Spectropolarimetry of PKS 0040−005 and the Orientation of Broad Absorption Line Quasars

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ABSTRACT

We have used the Very Large Telescope (VLT) to obtain spectropolarimetry of the radio-loud, double-lobed broad absorption line (BAL) quasar PKS 0040−005. We find that the optical continuum of PKS 0040−005 is intrinsically polarized at 0.7% with an electric vector position angle nearly parallel to that of the large-scale radio axis. This result is naturally explained in terms of an equatorial scattering region seen at a small inclination, building a strong case that the BAL outflow is not equatorial.

In conjunction with other recent results concerning radio-loud BAL quasars, the era of simply characterizing these sources as “edge-on” is over.

Key words: polarization - quasars: individual (PKS 0040−005).

1 INTRODUCTION

Depending on the selection techniques used, some 10-30% of luminous quasars show blueshifted broad absorption lines (BALs) indicative of substantial outflows. By carrying away angular momentum, these outflows may be a fundamental part of the accretion process, and they may also be important for chemically enriching the interstellar and even intergalactic mediums. There is still no consensus about the nature of BAL quasars, however, although many possibilities have been discussed (e.g. Weymann et al. 1991).

One possibility is that quasars only possess such high-velocity outflows during a relatively short-lived evolutionary phase during which they blow material out of the nuclear region (e.g., Voit et al. 1993; Becker et al. 2000; Gregg et al. 2002; Gregg et al. 2006). Another is that BAL quasars and normal quasars may be unified through orientation as for some other AGN classes. In this popular equatorial paradigm, BALs are seen in quasars viewed at high inclination angles such that the line of sight passes through an equatorial wind (e.g., Hines & Wills 1995; Cohen et al. 1995; Goodrich & Miller 1995; Murray & Chiang 1995).

Polarimetry can be a useful tool for testing the latter idea, “unification by orientation,” because scattering processes leading to polarization when geometric asymmetries are present. Antonucci (1983) first pointed out that Seyfert 1 and Seyfert 2 galaxies both display optical polarization, but in the type 1 galaxies the polarization electric vector is parallel to the radio axis, while in type 2 galaxies the two are perpendicular, suggesting different geometries for the two types and helping to lead to the unification of Seyfert galaxies through orientation. Spectropolarimetry of NGC 1068 (Antonucci & Miller 1983) showing a type 1 broad-lined spectrum in polarized light made the case compelling. Broadlines and continuum may be scattered by a polar scattering region along the jet axis, leading to perpendicular angles, while equatorial scattering in a Seyfert 1 leads to the parallel angles. This work has been greatly expanded in recent years (e.g., Smith et al. 2004) and also applied to radio-loud AGNs at both low and high redshift (e.g., Cimatti et al. 1993; Cohen et al. 1999; Vernet et al. 2001).

When radio-loud BAL quasars began to be found (Becker et al. 1997; Brotherton et al. 1998; Becker et al. 2000), Brotherton et al. (1997) proposed that the alignments of the jet axes and polarization angles should be measured to test BAL quasar geometry in the same way as in other AGNs. Despite the discovery of radio-loud BAL quasars, very few have shown extended jets permitting this test.

In order to pursue questions concerning the nature of BAL quasars, we searched for BAL quasars with extended radio structures by examining Sloan Digital Sky Survey quasars (Schneider et al. 2002) and their radio maps from FIRST Survey (Becker, White, & Helfand 1995). We classified SDSS 004323.43−001552.43 as an extended, radio-loud FR II BAL quasar. This quasar was previously detected by

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many radio surveys and is better known as PKS 0040–005. PKS 0040–005 (z = 2.806) has also been recently classified as a FR II BAL quasar by Gregg et al. (2006) and Zhou et al. (2006). We targeted PKS 0040–005 for spectropolarimetry to test the geometry of BAL quasars.

2 OBSERVATIONS AND DATA

2.1 VLT Spectropolarimetry

We obtained spectropolarimetric observations of PKS 0040–005 on UT 2003 September 20 and 21 using the PMOS mode of the FORS1 spectrograph (Appenzeller et al. 1998) on the Antu unit of the ESO Very Large Telescope (VLT). On September 20, we observed the source at airmass between 1.83 and 1.62 with 1.0″ seeing. To obtain more sensitive data, we re-observed the source during the next night with airmass 1.15 and 0.7″ seeing. Conditions were photometric on both nights. The observations were split into four 300s exposures, each at a different orientation of the half-wave plate (0°, 22.5°, 45°, 67.5°). We used the 300V grism with a 1.0″ wide slit oriented North-South, resulting in a spectral resolution of ~10 Å (FWHM).

We reduced the data using standard IRAF procedures. We extracted the spectra with identical 4″ wide apertures for the o and e-rays, and re-sampled all 8 individual spectra for both half-wave plate positions to the same linear dispersion (2.6Å/pix) in order to calculate the polarization in identical spectral bins. We used the procedures of Vernet (2001; see also Vernet et al. 2001), which are based on the method described by Cohen et al. (1997). We checked the polarization angle offset between the half-wave plate coordinate and the sky coordinates against values obtained for the polarized standard stars BD+22°5133 and NGC 2024 NIR1 and the unpolarized standard star GD 50; our values are within < 1° from the published values, and the polarization percentage within 0.1%. Figure 1 shows our results.

2.2 Supplemental Data and Information

The 1.5GHz map of PKS 0040 – 005 from FIRST (Becker et al. 1995) shows a double-lobed source that has a position angle of 51°. Gregg et al. (2006) show the map, and provide additional measurements based on the radio image and the optical SDSS spectrum. They assume a cosmology of $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$, and report a 1.4 GHz radio luminosity (ergs s$^{-1}$) of log $L_{1.4GHz} = 34.1$, an absolute $g$ magnitude of $M_g = -26.44$ (and -26.78 after correcting for an estimate of small intrinsic reddening), and a radio loudness parameter log $R^*$ (Stocke et al. 1992) of 2.9 (2.7 dereddened). The radio source is 117 kpc across for this cosmology, the smallest of their eight sources. The radio core dominance, or core-to-lobe flux at 1.4 GHz, they report to be 0.09. The C IV BAL has a balnicity index (Weymann et al. 1991) of 1073 km s$^{-1}$.

The homogenized radio data available through the NASA Extragalactic Database (NED) shows that the radio spectrum of PKS 0040 – 005 is steep, with a radio spectral index $\alpha = -1.2$ ($S \propto \nu^\alpha$).

3 RESULTS

Averaging over the central spectral region where the signal-to-noise ratio is high and the data are well behaved, PKS 0040-005 shows intrinsic continuum polarization (0.72 ± 0.08%) at a well-defined position angle(36 ± 3°). The polarization is intrinsic. The interstellar polarization (ISP) from...
aligned dust grains is expected to be very low toward this sight line, since the Schlegel et al. (1998) extinction E(B-V) is only 0.017 mag, and the maximum ISP polarization should be less than 9 \times \epsilon(B-V)/% (Serkowski et al. 1975), or 0.15%. Furthermore, the polarization rises in the C IV BAL trough bottom (and perhaps Lyman \alpha) showing that the polarization must be intrinsic. Rising polarization in trough bottoms is seen in many BAL quasars and has been interpreted as the result of the scattered line of sight being less absorbed than the direct line of sight (e.g., Ogle et al. 1999).

While we prefer an explanation of scattering as the origin of the polarization, the data quality is insufficient to completely rule out synchrotron emission. The polarized flux spectrum is noisy and not inconsistent with a power-law. PKS 0040–005 is a steep spectrum FR II radio source with strong lobes and a weak core, suggestive that it is not being viewed directly jet on which is usually required for synchrotron to be important, but the polarization level here is relatively weak and it is possible and has been seen in other sources (Schmidt & Smith 2000). We argue below, under the assumption that the polarization arises from scattering, that PKS 0040–005 and its BAL outflow is not seen at a particularly high inclination angle. The case for this is only stronger if the polarization is from beamed synchrotron.

4 DISCUSSION

The position angle of the continuum polarization (36° ± 3°) is close to parallel to the large-scale radio axis (∼ 51°), a difference of 15°, and is the first BAL quasar found with this property. In analogy to the Seyfert galaxies and radio galaxies/quasars, this suggests a geometry in which PKS 0040–005 is not seen edge-on, but at some modest inclination angle (consistent with the smallish but double-lobed radio structure), and the scattering takes place in an equatorial scattering region. Good illustrations of this geometry can be seen in Figures 6 and 10 of Smith et al. (2004).

Lamy & Hutsemékers (2004) explored the concept of a “two component wind” for BAL quasar outflows, that included both equatorial and polar outflows, and had support from theoretical models (e.g., Proga 2000, 2003; Pereyra et al. 2004), which are variations of the disk wind of Murray et al. (1995). Lamy & Hutsemékers (2004) were trying to explain not only some correlations they found in the polarimetric properties and their relationship to BAL properties, but also the source of the polar scattering region. The fact that sometimes polarization angle rotations are seen across emission lines in BAL quasars, or with changes in wavelength, is suggestive that more than one scattering path is likely present. Our observation of PKS 0040 – 005 fits into this picture, and in fact its other properties are also consistent with the relationships Lamy & Hutsemékers (2004) report: the continuum polarization is low which corresponds to a large BAL detachment and weak absorption in the polarized flux spectrum.

We can compare the alignment in PKS 0040 – 005 to other BAL quasars. Table 1 summarizes the optical polarization properties and radio position angles of BAL quasars for which both quantities have been reported. References provided for each are relevant to the discovery or classification, or provide details for the information given in the table. Some entries are averages over a wide range of wavelengths (e.g., broad band or white light observations), but when explicit ranges are given, it indicates that the values change as a function of wavelength.

Figure 2 shows histograms of the difference in position angle between the electric vector of the optical/ultraviolet continuum linear polarization. The top panel shows broad-lined type 1 AGNs, including Seyfert 1 galaxies (shaded), broad line radio galaxies, and some scattered-light quasars (see text). The bottom panel shows narrow-lined type 2 AGNs, including hidden-broad-line Seyfert 2 (shaded) and radio galaxies (see text). The middle panel shows BAL quasars from Table 1.
with the jet in the plane of the sky (as would young sources), and will be less likely to be resolved in FIRST maps. Furthermore, sources dominated by equatorial rather than polar scattering often have weak polarization due to larger dilutions from the face-on quasar (although dust present in some BAL outflows, especially low-ionization BAL quasars, may also reduce dilution), and for AGNs seen directly face-on the scattering polarization is expected to be zero. For instance, the highly polarized low-ionization BAL quasar FIRST J1556+3517 (Brotherton et al. 1997) has a flat and instance, the highly polarized low-ionization BAL quasar may also reduce dilution), and for AGNs seen directly face-on the scattering polarization is expected to be zero. For instance, the highly polarized low-ionization BAL quasar FIRST J1556+3517 (Brotherton et al. 1997) has a flat and variable radio spectrum, signs of a jet-on source, but has not been resolved even with VLBI (Jiang & Wang 2003).

While our spectropolarimetry of PKS 0040−005 represents only one data point, it joins a growing list of observations that pose problems for the equatorial paradigm.

4.1 More Evidence Against Edge-On Only Orientation in BAL Quasars

The present observation is not the only evidence against simple orientation schemes. Over the last decade, evidence against edge-on geometries has emerged from several avenues, the strongest involving radio emission. The properties of radio sources have long been understood to depend greatly upon how they are seen.

Barvainis & Lonsdale (1997) and Becker et al. (2000) pointed out that BAL quasars have both flat and steep radio spectra. Typically, jet-on sources with optically thick beamed synchrotron radiation have flat radio spectra, while edge-on sources are dominated by optically thin radio lobe emission which has a steep spectrum. The first study was on formally radio-quiet objects, but the Becker et al. (2000) sample has radio-loud objects of both types. Furthermore Becker et al. (2000) noted that very few of the radio-selected BAL quasars were extended at FIRST Survey resolutions compared to similarly selected, unabsorbed quasars. Some of these BAL quasars were compact steep spectrum sources, which have been hypothesized to be young sources (O’Dea 1998). Gregg et al. (2002) and Gregg et al. (2006), studying examples of FR II BAL quasars developed this idea into an evolutionary hypothesis, that a BAL phase evolves into a radio-loud phase, with only a short temporal overlap. Zhou et al. (2006) find a number of BAL quasars associated with radio sources that vary on relatively short timescales indicating extreme brightness temperatures that can only be explained by beaming within 20 degrees of the jet direction.

Another radio oddity for BAL quasars is noted by White et al. (2006), reporting that BAL quasars on average seem to have higher average radio fluxes than unabsorbed quasars (it should be noted that the majority are not radio loud). These radio properties seem quite difficult to explain in terms of a single preferred orientation.

Additionally, at optical/ultraviolet wavelengths, BAL quasars have been noted to lie at an extreme of the “eigen-vector 1” of Boroson & Green (1992), showing an excess of broad optical Fe II emission and a deficit of [O III] emission (Boroson 2002; Yuan & Wills 2002). Turnshek et al. (1997) followed up on this idea, using the Hubble Space Telescope (HST) to obtain ultraviolet spectra of quasars with weak [O III] emission, finding approximately 1/3 of these to show C IV BALs. Telfer et al. (2000) conducted an HST imaging survey for extended narrow-line regions they expected to see if BAL quasars were edge-on quasars, but no such extensions were found. The weak NLR emission in particular is difficult for orientation models to explain, since the spectra of edge-on type 2 objects are remarkable for their prominent narrow emission lines.

X-ray observations of BAL quasars may also be problematic for the equatorial paradigm. Punsly (2006) points out that the absorbing columns measured with X-ray telescopes toward BAL quasars are not smaller than those toward type 2 quasars. Disk wind models predict they should be, and Punsly argues that the observational selection effects seem insufficient to account for this inconsistency.

Finally, we have omitted one object from Table 1 that may also have aligned axes and a polar BAL outflow, but the situation is not clear cut. Markarian 231 has appeared in the literature with both small (Antonucci 1983) and large $\Delta \theta$ (Smith et al. 2004). The VLBA observations of Ulvestad et al. (1999) may indicate a jet direction ($\sim 65^\circ$) quite different from the large scale radio structure ($\sim 5^\circ$), which may be an issue of general concern, although Mrk 231 is not radio-loud like the high-redshift entries in the table. Another difficulty involves the fact that the polarization angle rotates significantly in the far ultraviolet (Smith et al. 1995), and that in Mrk 231 and other objects it is not al-

| Object          | $z$ | Type     | Optical Polarization | Radio P.A. | Angular $\Delta \theta$ | References               |
|-----------------|----|----------|----------------------|------------|--------------------------|--------------------------|
| PKS 0040−005    | 2.81 | HiBAL    | 0.72 ± 0.08%         | 36 ± 3     | 51                        | This Paper               |
| FIRST J1016+5209| 2.46 | HiBAL    | 2-3                  | 75-85      | 146                       | Gregg et al. 2000        |
| UN J1053−0058   | 1.55 | LoBAL    | 1.9                  | 90         | 27                        | Brotherton et al. 1998   |
| FBQS 1312+2319  | 1.52 | HiBAL    | 1.1                  | 166        | 59                        | Lamy & Hutsemekers 2000 (pol) |
| LBQS 1138−0126  | 1.27 | LoBAL    | 3-4                  | 150-180    | 52                        | Becker et al. 2000       |
| PG 1700+5153    | 0.29 | LoBAL    | 0.6                  | 55         | 145                       | Sluse et al. 2004 (pol)   |
| PKS 1004+130    | 0.24 | HiBAL    | 0.7-1.6              | 24-63      | 117                       | Jiang & Wang 2003 (rad)   |
|                  |     |          |                      |            |                            | Brotherton et al. 2002    |
|                  |     |          |                      |            |                            | Kellerman et al. 1994 (rad) |
|                  |     |          |                      |            |                            | Schmidt & Hines 1999 (pol) |
|                  |     |          |                      |            |                            | Wills et al. 1999         |
|                  |     |          |                      |            |                            | Webb et al. 1993 (pol)    |

Table 1. Polarization-Radio Alignments of Broad Absorption Line Quasars
ways clear at what wavelength the polarization position angle should be compared to the radio position angle. Angle rotations indicate multiple scattering axes in a number of BAL quasars, and type 1 Seyferts can show both polar and equatorial scattering (Smith et al. 2004). Supporting a polar outflow in Mrk 231, Punsly & Lipari (2005) claim there is equatorial scattering (Smith et al. 2004). Supporting a polar rotation, indicate multiple scattering axes in a number of radio galaxies. Our result, taken in conjunction with other results in the literature, seems to be the end of the popular but apparently too simple idea that BAL outflows are always equatorial.

5 CONCLUSIONS

PKS 0040−005 is a radio-loud BAL quasar with low but intrinsic continuum polarization. The electric vector of the continuum polarization is close to parallel to the position angle of the quasar's extended radio structure. This is naturally explained as the result of scattering in an equatorial region with a face-on geometry, just as in Seyfert 1 and broad-line radio galaxies. Our result, taken in conjunction with other results in the literature, seems to be the end of the popular but apparently too simple idea that BAL outflows are always equatorial.

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