 | 0.99 | 3.46 |
| 08 00 16.058 | 40 29 55.990 | 2.02 | 1114 | 199 | 27.7/ | 68 | – | 0.88 | – | 2.91 |
| 08 15 34.184 | 53 05 29.28 | 2.43 | 74/ | 542 | 28.19 | 112 | – | 0.90 | – | 2.20 |
| 09 28 24.133 | 44 46 04.68 | 1.90 | 293 | 162 | 27.60 | 256 | 229 | -0.37 | 0.32 | 2.64 |
| 10 05 15.961 | 48 05 33.21 | 2.37 | 783 | 209 | 27.95 | 70 | – | 0.88 | – | 2.47 |
| 10 13 29.931 | 49 18 41.11 | 2.20 | 361 | 269 | 27.98 | 167 | 106 | 0.38 | 0.83 | 3.09 |
| 10 18 27.837 | 05 30 29.90 | 1.94 | 441 | 296 | 27.89 | 654 | 300 | -0.64 (-0.10) | 1.42 (0.17) | 3.13 |
| 10 42 57.598 | 07 48 50.60 | 2.67 | 1011 | 381 | 28.33 | 167 | – | 0.66 | – | 3.20 |
| 10 57 26.608 | 03 24 48.47 | 2.83 | 440 | 157 | 28.01 | 70 | – | 0.65 | – | 3.03 |
| 11 03 44.536 | 02 52 09.74 | 2.51 | 460 | 165 | 27.91 | 107 | 90 | 0.35 | 1.05 | 2.67 |
| 11 39 44.832 | 01 12 36.87 | 2.00 | 28/ | 268 | 27.88 | 123 | 147 | 0.64 | -0.30 | 2.40 |
| 12 11 53.165 | 50 51 39.99 | 1.80 | 43/ | 228 | 28.40 | 110 | 117 | 0.30 | -0.11 | 2.42 |
| 14 05 07.795 | 40 56 58.06 | 1.99 | 780 | 214 | 27.7/ | 278 | 197 | -0.21 | 0.65 | 3.14 |
| 14 32 43.322 | 41 03 28.04 | 1.97 | 343 | 261 | 27.85 | 102 | – | 0.76 | – | 2.60 |
| 15 28 21.684 | 53 10 30.68 | 2.82 | 1701 | 232 | 28.09 | 76 | – | 0.90 | – | 3.32 |

Description of the columns: (1) & (2) source coordinates (J2000) extracted from FIRST, (3) redshift as measured from the SDSS, (4) absorption index taken from Trump et al. (2006), (5) total flux density at 1.4 GHz extracted from FIRST (VLA measurement), (6) log of the radio luminosity at 1.4 GHz, (7) total flux density at 4.85 GHz taken from Becker et al. (1991) if marked as Ch (single dish measurements), (8) total flux density at 8.4 GHz taken from Healey et al. (2007) (VLA measurement), (9) spectral index between 1.4 and 4.85 GHz calculated using flux densities in columns (5) and (7), (10) spectral index between 4.85 and 8.4 GHz calculated using flux densities in columns (7) and (8), (11) radio-loudness, the radio-to-optical (i-band) ratio of the quasar core (Kimball et al. 2011), which were calculated from $S_{1.4\,GHz}$ taken from Trump et al. (2006), and the assumption of a radio core spectral index of 0 and an optical spectral index of -0.5.

Bajraszewska & Marecki 2007 Liu et al. 2008 Montenegro-Montes et al. 2008 Doi et al. 2009 Kunert-Bajraszewska et al. 2010 Gawronski & Kunert-Bajraszewska 2010 Bruni et al. 2012 Kunert-Bajraszewska et al. 2010 Kunert-Bajraszewska et al. 2010 Bruni et al. 2013 Hayashi et al. 2013 Kunert-Bajraszewska & Marecki 2007 Kunert-Bajraszewska et al. 2010 Kunert-Bajraszewska et al. 2010 Kunert-Bajraszewska et al. 2010 Montenegro-Montes et al. 2008 Liu et al. 2008 Kunert-Bajraszewska et al. 2010. Mouret, however, are not oriented along a particular line of sight, although they are more often observed farther from the jet axis compared to normal quasars.

On the other hand, since the GPS and CSS sources are considered to be young radio objects, progenitors of large-scale radio-loud AGNs, the evolution scenario has been proposed for BALQSOs (Becker et al. 2000). The BAL phase appears together with the birth of a quasar and is systematically destroyed by the radio jets during quasar lifetime (Urrutia et al. 2009). It is still uncertain which scenario, maybe mixture of both, is most suitable.

This paper presents our VLBI observations and analysis of a sample of BALQSOs selected from the Trump et al. (2006) catalogue. The authors classify the Sloan Digital Sky Survey Third Data Release (SDSS/DR3) sources as BALQSOs based on the more liberal absorption index, although the values of both, the AI and BI indices, are calculated for all quasars. Therefore all sources from the catalogue in a natural way falls into two groups: 1) objects with AI>0 and BI=0, the mini-BALs (hereafter AI quasars) and 2) objects with AI<0 and BI>0, the so-called 'true BALQSOs' (hereafter BI quasars). The study of the sources from the second group will be reported in a separate paper. Here we focus on the AI quasars.
groups. Finally our sample of compact BALQSOs - which we define as the 'parent sample' - consists of 309 sources, out of which 105 are the BI quasars and 204 are the AI objects (Fig. 1).

In the next step we selected comparably numbered samples of AI and BI sources with the largest 1.4 GHz flux densities for further high resolution VLBI observations. This resulted in 16 AI quasars with flux densities $S_{\text{1.4GHz}} > 150 \text{ mJy}$ and 15 BI objects with flux densities $S_{\text{1.4GHz}} > 20 \text{ mJy}$. Note that statistically, compact BI objects are fainter than AI objects and all BI quasars from our sample have flux densities $S_{\text{1.4GHz}} < 80 \text{ mJy}$ (Fig. 1). In this paper we analyse the observations and properties of AI quasars (Table 1).

We observed the AI quasars with EVN at 1.7 GHz and with VLBA at 5 and 8.4 GHz. However, during the sample preparations we noticed that five of our objects had already been observed with VLBA at 5 GHz as part of the VLBA Imaging and Polarimetry Survey (VIPS; Helmboldt et al., 2007). Therefore we continued observations with the VLBA in the same fashion in order to acquire radio maps with comparable dynamical range for the rest of our sources. Each target source was observed using EVN or VLBA for approximately two hours on each frequency in phase-referencing mode. We have observed all 16 objects at 8.4 GHz and 11 sources at 5 GHz with VLBA. Ten sources were observed at 1.7 GHz with EVN. We failed to proper image 2 objects (0800+4029, 1528+5310) due to detection problems at 1.7 GHz with EVN and at 5 GHz with VLBA.

L-band observations were carried out with EVN on 27-28th of October in 2008. Antennas in Jodrell Bank, Westerbork, Effelsberg, Onsala, Medicina, Torun, Shanghai, Urumqi, Noto and Robledo took part in our experiment. The data were correlated at the Joint Institute for VLBI in Europe (JIVE) correlator in Dwingeloo (The Netherlands).

C and X-band observations were performed by VLBA array in two runs, first on 27-30th of August and second on 6-7th of September in 2008. The correlation was performed with the VLBA correlator at the National Radio Astronomy Observatory (NRAO) in Socorro (US). The data were then processed with the Distributed FX (DiFX) software correlator (Deller et al., 2007).

Data reduction including calibration and fringe-fitting was performed using Astronomical Image Processing System - AIPS package. Imaging and self-calibration part was performed using Difmap software (Shepherd et al., 1994). Source components were fitted with circular Gaussian model on the final, self-calibrated visibility data using the MODELFIT programme. The final images of the radio-loud BALQSOs are presented in Fig. 1 and Fig. 2 and the modelfit parameters are listed in Table 2.

Throughout the paper, we assume a cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$. The adopted convention for the spectral index definition is $S \alpha = -\alpha$.

2.1 Possible biases in the sample

This paper in detail presents analysis of BALQSOs with BI=0, called by us AI sources. However, to capture a wider perspective of the blushed BAL phenomenon we complement this information of findings for BI sources - objects with BI>0. Notice that we have focused mainly on the objects which where unresolved in FIRST survey and do not have any additional components within 1 arcminute. Therefore, the statistical analysis of the BALQSOs is devoid of error connected with pinpointing the radio core in sources which posses more than one counterpart on VLA. Definitely most of the BALQSOs are single, unresolved objects on the VLA resolution and we found only 41 sources out of 350 (both AI and BI sources) that could be classified as large-scale ones. Even after the rejecting of large-scale BALQSOs from our sample we still draw the statistical conclusions based on the significant fraction of BALQSO population.

We have also found that the number of extended objects decreases with increasing the value of the flux density in both subsamples and amounts to 7% and 17% for BI and AI quasars, respectively. Note that possible bias can account for the above percentage difference. Radio luminosity of objects from BI sample strongly correlates with redshift (Fig. 2), with Pearson correlation coefficient $r=0.77$. The correlation in AI sample is weaker, $r=0.46$. This could be the result of flux density limit superimposed on our samples and generally present in radio surveys. We might simply not by detecting weak extended sources.

Finally, we report one more bias that can be present in our sample and is connected with the process of identification of BALQSOs. Ganguly et al. (2007) has performed their own classification of BALQSOs from SDSS DR3 survey and reported that the catalogue of Trump et al. (2006) suffers a 15% rate of false positives for BI quasars. However, the method used in Ganguly et al. (2007) to classify sources as BALQSOs is subjective (by visual inspection) and therefore it is difficult to estimate its accuracy. Additionally, our analysis is limited to a small sample of radio-loud BI quasars and we argue that the effect of this bias is not significant.

3 NOTES ON INDIVIDUAL SOURCES

In this section we briefly describe morphology of BALQSOs based on radio maps obtained from our VLBI observations. Moreover, we summarize information from literature considering previous interferometric observations as well as single dish flux measurements (Table 1). During our observations major axis of beam on L, C and X-band were approximately 25, 3, 1.5 mas respectively. 3σ level was usually 1.1, 0.9, and 0.5 mJy beam$^{-1}$ for 1.7, 5, 8.4 GHz respectively. The classification of the radio components was feasible due to multi-frequency observations, which provide us with spectral indices. We assigned different letters to describe components depending on the source structure. In the first place we used C to indicate component consisting of radio core, or E for eastern, S
Although it is not straightforward, we suggest core-jet morphology of this source, where the radio core is still hidden in the C2 component. The brightness temperature calculated for C2 is not high, but close to the equipartition value proposed by Readhead (1994) and in the frame of above discussion should be treated as a lower limit (Table 2).

0815+3305. The map at 1.7 GHz shows a structure resolved into two main components, which are separated by ~ 6 kpc. This source is the largest one in our whole sample of AI quasars. Both, the northern and southern parts consists of 3 components and are elongated in the direction which suggest there might be an extended bridge of emission between them. At 5 and 8.4-GHz only the more compact southern part is detected with components C1.2 or C1.3 being probably a radio core. Indeed, the EVN and VLBA observations of 0815+3305 can account only for ~ 43% and ~ 20% of the total flux at 1.7 and 5 GHz respectively indicating the existence of additional structure on angular scales not sampled by the EVN/VLBA. The overall spectrum of 0815+3305 is steep and does not present a peak in the gigahertz range. The classification of this source is difficult and thus we marked it as ‘Other’ in Table 2.

0928+4446. This source has been observed with the VLBA at 5 GHz as part of the VIPS project (Helmmboldt et al. 2007) and we present this image in Fig. 1. Our 1.7- and 8.4-GHz observations are consistent with those observations showing flat spectral component C being a radio core and steep spectrum one-sided jet E. The same results were obtained by VLBA observations made by Hayashi et al. (2013). We report however, ~ 50% and ~ 23% increase of the 1.7- and 8.4-GHz flux density, respectively in our observations compared to single dish measurements (Table 1). This could be connected with the nature of 0928+4446. This source has been classified as flat spectrum radio quasar (FSRQ) by Hewett & Wild (2010) and indicated as a good candidate for variable, blazar-type object by Hayashi et al. (2013). We classified the morphology of 0928+4446 as a core-jet.

1005+4805. A point-like object on the 1.7-GHz image has been resolved into a more complex structure in the 5- and 8.4-GHz maps. The brightest component C1 is probably a radio core and the steep spectrum components C2 and S are parts of the one-sided radio jet. The overall spectrum of 1005+4805 is steep and does not present a peak in the gigahertz range. The large fraction of the total flux density, ~ 85% at 1.7 GHz and ~ 49% at 5 GHz, is lost in our observations implying the existence of extended emission not sampled by EVN/VLBA spacings. Structure and spectral indices of this object suggest core-jet morphology.

1013+4918. The radio structure of 1013+4918 visible in our 1.7- and 8.4-GHz observations is consistent with that obtained in the VIPS project (Helmmboldt et al. 2007) and we present all three images in Fig. 1. The inverted-spectrum C1 component is a radio core and three northern steep spectrum components (N1, N2, N3) are parts of the one-sided radio jet. The overall spectrum of 1013+4918 is steep. Its morphology can be classified as core-jet.

1018+0530. This source was observed only at 5 and 8.4 GHz with VLBA (Fig. 2). The same results have been obtained in VLBA observations made by Hayashi et al. (2013). The brightest component C1 is a radio core and steep spectrum C2 is probably a radio jet. The angular size of 1018+0530 indicates it is one of the most compact objects in our sample of AI sources. 1018+0530 has been classified as flat spectrum radio quasar (FSRQ) by Hewett & Wild (2010). The large flux variations observed in this quasar (Gorshkov et al. 2008) make it a good candidate for variable, blazar-type object. It has also a FERMI-LAT detection (Nolan et al. 2012). We have classified this source as a core-jet.
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Figure 1. Sources with observations at all three frequencies: EVN 1.7 GHz and VLBA 5 and 5.4 GHz. Contours increase by a factor 2, and the first contour level corresponds to $3\sigma$. 
Figure 1. Sources with observations at all three frequencies (cont.).
Figure 2. Sources observed only with VLBA at 5 and 8.4 GHz. Contours increase by a factor 2, and the first contour level corresponds to $\approx 3\sigma$. 
Table 2. Flux densities of the principal components of the sources from the 1.7, 5, and 8.5 GHz observations.

| RA(J2000) | Dec(J2000) | Components | S_{1.7 GHz} | S_{5 GHz} | S_{8.4 GHz} | \alpha_{5GHz/1.7GHz} | \alpha_{8.4GHz/5GHz} | \theta_T(bvl) | \tau_v(bvl) | 10^{\delta-1} (K \cdot \delta^{-1}) | \text{LAS (mas)} | \text{LLS (mas)} | \text{Type} |
|-----------|------------|-----------|------------|-----------|------------|----------------|----------------|----------|----------|-------------------------------|-------------|-------------|---------|
| 02 17 28.614 | -00 52 26.880 | C | 29.24 | 24.71 | -0.32 | 3.46 | 3.30 | 2.8 | 0.84 | - | - | - | - | - |
| 07 56 28.26 | 37 14 55.000 | C1 | 98.31 | 49.00 | -1.34 | 0.53 | 0.49 | 41.0 | 4.7 | 37.9 | CJ | - | - | - |
| 08 15 34.184 | 33 05 29.280 | C1 | 8.90 | 2.70 | -2.48 | 0.53 | 0.34 | 3.4 | - | - | - | - | - |
| 09 28 24.133 | 44 46 04.680 | C1 | 231.30 | 245.40 | -0.05 | 1.00 | 0.39 | 168.20 | 4.0 | 33.6 | CJ | - | - | - |
| 10 05 15.961 | 48 05 33.210 | C1 | 30.62 | 4.00 | -0.78 | 1.32 | 1.15 | 5.19 | 19 | 118.3 | CJ | - | - | - |
| 10 13 29.931 | 49 18 41.110 | C1 | 55.2 | 12.8 | - | 16.86 | - | 726.2 | 5895.8 | O | - | - | - |
| 10 18 27.837 | 05 30 29.900 | C1 | 327.33 | 261.29 | - | 0.53 | 0.34 | 167.00 | 3.4 | 28.5 | CJ | - | - | - |
| 10 42 57.598 | 07 48 50.600 | N1 | 39.74 | - | - | - | - | - | - | 13.7 | 108.9 | O | - | - |
| 10 57 26.608 | 03 24 48.470 | C1 | 12.50 | 12.74 | -0.04 | 1.84 | 1.05 | 1.11 | - | - | - | - | - |
| 11 03 44.536 | 02 32 09.740 | C1 | 64.24 | 51.26 | -0.43 | 1.84 | 1.57 | 1.83 | 10.2 | 82.2 | CJ | - | - | - |
| 11 59 44.832 | 01 12 06.870 | C1 | 110.44 | 134.39 | -0.38 | 0.59 | 0.41 | 6.02 | 0.4 | 3.3 | S | - | - | - |
| 12 23 43.165 | 50 37 53.490 | C1 | 102.57 | 29.59 | -0.33 | 2.17 | 1.17 | 2.47 | 71.2 | 521.7 | CJ | - | - | - |
| 12 05 07.795 | 40 56 58.060 | C1 | 316.39 | 185.62 | 0.49 | -0.19 | 2.27 | 0.19 | 0.43 | 83.20 | 2.8 | 23.4 | CJ | - | - |
| 14 32 43.322 | 41 03 28.040 | C1 | 20.00 | 16.5 | -0.37 | 0.58 | 0.49 | 5.12 | - | - | - | - | - |

Description of the columns: (1) & (2) source coordinates (J2000) extracted from FIRST, (3) components as indicated on the images, (4) flux density measured with the EVN on 1.7 GHz, (5) & (6) flux density measured with the VLBA on 5.0 GHz and 8.4 GHz, (7) spectral index between 1.7 and 5.0 GHz calculated using flux densities in columns (4) and (5), (8) spectral index between 5.0 and 8.4 GHz calculated using flux densities in columns (5) and (6), (9) deconvolved major axis of the Gaussian fit on 1.7, 5, and 8.4 GHz, (10) brightness temperature calculated based on the component’s size and flux density measured at the highest resolution map available using equation [11] largest angular size (LAS) measured at resolving frequency, LAS is defined as a separation between the two outermost Gaussian components, (12) largest linear size (LLS) calculated based on the LAS, (13) radio morphology: CJ - core-jet, O - other, S - single.
### Table 3. Candidates for variable sources

| RA(J2000) | Dec(J2000) | $\delta$ | $F_{\text{peak}}$ (mJy) | $\sigma_{F_{\text{peak}}}$ (mJy) | Epoch$_{F}$ | $N_{\text{int}}$ | $\sigma_{N_{\text{int}}}$ | Epoch$_{N}$ | AI | BI | $R_{2}$ | $T_{1}(\text{var})$ | $\delta_{1}$ | $\theta_{1}$ | $\delta_{2}$ | $\theta_{2}$ |
|-----------|------------|--------|---------------------|---------------------|----------|------------|---------------------|----------|----|-----|-------|---------------|--------|--------|--------|--------|
| 07 53 10.42 | 21 02 44.31 | 2.29 | 16.78 | 0.15 | 1998.695 | 14.4 | 0.6 | 1993.836 | 7479 | 3526 | 1.95 | 5.7 | >1.79 | <34.0 | <1 | – |
| 08 11 02.93 | 50 07 24.52 | 1.84 | 23.07 | 0.19 | 1997.262 | 19.5 | 0.7 | 1993.874 | 1573 | 371 | 2.14 | 12.1 | >2.29 | <25.9 | >1.06 | <70.6 |
| 08 53 42.02 | 06 56 55.18 | 2.39 | 6.89 | 0.14 | 2000.091 | 5.6 | 0.4 | 1993.874 | 1980 | 275 | 1.65 | 2.9 | >1.43 | <44.4 | <1 | – |
| 11 44 36.66 | 09 59 04.80 | 3.15 | 12.83 | 0.14 | 2000.045 | 11.2 | 0.5 | 1995.159 | 783 | 105 | 1.48 | 6.9 | >1.91 | <31.6 | <1 | – |
| 14 01 26.16 | 52 08 34.63 | 2.97 | 36.18 | 0.14 | 1997.337 | 30.4 | 1 | 1993.874 | 517 | 70 | 2.02 | 42.8 | >3.50 | <16.6 | >1.62 | <38.1 |
| 14 41 36.26 | 63 25 18.76 | 1.78 | 7.69 | 0.23 | 2002.594 | 4.4 | 0.4 | 1993.896 | 2833 | 150 | 1.50 | 1.6 | >1.17 | <58.7 | <1 | – |
| 14 59 26.33 | 49 31 36.79 | 2.37 | 5.22 | 0.14 | 1997.291 | 3.8 | 0.4 | 1995.194 | 14001 | 9419 | 1.24 | 19.6 | >2.69 | <21.8 | >1.25 | <53.1 |
| 15 37 03.95 | 53 32 19.93 | 2.40 | 9.28 | 0.14 | 1997.347 | 7.1 | 0.4 | 1993.874 | 2398 | 934 | 1.30 | 11.5 | >2.26 | <26.3 | >1.05 | <72.2 |
| 21 07 57.68 | -06 20 10.49 | 0.65 | 20.29 | 0.15 | 1997.145 | 12.4 | 0.6 | 1993.720 | 1309 | 559 | 1.41 | 3.4 | >1.51 | <41.5 | <1 | – |

Description of the columns: (1) & (2) source coordinates (J2000) extracted from FIRST, (3) redshift as measured from the SDSS, (4) FIRST peak flux density, (5) uncertainty of the FIRST peak flux density, (6) FIRST observation time, (7) NVSS integrated flux density, (8) uncertainty of the NVSS integrated flux density, (9) NVSS observation time, (10) absorption index AI taken from [Trump et al. 2006], (11) balincity index BI taken from [Trump et al. 2006], (12) radio-loudness, the radio-to-optical (i-band) ratio of the quasar core [Kimball et al. 2011], which were estimated as described in section 4.2.2 using the value of $\delta_{1}$, (13) minimum Doppler factor calculated using the equipartition brightness temperature value of $10^{11}$ K, (14) maximum viewing angles estimated as described in section 4.2.2 using the value of $\delta_{2}$.
1042+0748. This source has been observed only at 5 GHz and it has been complex radio structure. Integrated flux density from the 5-GHz VLBA image is comparable with single dish measurement (Table 1) and thus we have detected its whole structure. The overall spectrum of 1042+0748 is steep. The classification of this source is difficult and thus we marked it as ‘Other’ in Table 2.

1057+0324. This source has three components on the C-band map which are resolved out in 8.4-GHz observations. The flat spectrum component C1 is likely a radio core. The 5-GHz integrated flux density is significantly smaller (∼27%) compared to a single dish observations (Table 1). However, we are unable to unambiguously determine whether it is a result of lack of short spacings or due to intrinsic variability. The overall spectrum of 1057+0324 is steep. Based on its structure and spectral index we classified this source as a core-jet.

1103+0232. This source was observed only at 5 and 8.4-GHz with VLBA (Fig. 2). The brightest component C1 is radio core and steep spectrum components C2 and C3 are probably parts of a radio jet. Its morphology can be classified as a core-jet.

1159+0112. This source was observed by us only at 5 and 8.4 GHz with VLBA and remained unresolved (Fig. 2). Spectral index αuv = −0.37 indicates this object is core dominated. Bruni et al. (2012) compared their flux densities measurements of 1159+0112 with those previously reported by Montenegro-Montes et al. (2008). The higher frequency they contrast the more significant variability occurred. Nevertheless they could not conclude whether it is intrinsic or due to different resolution (dissimilar VLA configuration). Based on the complex spectral energy distribution Montenegro-Montes et al. (2008) concluded that the source may consists of more extended, diffuse emission and compact part with a peak frequency of νp = 6.3 GHz implying the young age of the compact structure. 1159+0112 has been also observed by Hayashi et al. (2013) on L, C and X band with VLBA. Their radio map on 1.7 GHz proves that this source posses extended emission on lower frequencies and our images at 5 GHz and 8.4 GHz are zoom in version of probable radio core. Interestingly, Hayashi et al. (2013) detected additional component on C-band in a core proximity - likely a radio jet. It is not visible on our map. This may suggest that this part of radio jet was very recently lunched from the core and such events in the past could be responsible for flux density variability detections. Based on the overall structure of 1159+0112 Hayashi et al. (2013) suggested a re-activation scenario for this object with the compact core being the new activity phase.

1223+5037. The EVN 1.7 GHz image shows double structure with a weak eastern component E, which is not present in 5- and 8.4-GHz observations. Our VLBA 8.4 GHz map is consistent with that obtained in the VIPS project (Hemboldt et al. 2007) at 5 GHz and we present all three images in Fig. 1 The inverted spectrum component C1.1 is probably a radio core, components C1.2 and C2 are parts of the radio jet and E might be a part of radio lobe. We lost ~26% of the total flux density at 1.7 GHz probably connected with the extended emission that can be present between the eastern and central components. The overall spectrum of 1223+5037 is steep. We have classified this source as a core-jet.

1405+4056. Our 1.7- and 8.4-GHz images are consistent with the 5-GHz VIPS image (Hemboldt et al. 2007). They show double structure with component C1 being a radio core (Fig. 1). The same result was obtained in VLBA observations made by Hayashi et al. (2013). Contrasting single dish flux density measurements with those reported in this paper and provided by Hayashi et al. (2013) meaningful differences (~30%) are clearly visible at 1.7 and 5 GHz. However, we are unable to unambiguously determine whether it is a result of different uv-coverage or due to intrinsic variability. 1405+4056 is a candidate for GPS object (Marecki et al. 1999).

1432+4103. This source posses double structure in the 1.7-GHz EVN map which has been resolved into complex structure in VLBA 5- and 8.4-GHz observations. Component C1 with the most flat spectrum of all detected parts is probably a radio core, the other components are parts of the one-sided jet. We lost (~23%) of the 1.7-GHz total flux density probably due to poor uv-coverage. The overall spectrum of 1432+4103 is steep. We have classified this source as a core-jet.

4 RESULTS & DISCUSSION

4.1 Parameters from VLBI imaging

During three observational campaigns 14 out of 16 sources were detected. All 14 sources but one (1159+0112) were resolved, the majority of which fall under core-jet classification (11 out of 14) thus confirming the existence of non-thermal jets in BALQSOs. We have radio maps for four sources at three different frequencies. For the rest other than one (1042+0748), we obtained images on C and X-band. The measured and derived quantities for individual components of the sources as well as their classification are presented in Table 2.

When creating the samples of BI and AI quasars we did not put any constrains on the shape of the spectrum. It has already been shown by Becker et al. (2000) that there is wide variety of spectral indices among the BALQSOs. However, most of the observed AI sources possess steep spectra and in the few cases (0217-0052, 0815+3305, 1005+4805, 1057+0324) we have noticed significant lack of flux density comparing to VLA or single dish observation. This is probably connected with more diffuse structures present in these sources which we did not fully detect in our observations due to their weakness. One source, 1159+0112, remained unresolved even at 8.4 GHz. It looks however, that due to the lack of short spacings we lost extended structures present in this source which in turn can suggest previous phase of the activity (Hayashi et al. 2013). Similar findings concerning BALQSOs have been recently reported in the work of Bruni et al. (2013). The missing flux density between VLA and VLBI observations in some cases can be attributed to the low frequency remnant of the previous phase of the radio source activity (Kunert-Bajraszewska et al. 2010, Kunert-Bajraszewska & Labiano 2010).

Finally, two of our quasars (0928+4446, 1018+0530) have been classified as flat-spectrum radio quasars (FSRQ) and one (1405+4056) is a GPS candidate (Marecki et al. 1999). The radio morphology of these three sources (0928+4446, 1018+0530, 1405+4056) and their significant flux density variations reported in the literature imply they are blazar candidates (Hayashi et al. 2013), see also Table 1. Comparing radio morphology of our sources with QSO structures (Kimball et al. 2011) we conclude that they represent typical quasar geometries.

4.1.1 VLBI brightness temperature

Additional parameter which can shed some light on the concept of orientation scenario is the brightness temperature which can be derived directly from interferometric observation or from the flux density variability. By imaging analysis, the brightness temperature in the rest frame is calculated using following equation:
Sources should be in the range of 10^18 K. In the case of three flat spectrum sources (0928+4446, 1018+0530, 1223+5037) the value of the brightness temperature is the highest among our AI quasars and exceeds 10^18 K.

The intrinsic brightness temperature of extragalactic radio sources should be in the range of 10^{11}−10^{15} K. The value of 10^{13} K is a theoretical limit which when it is exceeded leads to the well-known inverse Compton catastrophe. The 10^{11} K is an empirical value derived for a sample of variable extragalactic radio sources by Lahav et al. (1999). Taking the second limit we estimated the minimum Doppler factor that avoids the inverse Compton catastrophe as follows: \( \delta_{\text{min}} = \frac{T_{\text{b},\text{vlbi}}}{10^{11}\text{K}} \). After we estimated the viewing angle \( \theta \) of each object, defined as an angle between the jet axis and the observer, as the maximum of the following function (Ghosh & Punsly 2007):

\[
\cos \theta \leq \max \left[ \frac{\delta - \sqrt{1 - \beta^2}}{\beta \delta} \right]
\]

where \( \beta \) is the velocity of the jet and \( \delta \) is a Doppler factor.

The obtained values of the viewing angle are 36.5°, 37° and 22.6° for 0928+4446, 1018+0530 and 1223+5037, respectively. These are, however, the maximum allowed values which means that the viewing angles of the above quasars are < 37°. This result is in agreement with previously reported large flux density variations found in these objects. This in turn may imply that the sources can be larger and older than estimated by us based on the projected angular size.

### 4.2 Statistical analysis of parent sample

In the next step, using the parent sample of BALQSOs (309 sources) selected from Trump et al. (2006) we performed statistical studies concerning orientation of these objects. We also compared the properties of the two subgroups of sources, namely the AI quasars (204 objects) and BI quasars (105 objects).

#### 4.2.1 Radio-loudness distribution

The radio-to-optical ratio of the quasar core is thought to be a strong statistical indicator of orientation (Wills & Brotherton 1995). An analysis of its distribution among BALQSOs can be another way to deal with the enigma of their nature. We adopted radio-loudness definition from Kimball et al. (2011): \( R_l = (M_{\text{radio}} - M_{\text{i}})/\delta - 2.5 \), where \( M_{\text{radio}} \) is a K-corrected radio absolute magnitude and \( M_{\text{i}} \) is a Galactic reddening corrected and K-corrected i-band absolute magnitude. If indeed radio-loudness parameter is indicative of line-of-sight orientation, then its large numbers, possibly \( R_l > 2.5 \), could mean close to the radio jet axis orientation. Quasars with \( R_l < 1.5 \) are thought to be viewed at small angles relative to the plane of the disk (Kimball et al. 2011). Since all our sources are unresolved by FIRST we used their integrated 1.4-GHz flux densities as a core flux and assume the radio core spectral index and optical spectral index to be 0 and -0.5 respectively. The histogram in Fig. 3 shows the number of BALQSOs versus the radio-loudness parameter \( R_l \) for both, BI and AI, samples. The result of Kolmogorov-Smirnov (K-S) test (D=0.34) implies that both distributions are dissimilar at the 0.05 confidence level. Histogram clearly hints that while \( R_l \) rises AI sample outnumbers BI. While BI distribution peaks between 1.0 and 1.5 (fitting Gauss results in \( \log R_l = 1.24 \pm 0.30 \)) AI distribution is shifted and apex between 1.5 and 2.0 (fitting Gauss results in \( \log R_l = 1.72 \pm 0.06 \)). Thus, on average BI quasars are viewed closer to the disk plane than AI sources.

The majority of AI objects observed by us in the VLBI technique have \( R_l > 2.5 \) so they belongs to the tail of \( R_l \) distribution for AI quasars and constitute the most luminous subgroup of AI population.

#### 4.2.2 Variability brightness temperature

Significant flux density variations can signal Doppler boosting, which in turn indicates that a jet points close to the line of sight toward the observer. Therefore the flux density variability is an additional statistical indicator of orientation (Wills & Brotherton 1995). An analysis of its distribution among BALQSOs can be another way to deal with the enigma of their nature. We adopted radio-loudness definition from Kimball et al. (2011): \( R_l = (M_{\text{radio}} - M_{\text{i}})/\delta - 2.5 \), where \( M_{\text{radio}} \) is a K-corrected radio absolute magnitude and \( M_{\text{i}} \) is a Galactic reddening corrected and K-corrected i-band absolute magnitude. If indeed radio-loudness parameter is indicative of line-of-sight orientation, then its large numbers, possibly \( R_l > 2.5 \), could mean close to the radio jet axis orientation. Quasars with \( R_l < 1.5 \) are thought to be viewed at small angles relative to the plane of the disk (Kimball et al. 2011). Since all our sources are unresolved by FIRST we used their integrated 1.4-GHz flux densities as a core flux and assume the radio core spectral index and optical spectral index to be 0 and -0.5 respectively. The histogram in Fig. 3 shows the number of BALQSOs versus the radio-loudness parameter \( R_l \) for both, BI and AI, samples. The result of Kolmogorov-Smirnov (K-S) test (D=0.34) implies that both distributions are dissimilar at the 0.05 confidence level. Histogram clearly hints that while \( R_l \) rises AI sample outnumbers BI. While BI distribution peaks between 1.0 and 1.5 (fitting Gauss results in \( \log R_l = 1.24 \pm 0.30 \)) AI distribution is shifted and apex between 1.5 and 2.0 (fitting Gauss results in \( \log R_l = 1.72 \pm 0.06 \)). Thus, on average BI quasars are viewed closer to the disk plane than AI sources.

The majority of AI objects observed by us in the VLBI technique have \( R_l > 2.5 \) so they belongs to the tail of \( R_l \) distribution for AI quasars and constitute the most luminous subgroup of AI population.
This time we took both, $10^{11}$ K and $10^{12}$ K limits, and we estimated the minimum Doppler factor as follows: $\delta_1 = \left( \frac{T_b(\text{var})}{10^{11} \text{ K}} \right)^{1/3}$ and $\delta_2 = \left( \frac{T_b(\text{var})}{10^{12} \text{ K}} \right)^{1/3}$. The maximum value of function $\delta$ for both, $\delta_1$ and $\delta_2$, allowed us to determine the range where the maximum viewing angle of the quasar should be found.

The obtained range of viewing angles is wide, reaching very large values in a few cases (Table 3). One of the AI quasars from our VLBI sample, namely 0756$+3714$, also show flux density variability and is listed in Table 3. We classified this source as a core-jet, although an alternative interpretation as double-lobed young radio source has been proposed by Bruni et al. (2013). The value of the VLBI brightness temperature of 0756$+3714$ is not high, but it is close to the equipartition limit of $5 \times 10^{10}$ K proposed by Readhead (1994). It is however, much lower than the variability brightness temperature we obtained for this object. We suggest that the possible flux density variations (sec. 3) and very high value of the radio-loudness parameter allow for the core-jet classification of 0756$+3714$. VLBI observations with higher angular resolution may help to resolve puzzle of radio morphology of this source.

### 4.2.3 Orientation of BALQSOs

Estimations of the upper limit of viewing angles $\theta$ show that $\theta$ can reach value as large as $\sim 70^\circ$ for AI and BI quasars with $\log R_I < 1.5$ (Table 3). This range changes as a function of radio-loudness parameter, $\log R_I$, what is well visible in Figure 4. For the middle group, $1.5 < \log R_I < 2.5$, where the peak of the AI quasars distribution is present, the viewing angles are less than $45^\circ - 56^\circ$. We are aware that the viewing angle analysis based only on the upper limits might be burdened with significant error. However, the obtained trend seems to be in agreement with recent report about radio-loudness parameter as an orientation indicator (Kimball et al. 2011).

We contrasted then the radio-loudness values with the absorption index (AI) for the whole parent sample (Fig. 5 top panel). It is visible that stronger absorption is associated with lower values of radio-loudness parameter, $\log R_I < 1.5$. The same trend is present for BI quasars only (Fig. 5 bottom panel). This relationship however, is not so obvious for radio stronger AI quasars (Fig. 5 middle panel). Nevertheless it can be noticed that the fraction of quasars with AI value grater than 2000 starts to drop for $\log R_I < 2$.

Additionally VLBI observations of three AI quasars allowed us to verify this conclusion by independent viewing angles determination. The estimated values of the viewing angles of 0928+4446, 1018+0530 and 1223+5037 amounts to $\theta < 37^\circ$ for $\log R_I > 2.4$. And the values of absorption index for these three objects are the ones of the lowest in our sample of AI quasars indicating relatively weak absorption (Table 3).

Based on our studies presented here we conclude that there exist a preferable orientation, possibly $\theta \geq 37^\circ$, in which absorbing screen reaches maximum covering factor.
3. AI versus BI quasars

In the QSO unification scheme of Elvis (2000), both broad and narrow absorption lines are assumed to be formed in the same disc and orientation is the parameter which determines our ability to detect them as AI or BI sources. On the other hand, radio, optical, and X-ray studies of BI and AI quasars revealed many differences between them indicating that they constitute two independent classes (Knuige et al. 2008, Strebylanska et al. 2010) or are connected by the ‘evolution of the flow’ scenario, namely the weaker and much narrower absorption lines may represent the late evolutionary stages of classical BALs (Ganguly et al. 2007, Strebylanska et al. 2010). The strong influence of evolution on broad absorption lines phenomenon is supported also by the radio observations of BALQSOs (Becker et al. 2000, Gregg et al. 2006, Hewett & Foltz 2003). The fact that most of radio-loud BALQSOs are compact, so young sources, introduced the scenario in which absorption lines are present in the early evolution phase of quasars.

The results presented in this paper confirm the fact that AI and BI quasars are statistically independent. Both groups of sources differ in the value of the absorption, its distribution versus the radio-loudness parameter and the radio-loudness distribution itself. Stronger absorption is associated with smaller values of log $R_{1}$ < 1.5 which in turn can indicate small inclination angles with respect to the disk plane. Orientation is then indeed an important parameter determining the possibility of absorption line detection. However, there is another important conclusion that can be drawn from our studies of the relationship between the radio-loudness parameter and absorption. We have to emphasize that there is no correlation between the radio-loudness parameter and the AI/BI absorption. We have to emphasize that there is no correlation between the radio-loudness parameter and the AI/BI index since a

*The radio-loudness parameter is thought to be a good indicator of source orientation and therefore its low values, log $R_{1}$ ≤ 1.5 may imply large viewing angles. Since, the AI quasars have on average larger values of log $R_{1}$, the orientation can mean that we see them less absorbed.

• Orientation is an important but not the only one parameter that determines our ability to detect absorption lines. We suggest also that the radio evolution itself is not directly connected with BAL phenomenon but is rather superimposed on the radio-loud BALQSO population.

6 ACKNOWLEDGMENTS

This work was supported by the National Scientific Centre under grant DEC-2011/01/D/ST9/00378.

The research leading to these results has received funding from the European Commission Seventh Framework Programme (FP/2007- 2013) under grant agreement No 283209 (RadioNet3). The European VLBI Network is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

The research described in this paper makes use of Filtergraph, an online data visualization tool developed at Vanderbilt University through the Vanderbilt Initiative in Data-intensive Astrophysics (VIDA).

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5 CONCLUSIONS

BALQSO phenomenon is usually explained by either an orientation scenario in which structures responsible for BALs are visible under specific inclinations or by an evolutionary scenario which connects BAL with young stage of QSO evolution. Despite long and thorough discussion over the last 20 years, the ambiguity in the origin of broad absorption lines in AGN spectra remains. To address this, we have presented 1.7-, 5- and 8.4-GHz interferometric observations of 14 AI quasars (BI = 0) and compared properties of AI and BI sources from a newly selected sample. Our main conclusions are as follows:

- All AI quasars but one have been resolved in VLBI observations showing typical for QSOs, core-jet morphology. Their high radio luminosities and compact sizes indicate they belong to the population of young AGNs. Simultaneously the bright sources are a minority among absorption quasars and thus these AI objects belong to the tail of radio power distribution for AI quasars.

- The statistical analysis of AI and BI sources shows that for the radio-loudness parameter, log $R_{1}$, the distribution of AI and BI quasars differ significantly, peaking at 1.2 and 1.7 for BI and AI, respectively. Notice that the strong absorption, which is exclusively visible in BI quasars, is connected with lower values of log $R_{1}$ and weak radio emission.

- The radio-loudness parameter is thought to be a good indicator of source orientation and therefore its low values, log $R_{1}$ ≤ 1.5 may imply large viewing angles. Since, the AI quasars have on average larger values of log $R_{1}$, the orientation can mean that we see them less absorbed.

- Orientation is an important but not the only one parameter that determines our ability to detect absorption lines. We suggest also that the radio evolution itself is not directly connected with BAL phenomenon but is rather superimposed on the radio-loud BALQSO population.
