MISALIGNMENT OF THE JET AND THE NORMAL TO THE DUSTY TORUS IN THE BROAD ABSORPTION LINE QSO FIRST J155633.8+351758

CORMAC REYNOLDS1, BRIAN PUNSLY2,3, AND CHRISTOPHER P. O’DEA4

1 ICRAR-Curtin University, GPO Box U1987, Perth, Western Australia 6102, Australia
2 1415 Granvia Altamira, Palos Verdes Estates, CA 90274, USA; brian.punsl y1@verizon.net, brian.punsl y2@comdev-usa.com
3 ICRANet, Piazza della Repubblica 10, I-65100 Pescara, Italy
4 Laboratory for Multiwavelength Astrophysics, School of Physics and Astronomy, Rochester Institute of Technology, 42 Lomb Memorial Drive, Rochester, NY 14623, USA

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ABSTRACT
We performed Very Long Baseline Array observations of the broad absorption line quasar FIRST J155633.8+351758, “the first radio loud BALQSO.” Our observations at 15.3 GHz partially resolved a secondary component at position angle (P.A.) ≈ 35°. We combine this determination of the radio jet projection on the sky plane, with the constraint that the jet is viewed within 14°3 of the line of sight (as implied by the high variability brightness temperature) and with the P.A. of the optical/UV continuum polarization in order to study the quasar geometry. Within the context of the standard model, the data indicates a “dusty torus” (scattering surface) with a symmetry axis tilted relative to the accretion disk normal and a polar broad absorption line outflow aligned with the accretion disk normal. We compare this geometry to that indicated by the higher resolution radio data, brightness temperature, and optical/UV continuum polarization P.A. of a similar high optical polarization BALQSO, Mrk 231. A qualitatively similar geometry is found in these two polar BALQSOs; the continuum polarization is determined primarily by the tilt of the dusty torus.

Key words: quasars: absorption lines – quasars: general

Online-only material: color figures

1. INTRODUCTION

Approximately 15%–20% of quasars have UV broad absorption line (BAL) outflows or winds, depending on the sample selection criteria (Hewett & Foltz 2003; Reichard et al. 2003; Trump et al. 2006; Gibson et al. 2009). The wind is believed to be a general feature in quasars, but it is seen only in favorable configurations due to a limited solid angle (Weymann 1997). The physical origin of the BAL wind is very uncertain. Knowing the orientation of the BAL wind relative to the accretion disk normal and dusty torus normal (within the “standard quasar model”; see Antonucci 1993) would advance our knowledge of the physics of the BAL wind launching mechanism.

 Gathering evidence of quasar orientation is difficult. Most of our knowledge derives from studies of radio-loud quasars (Orr & Browne 1982). Unfortunately, radio jets in broad absorption line quasars (BALQSOs) are suppressed and especially so on scales larger than a few kiloparsecs, a trend that strengthens with increasing BALnicity index (Becker et al. 2000, 2001). Motivated by the potential orientation information, studies of the rare subclass of radio-loud BALQSOs have been an active area of research. Statistical studies have been aimed at exploring the evidence for evolutionary models (e.g., Briggs et al. 1984; Sanders 2002) in which the BALQSO phenomenon is a transient stage or models based on a preferred line of sight to an ever-present BAL wind. The orientation models include various wind geometries: equatorial (Murray et al. 1995), mid-latitude (Elvis 2000); polar, Ghosh & Punsly (2007) or polar winds coexisting with equatorial winds (Punsly 1999). The radio surveys of Bruni et al. (2012), DiPompeo et al. (2011), and Montenegro-Montes (2008) have drawn no clear conclusions.

 Only recently has direct information on this geometric configuration become available from radio observations. If a source is highly variable, one might infer a brightness temperature, $TB > 10^{12}$ K, that requires a nearly pole-on orientation and relativistic motion for the jet in order to avoid the “inverse Compton catastrophe” (Marscher et al. 1979). Numerous BALQSOs in a pole-on orientation have now been found by this method (Zhou et al. 2006; Ghosh & Punsly 2007; Reynolds et al. 2009). The extra constraint provided by the polar orientation makes these BALQSOs valuable laboratories for studying quasar geometry. The position angle (P.A.) on the sky plane and kinematics of the radio jet provide probes of both the enveloping BAL wind and the geometry of the wind/accretion disk system. Another constraint on the quasar geometry is provided by the optical continuum polarization P.A. This relates directly to the geometry of the UV absorbing wind and, even more so, the scattering surface that is associated with the elevated polarization seen in some BALQSOs. Thusly motivated, we have begun a program to study subparsec and parsec scale radio jets in combination with optical polarization P.A.s in BALQSOs.

The Doppler enhancement associated with the polar orientation tends to make the jets in polar BALQSOs among the most luminous in a class of objects that have a strong propensity for weak jet emission. In order to pursue a study of polar BALQSO geometry, high resolution (high frequency), very long baseline interferometry (VLBI) observations with high sensitivity...
Table 1

Parameters of Core and Jet Components in FIRST J1556+357 at Epoch 2011.07

| Frequency (GHz) | Core Flux Density (mJy) | Secondary Flux Density (mJy) | Separation (mas) | Secondary (P.A.) (deg) |
|----------------|-------------------------|-------------------------------|------------------|------------------------|
| 1.6           | 16.5 ± 0.5              | ...                           | ...              | ...                    |
| 5.0           | 18.8 ± 0.5              | ...                           | ...              | ...                    |
| 8.4           | 17.2 ± 0.5              | 0.7 ± 0.1                     | 1.57 ± 0.09      | 61 ± 3                 |
| 15.3          | 14.1 ± 0.5              | 0.9 ± 0.1                     | 0.98 ± 0.08      | 35 ± 3                 |

Note. * Core and secondary not resolved.

(because of the weak secondary components and jets) are required in order to see the jet direction near the accretion disk. Mrk 231 is the best choice. The proximity, $z = 0.042$, and the large flux density of $\sim 100$ mJy at 22 GHz are two factors that greatly enhance the spatial resolution achievable in observations. We have examined high frequency Very Long Baseline Array (VLBA) radio observations of Mrk 231 and their geometrical implications (Reynolds et al. 2009). It is essential to do the same for more BALQSOs in order to understand which geometrical properties are endemic to the broad absorption phenomenon and which properties are unrelated idiosyncrasies of particular sources. This critical aspect challenges the limits of our observational tools since all other bona-fide BALQSOs are much fainter radio sources than Mrk 231. The next best choice after Mrk 231 is FIRST J155633.8+351758 (FIRST J1556+3517, hereafter), the high optical polarization quasar at $z = 1.50$, dubbed the first discovered radio-loud BALQSO (Becker et al. 1997). Strangely, like Mrk 231, this is a member of the rare class of BALQSOs known as FeLoBALQSOs due to absorption in low ionization species and strong Fe II emission. Being the “first” radio-loud BALQSO discovered led to a flurry of deep optical observations (Brotherton et al. 1997; Najita et al. 2000). The polarization P.A. $\approx 153^\circ$ from deep Keck spectroscopy and it has a flat 25–30 mJy spectrum from 1.4 to 5 GHz (Brotherton et al. 1997; Becker et al. 1997). FIRST J1556+3517 is viewed close to the polar axis ($\sim 43^\circ$) based on high variability brightness temperatures (Ghosh & Punsly 2007).

The Letter is organized as follows. In Section 2, we discuss our VLBA observations ranging from 1.6 GHz to 15.3 GHz and the implications for the quasar geometry. Section 3 is a consideration of the geometrical implications of the observations. The next section discusses the implicit geometry in a broader context that includes Mrk 231. Throughout this Letter, we adopt the following cosmological parameters: $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_L = 0.73$ and $\Omega_m = 0.27$.

2. THE VLBA OBSERVATIONS

A previous VLBI observation of FIRST J1556+3517 was unresolved with a flux density of 26 mJy with the European VLBI Network (EVN) at 1.4 GHz (Jiang & Wang 2003). Better resolution was needed to detect a jet, so we carried out observations at frequencies of 1.6, 5.0, 8.4 and 15.3 GHz with the VLBA at epoch 2011.07 (project code BR156)—see Table 1. A recording rate of 512 MHz (the best available at the time) was used in order to achieve the high sensitivity required to detect a weak jet. This provided 64 MHz of bandwidth in two polarizations with 2 bit Nyquist rate sampling at each frequency. The resultant image sensitivities were 0.11, 0.08, 0.08 and 0.15 mJy beam$^{-1}$ at 1.6, 5.0, 8.4 and 15.3 GHz respectively. The data were correlated on the VLBA correlator in Socorro, NM and calibrated was carried out in the standard way using NRAO’s Astronomical Image Processing System package via the Parsel Tongue interface (Kettenis et al. 2006). FIRST J1556+3517 was phase referenced to the nearby calibrator J1602+3326 to provide phase calibration and some astrometric information. Subsequent phase self-calibration of the target source was also possible at all frequencies.

3. RESULTS AND GEOMETRIC IMPLICATIONS

At 1.4 and 5 GHz, the source was unresolved with synthesized beam sizes of approximately $7 \times 10$ mas and $2 \times 3$ mas, respectively. As with previous VLA and EVN observations, there is no evidence of jet reorientation in these images in the form of resolved emission at a differing P.A. from the VLBI secondary component. However, at 8.4 and 15.3 GHz, with synthesized beams of $1.0 \times 1.8$ and $0.7 \times 1.1$ mas, respectively, we partially resolve a faint secondary component (see Figure 1) allowing us to determine the direction of the parsec-scale jet. We fitted a two Gaussian component model to the 8.4 and 15.3 GHz data using the DIFMAP software package (Shepherd et al. 1995), the results of which are given in Table 1. The positions of the 8.4 GHz and 15.3 GHz secondary components do not agree, likely a combination of inhomogeneous optical depth effects and a curving jet. The 15.3 GHz observation, sensitive to emission originating much deeper within the optically thick plasma, is more relevant for exploring nuclear geometry.

The VLBA observations, in conjunction with the UV polarization P.A., provide a set of tight constraints on the quasar geometry (the right frame of Figure 1). These can be summarized as follows.

1. The accretion disk position is associated with the high frequency radio core (right frame Figure 1).
2. In Ghosh & Punsly (2007), the variability brightness temperature was calculated as $T_B = 6.7 \times 10^3$ K, thereby restricting the jet axis to $< 143^\circ$ to the line of sight.
3. The projection of the radio jet axis on the sky plane, computed from the coordinates of the peaks of Gaussian components, is at P.A. $\approx 35^\circ$ (right frame Figure 1).
4. From 2 and 3 above, the accretion disk normal (parallel to the parsec radio jet) is rotated relative to the z-axis (the line of sight which comes out of the page) by $< 8^\circ$ about the vertical, y-axis (all rotations are in a left handed sense) and $< 11^\circ$ about the horizontal, x-axis (which points to the right); see Figure 2. The direction of the jet in Figure 2 represents the maximum angle from the line of sight.
5. The UV polarization direction is P.A. $\approx 153^\circ \equiv −27^\circ$ redward of 3000 Å (see Figure 2; Brotherton et al. 1997).
6. The scattered photons are along the line of sight by definition (the z-axis).
7. Since the line of sight is through the BAL wind and the jet is aligned close to the line of sight, the BAL wind is a polar outflow aligned close to the line of sight.

Combining these constraints, we deduce the relative orientation of the scattering surface that produces the high polarization and the BAL wind. Since the emission lines are polarized identically to the continuum, Brotherton et al. (1997) pointed out that the scattering surface lies well outside the broad emission line region, $\sim 1$ pc from the source. This is a typical distance to the inner edge of the dusty torus (Barvainis 1987). A scatterer containing some dust seems reasonable based on the reddened spectrum of the polarized emission (Najita et al. 2000). An asymmetric distribution of dusty scatterers has been routinely
Figure 1. On the left (right) is an 8.4 GHz (15.3 GHz) image of FIRST J1556+3517. Contours start at 3σ above the rms image noise. The 8.4 GHz contours start at ±0.23 mJy beam$^{-1}$ and increase by factors of two to a peak of 14.9 mJy beam$^{-1}$. The 15.3 GHz contours start at ±0.45 mJy beam$^{-1}$ and increase by factors of two to a peak of 11.2 mJy beam$^{-1}$. The position of the secondary jet component is indicated by the small crosses (the sizes of which indicate the 3σ position uncertainty along the major and minor axes of the restoring beam). The restoring beams are indicated in the bottom left insets. The right frame shows the relative orientation of the projection of the jet in the sky plane inferred from the secondary position and the optical/UV polarization P.A.

Figure 2. A simple geometry for FIRST J1556+3517 that is consistent with the VLBA observations and the Keck polarization data. A dusty torus in red harbors a small white (almost face-on) accretion disk at its center. Emanating from the accretion disk is a narrow radio jet that is depicted by a cone with black sides and a yellow cap. It is beamed almost directly toward Earth, but slightly to the north and east. It is nested within a coaxial diffuse light blue BAL conical wind. The density gradient in the conical wind is indicated schematically by a high opacity blue cone nested within a low opacity light blue cone. The tilt of the torus in the sky plane determines the polarization P.A. On the right is a zoom in of the central region. (A color version of this figure is available in the online journal.)

invoked to explain the similar polarization properties of another reddened BALQSO, Mrk 231, which also has a polarization level that rises rapidly into the near UV (Smith et al. 1995; Goodrich & Miller 1994; Schmidt & Miller 1985; Thompson et al. 1980). For example, within the context of the “standard model” we may have a torus with a symmetry axis that is tilted relative to the jet axis by 30°–40° by means of a rotation about a line that is parallel to the P.A. of the projection of the polarization on the sky plane, i.e., a line at P.A. = 153° in the x–y plane (see Figure 2). Misaligned tori are not an expected feature of the
Figure 3. The left frame shows a secondary 0.8 pc from radio core in this 43 GHz VLBA image of Mrk 231 from Reynolds et al. (2009). The optical and UV continuum polarization directions from Smith et al. (1995) are superimposed on the radio image. The left frame shows the relative orientation of the projection of the jet in the sky plane inferred from the secondary position and the optical/UV polarization P.A. The right frame depicts a three-dimensional physical representation of the two-dimensional data projected on the sky plane that is presented in the left frame.

(A color version of this figure is available in the online journal.)

standard model. However, direct evidence of misalignment of molecular gas on subparsec and parsec scales exists. There are 10 active galactic nuclei (AGNs) with water maser disks (viewed edge on) that have been observed which also have high resolution images of the radio jets (Greene et al. 2013; Kondratko et al. 2005). One of these AGN (NGC 1068) also has mid-IR interferometry on parsec scales that are typical for the dusty torus (Raban et al. 2009). Even though the statistics are small, the data indicates a significant misalignment of the normal to the plane of molecular gas rotation and the subparsec or parsec scale jet of $\geq 30^\circ$ in 20%–30% of AGN. So the occurrence of a misaligned torus in some BALQSOs should not be unexpected.

The angle of misalignment, although speculative, is motivated in the next section.

FIRST J1556+3517 is a very high polarization BALQSO with 12% continuum polarization in the near UV (Brotherton et al. 1997). A misalignment of the dusty torus and the radio jet is expected in high polarization (>3%) BALQSOs based on theoretical modeling of polarization in polar BAL wind models (Punsly 1999). Theoretically, large attenuation of the continuum is achieved in LoBALQSOs by the base of the BAL wind (electron scattering) and dusty gas that is entrained in the wind on parsec scales. Thus, there is a large contribution of scattered light to the net observed flux. Since the BAL wind is parallel to the jet and the line of sight, in order for high polarization to occur in polar BALQSOs, the symmetry of the system must be broken. This is either accomplished by anisotropic scatterers (see Kim & Martin 1995) or, as considered more likely here, an asymmetric distribution of isotropic scatters (Brown & McClean 1977). If the large polarization is from anisotropic scatterers, then the polarization direction might be determined by dust grain alignment in a large scale wind or a large scale ordered magnetic field. Although this alternative scattering scenario is not ruled out by observation, it is not pursued here.

4. ANALOGIES TO Mrk 231

In order to see if this scenario of an asymmetric distribution of isotropic scatters is reasonable, it would be instructive to compare our findings to another similar object. Mrk 231 is also a FeLoBALQSO with high near UV continuum polarization, $\sim 13\%$ (Smith et al. 1995). The data for Mrk 231 is superior due to its proximity to Earth. In Reynolds et al. (2009), we considered 2 epochs of 43, 22 and 15 GHz VLBA observations of the resolved core of Mrk 231 and also the time variability of the historic light curve at 22 GHz. A resolved secondary exists just 0.8 pc from the core (see Figure 3). Repeating the evidence and logic that we used to determine a nuclear geometry for FIRST J1556+3517 in Section 3 with the data gathered from observations of Mrk 231, we find:

1. The accretion disk position is associated with the radio core at 43 GHz (see Figure 3, left frame).
2. The variability brightness temperature, $T_B = 1.25 \times 10^{13}$ K, restricts the jet axis to $<25^\circ:6$ to the line of sight (Reynolds et al. 2009).
3. The projection of the radio jet axis on the sky plane is at P.A. $\approx -112^\circ$ (see Figure 3, left frame).
4. From items 2 and 3 above, the accretion disk normal (parallel to the parsec radio jet) is rotated relative to the $z$-axis (the line of sight which is out of the page) by $<23.5^\circ$ about the vertical, $y$-axis (all rotations are in a right handed sense) and $<10:1$ about the horizontal, $x$-axis (which points to the right). The angle of the jet in Figure 3 represents the maximum angle from the line of sight.
5. The polarization direction from Hubble Space Telescope and ground-based observations in Smith et al. (1995) is $90^\circ < $ P.A. $< 100^\circ$ redward of 3000 Å (as depicted in the left frame of Figure 3).
6. The scattered photons are along the line of sight by definition (the z-axis).

7. Since the line of sight is through the BAL wind and the jet is aligned close to the line of sight, the BAL wind is a polar outflow aligned close to the line of sight.

The right frame of Figure 3 is a realization of the polarization and radio data in terms of the components of the standard model. A tilted dusty torus exists as for FIRST J1556+3517. The polar BAL wind directed close to the line of sight simplifies the scattering geometry. The scattering mirror is essentially the small unshadowed region of the surface that bounds the hole of the torus almost due south. The projection of the tangent plane at the “centroid” of this effective mirror, as seen in the sky plane, is almost parallel to the P.A. of the continuum plane at the “centroid” of this effective mirror (Reynolds et al., in preparation). This result is assumption-dependent and to match the polarization and attenuation in the UV requires the entrainment of exotic dust in the BAL wind, the type of non-Galactic dust that is seen in some distant galaxies (Eliasdottir et al. 2006; Folatelli et al. 2010). The large attenuation in the UV requires small grain sizes (Kim & Martin 1995), and we assume them to be isotropic scatterers. The dust entrained in the BAL wind attenuates both the continuum and the light reflected from the torus, but does it not polarize the emission that it scatters similar to what is seen in the centers of cold dark clouds in the Galaxy (Goodman et al. 1995). The large number of free parameters in the models detracts greatly from their predictive power.

5. CONCLUSION

In this Letter, we demonstrated how $T_B$, the optical continuum P.A. and the radio jet direction can be used to determine a compatible geometry for individual BALQSOs within the context of the fundamental elements of the standard model. This was illustrated with two similar high polarization sources—FIRST J1556+3517 and Mrk 231, indicating a misaligned accretion disk and dusty torus. Higher frequency and higher sensitivity VLBA observations of FIRST J1556+3517 (using the new wideband digital backend system) will allow us to better determine the direction of the jet on even smaller scales and better constrain the geometry (recall the evidence for a curving jet discussed in Section 3). If higher resolution observations indicate a change to the estimate of the jet P.A. then the methods presented here are robust and the geometric picture in Figure 2 (the jet direction) can be modified in a straightforward manner. Furthermore, multi-epoch monitoring of superluminal motion of secondaries in FIRST J1556+3517 and Mrk 231 can supplement the $T_B$ estimates in our determination of the angle between the line of sight and the jet direction.

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