Keck Spectropolarimetry of BALQSO

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Abstract.

Spectropolarimetry of broad absorption line quasi-stellar objects with the W. M. Keck Telescope is used to put constraints on their nuclear structure. If the continuum polarization is due to electron (or dust) scattering, then the scattered and direct rays probe the nucleus along multiple lines of sight, which suffer differing amounts of absorption. Multiple sources of polarized light contribute to the quasar emission, and the relative sizes and symmetries of these sources can be ascertained. The size of the electron scattering region relative to continuum source, broad emission line region, and broad absorption line region is determined using spectropolarimetry. The geometries of the scattering and broad absorption line regions are discussed in an attempt to discriminate between polar and equatorial outflows. The variation of polarization with velocity in the broad absorption troughs may also be used to study the dynamics of the absorbing gas.

1. Observations

Observations were made with the Low-Resolution Imaging Spectrograph on the W. M. Keck 10m Telescopes of 19 broad absorption line quasi-stellar objects (BALQSO) with a variety of absorption trough morphologies, with $m_V \sim 18$, and redshift $z = 1.6 - 3.5$. The spectra cover the observed wavelength range of 3800-8800 Å. Total exposure times range from 1 to 6 hr per object. Results for the first two objects in this survey are presented by Cohen et al. (1995).

The object studied in most detail is 0226-1024 (Fig. 1), a bright BALQSO with $m_V = 16.9$ and multiple troughs extending to at least 0.1c blue-ward of the permitted emission lines. Its polarimetric features are representative of most objects in the sample, so it is the primary focus of this paper. The continuum polarization ($P$) rises to 2% in the blue, and the polarized flux has a spectral index of -0.3. $P$ dips across all of the broad emission lines, so they have considerably lower polarization than the continuum.

$P$ rises dramatically to $\sim 8\%$ in the C IV absorption trough and to $\sim 5\%$ in the Si IV absorption trough. The troughs are therefore shallower in polarized flux than in total flux (with one exception, which is discussed below). This illustrates the importance of partial coverage of the continuum sources by the broad absorption line region (BALR), and the potential difficulties in determining the optical depth of the BAL troughs due to filling in by scattered light. A
significant portion (8%-100%) of the total flux in the bottom of the C IV trough is scattered light.

2. Relative Sizes

There is much uncertainty in the absolute sizes of the various emitting and absorbing regions in BALQSO and QSO in general. There are some constraints from variability studies (Barlow et al. 1992; Kaspi et al. 1996), but they are not stringent. There are two constraints on relative sizes from spectroscopy. First, the continuum source must be smaller than the broad absorption line region (BALR) so that the BALR blocks the continuum emission (at least partially). Second, the N V BALR commonly blocks the Lyα emission line (e.g., Turnshek et al. 1988), indicating that the BALR is larger than the broad emission line region (BELR).

Spectropolarimetry provides an additional constraint on the sizes of the quasar emitting and absorbing regions. The low polarization of the broad emission lines (BEL) relative to the continuum indicates that the BELR is extended, while the continuum source is compact relative to the electron scattering region. In other words, the electron scattering region is either smaller than or roughly cospatial with the BELR. The relative sizes of the various regions are summarized in Figure 2. Note that the BALR partially blocks the electron scattering region, leading to shallow absorption troughs in polarized flux. Continuum light is scattered, then absorbed, and not the reverse.
3. Geometry

There are a number of possible axisymmetric configurations of the scattering region and BALR (Fig. 3). In the case where the BALR is an equatorial outflow (Figs. 3a and 3b), the QSO is viewed at high inclination to its symmetry axis. The continuum shows relatively high polarization, by scattering from either a polar (Fig. 3a) or equatorial (Fig. 3b) distribution of electrons. If the scattering electrons are situated along the AGN axis, then any light resonantly scattered in the BALR is polarized perpendicular to the continuum light. On the other hand, if the scattering electrons are in the same plane as the BALR outflow, then the resonantly scattered light is polarized at the same position angle as the continuum. In the first case, the polarization vectors cancel, giving a deficit of polarized flux, while in the second case, they add, giving a surplus of polarized flux. The argument is similar if instead the BALR outflow is along the AGN axis (Figs. 3c and 3d). The main difference is that the degree of polarization is lower because the distribution of scatterers in the plane of the sky is more symmetric. Finally, it is possible that the BALR is arranged in a patchy spherical or asymmetric geometry with low covering factor.

Spectropolarimetry can help distinguish among the possible geometries of the BALR and electron scattering region. Discriminating between polar and equatorial outflow is problematic, since the main difference is in the magnitude of the continuum polarization. If the BALR outflow covers about 12% of the continuum source, then most non-BAL QSO are just BALQSO viewed on a line of sight not intersecting the BAL outflow (Weymann et al. 1991). Few high-redshift non-BAL QSO have been observed with high polarimetric accur-
Figure 3. BALR (filled) and electron scattering region (empty) geometries, viewed in the plane of the sky. Polarization vectors from the two regions are shown. (a, b) Equatorial (E) BALR outflows viewed at high inclination have high polarization. (c, d) Polar (P) BALR outflows viewed at low inclination have low polarization.

racy, however they generally have lower polarization than BALQSO (see, e.g., Antonucci et al. 1996). This suggests that BALQSO are observed at greater inclination than non-BAL QSO, leading to the conclusion that the BALR outflow is equatorial.

Three of the objects in the sample show a deficit of polarized flux red-ward of their permitted emission lines (0226-1024, CSO 755, and RS 23). Figures 1 and 4 show this effect in NV, C IV and perhaps Si IV in 0226-1024. This could be due to either resonance scattering in the BALR or residual polarization of the BEL by electron scattering. If resonance scattering is the cause and the BALR flow is equatorial, then the scattering electrons are distributed in a polar configuration. Hence, the geometry of Figure 3a is in best agreement with the polarimetric observations. Taking a closer look at the spectropolarimetry of 0226-1024 (Fig. 4), it is seen that in addition to the deficit of polarized flux red-ward of C IV, there is a $+5^\circ$ rotation in position angle (PA) which extends from $-14,000$ to $+14,000$ km s$^{-1}$, well outside the velocity range of the emission line. This rotation must be associated with resonantly scattered polarized flux from the BALR, and indicates a misalignment between the axes of the BALR outflow and the electron scattering region.

4. Dynamics

A common effect seen in BALQSO is greater polarization at low velocity than at high velocity in each sub-trough (Fig. 4). This is easily explained if the electron scattering region is only partially covered by BALR clouds and coverage increases with outflow velocity (Fig. 5). If the BALR flow expands as it accelerates
outward, then the higher velocity gas covers a larger portion of the electron scattering region, leading to lower polarization (for a given trough depth) at high velocities.

The sub-troughs also show PA rotations of up to $-15^\circ$ (Fig. 4), which are correlated to their velocity structure in polarized flux. This is naturally explained if the flow crosses the line of sight at an angle to the axis of the scattering region (Fig. 5b). Note that the rotations in the troughs are opposite to the rotation due to resonance scattering in the BALR, allowing a distinction between the two effects. This is expected since BALR streamers crossing the line of sight absorb polarized light at the same PA that they scatter light from the central continuum source. The PA in the troughs is driven away from the PA of the obscured electron scattered light.

Another striking detail in the spectropolarimetry of 0226-1024 is the absence of a polarization increase in the lowest velocity trough (Fig. 4). This suggests that it covers the electron scattering region almost completely. Perhaps it is due to BAL gas at a different radius or a completely different class of associated absorber. This is supported by the Keck HIRES data of T. Barlow and V. Junkkarinen (priv. comm.), which show that this trough breaks up into a number of sub-troughs at high resolution, whereas the other troughs remain smooth.

5. Conclusions

BALQSO continuum light is polarized by electron (or dust) scattering from an extended region smaller than or the same size as the BELR, then is partially
absorbed by clouds in the BALR. Resonantly scattered continuum light from the BALR has been detected for the first time and is polarized roughly perpendicular to the continuum, suggesting that the electron scattering and BALR structures are perpendicular. If the BALR outflow is equatorial, then the electron scattering region lies near the polar axis. Velocity-dependent polarization and PA changes in the BAL troughs are consistent with an accelerating BALR outflow crossing the line of sight at an angle to the symmetry axis of the electron scattering region.

References

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