WHAT IS THE TRUE COVERING FACTOR OF ABSORBING MATTER IN BALQSOs?

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ABSTRACT

Spectropolarimetry of broad absorption line quasars (BALQSOs) has demonstrated that the geometry of the absorbing material is far from spherically symmetric. Calculations of accretion disk spectra suggest that the intrinsic radiation pattern of quasars is also anisotropic. Because the quasar count distribution is very steep, if the orientations of these two anisotropies are correlated, optical flux–limited samples would be very strongly biased with respect to the discovery of BALQSOs. In particular, currently favored models suggest that BALQSOs may be much more common than they appear in the samples. If so, the intrinsic covering fraction of absorbing matter must be relatively large. Numerous consequences follow, including the prediction of a new population of hard X-ray sources (as may have been seen already by ASCA) and a possible explanation for the anomalously strong N v λ1240 lines seen in many high-redshift quasars.

Subject headings: accretion, accretion disks — galaxies: active — quasars: absorption lines — quasars: emission lines — quasars: general

1. ASYMMETRIC ABSORPTION AND ANISOTROPIC INTRINSIC RADIATION

Only about 10% of the quasars found in optical flux–limited samples exhibit broad absorption lines, resonance line absorption troughs that extend ~0.1 Å bluward of the emission-line centers (Weymann et al. 1991). Because in most other respects broad absorption line quasars (BALQSOs) are quite similar to ordinary quasars, it is generally thought that rapidly moving absorbing matter exists in all quasars but occupies only a fraction of the solid angle around them (Weymann et al. 1991). The fact that the remaining light in the troughs is often strongly polarized indicates that the obscuration is not randomly distributed around the quasar in a statistically spherically symmetric manner but is, instead, strongly aspherical. Equatorial wedges are the most popular geometry used to explain the observations (Goodrich & Miller 1995; Cohen et al. 1995; Brotherton et al. 1997).

Quasars are also likely to be anisotropic in their intrinsic continuum emission. The most plausible source for the photons they produce in the rest-frame optical and ultraviolet bands is an accretion disk, although detailed models for this emission have not been altogether successful (cf. Blaes 1998 and Krolik 1998 for reviews). While the specific character of the intrinsic angular radiation pattern is highly model dependent, in virtually every model the anisotropy is significant. Typically, the wavelength range around 1000–2000 Å is limb-darkened, while shorter wavelengths, produced closer to the black hole, are limb-brightened (Sun & Malkan 1989; Laor & Netzer 1989; Agol 1997).

If the orientations of the intrinsic radiation pattern and the absorbing matter are correlated, optical flux–limited samples will be biased with respect to the detection of BALQSOs (see Goodrich 1997, who suggested that there is bias due to extra attenuation on the lines of sight through the absorbing matter). This effect is strengthened by the steepness of the quasar counts distribution.

For example, suppose that the differential source count distribution if quasars radiated isotropically were dN/dF = KFα, where N(>F) is the number of quasars per sky solid angle with flux greater than isotropic flux F. Then the distribution per cosine of the viewing angle would be d²N/dFdμ = (K/2)Fα. If we now allow for anisotropy by setting Fobs = Fβf(μ) (implicitly assuming that the angular radiation pattern is independent of all other quasar characteristics such as luminosity or redshift), the differential source count distribution that we would actually observe is

\[
\frac{\partial N}{\partial F_{\text{obs}}} = \int_{-1}^{1} d\mu \frac{\partial^2 N}{\partial F_{\text{obs}} \partial \mu} = \int_{-1}^{1} d\mu \frac{\partial^2 N}{\partial F \partial \mu} \frac{\partial F}{\partial F_{\text{obs}}}
\]

\[
= \frac{K}{2} F_{\text{obs}}^\alpha \int_{-1}^{1} d\mu f^{\alpha-1}(\mu).
\]

(1)

For optical fluxes in the neighborhood of m_o = 16–17, α = 3.25 (Hartwick & Schade 1990). Since a quasar is called a BALQSO only if it is found within an equatorial wedge defined by |μ| ≤ μ_s, the BAL fraction in a flux-limited sample is

\[
f_{\text{BAL}} = \frac{\int_{0}^{\mu_s} d\mu \frac{\partial^2 N}{\partial F_{\text{obs}} \partial \mu}}{\int_{0}^{\infty} d\mu \frac{\partial^2 N}{\partial F_{\text{obs}} \partial \mu}} = \frac{\int_{0}^{\mu_s} d\mu f^{\alpha-1}(\mu)}{\int_{0}^{\infty} d\mu f^{\alpha-1}(\mu)}.
\]

(2)

Thus, if quasars are dimmer in the BAL direction, their population fraction at fixed observed flux is diminished because they are submerged in the larger population of intrinsically fainter non-BAL quasars.

As we have already remarked, we cannot compute f(μ) with great confidence. However, two plausible guesses will illustrate the possible magnitude of its effect. The first guess is the simplest possible model: that the local limb darkening is given by the form appropriate to a gray atmosphere in the Eddington approximation (Mihalas 1978), but that the integrated flux is further multiplied by a factor of μ because the radiation comes from a flat disk. Then f(μ) = μ(1 + 1.5μ). As a foil to this form, we use a rough analytic fit to detailed radiation transfer calculations which also include a complete treatment of general

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relativistic corrections (E. Agol 1997, private communication). This analytic fit is \( f_\mu(\mu) \approx 0.23 + 1.54|\mu| \).

The predicted BAL fractions are shown in Figure 1. Generically, any significant limb darkening in the direction of the absorbing matter leads to a very strong bias against the discovery of BALQSOs. In order to find a population of ~10% BALQSOs in an optical flux–limited sample of limb-darkened sources, the true covering fraction \( \mu_5 \approx 0.5 \). When \( \mu_5 \) exceeds ~0.5, the fraction of BALQSOs discovered in a flux-limited sample rapidly approaches unity as the limb darkening weakens and the fraction of non-BALQSOs falls. Conversely, if the absorbing matter is correlated with the bright direction, the true fraction might be substantially less than the fraction inferred from flux-limited samples.

This picture also has one more corollary regarding the BAL fraction: if the absorbing matter is in the dim direction, the very faintest quasars (i.e., those at flux levels where \( \alpha \) falls below unity) should be disproportionately BALQSOs.

### 2. CONSEQUENCES OF LARGE COVERING FRACTIONS

If the true covering fraction of absorbing matter is as large as would be predicted if the dim continuum direction were correlated with the direction in which absorption is found, our picture of quasars would change substantially. The outward flow of matter moving at \( \sim 0.1c \) is no longer a small effect present in only a limited solid angle; rather, it is a major element of the system, carrying substantially greater amounts of momentum and energy. Moreover, the velocity is no longer directed only within a small range of directions close to the surface of the accretion disk; there are fluid elements moving at very substantial angles relative to the disk surface. These considerations are likely to change our approach in dynamical studies of the BAL material.

Beyond these dynamical issues, there are also a number of phenomenological consequences to this changed point of view.

#### 2.1. A New Active Galactic Nucleus X-Ray Population

For only one BALQSO, PHL 5200, has an X-ray spectrum of good enough quality to determine an absorbing column been obtained; in this instance, it is \( \approx 1 \times 10^{22} \) cm\(^{-2}\) (Mathur et al. 1995). However, it has been possible to show statistically that most BALQSOs are relatively weak in the soft X-ray band relative to their optical/ultraviolet flux. Interpreted as the result of absorption, the depression corresponds to columns of \( \sim 10^{23} \) cm\(^{-2}\) (Green & Mathur 1996).

If the fraction of BALQSOs is nearer to 0.5 than to 0.1, and absorbing columns \( \sim 10^{22} \)–\( 10^{23} \) cm\(^{-2}\) thick are a generic feature of BALQSOs, the number of quasars found in X-ray surveys sensitive to rest-frame photon energies greater than a few keV should increase by roughly a factor of 2 relative to the number found by soft X-ray surveys. Anisotropy in the X-ray emission is likely to be rather weaker than in the ultraviolet, but if present it could modify this prediction. These new quasars should have hard X-ray spectra at rest-frame energies of 1–5 keV (as a result of the absorption), and most of them should also show BAL features in their rest-frame ultraviolet spectra.

Interestingly, the ASCA source count distribution shows exactly this effect: the number of sources seen by ASCA with fluxes of \( \sim 10^{-15} \)–\( 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\) in the 2–10 keV band is several times as great as the number that would be predicted on the basis of the corresponding ROSAT counts if the sources had conventional quasar spectra (Cagnoni et al. 1998). Some of these may be active galactic nuclei (AGNs) obscured by dusty tori, as in Seyfert galaxy unification models (Madau, Ghisellini, & Fabian 1994; Comastri et al. 1995), but others may be BALQSOs.

#### 2.2. The Radio Loudness of BALQSOs

As was already discussed by Goodrich (1997), a reduction in the optical flux of BALQSOs increases their ratio of radio to optical flux. He found that the (rough) statistics of known BALQSOs indicated that their optical flux had been depressed relative to the mean of all quasars by a factor of 3–5.

More precisely, we wish to compute the ratio of radio flux (preferably extended radio flux, so that it is isotropic) to observed optical flux for quasars found in optically selected samples, i.e., at fixed observed optical flux. If the radio flux \( F_r = R F_s \), then, for a single quasar, the ratio of observed radio flux to observed optical flux is \( F_r/F_s = R f(\mu) \). Averaging over viewing angle at fixed \( F_s \), the mean radio-to-optical ratio for BALQSOs is

\[
\langle F_r/F_s \rangle_{\text{BAL}} = \frac{\int^\mu_0 d\mu \left[ \frac{R}{F_s} \right] \frac{\partial^2 N}{\partial F_s \partial \mu} \partial \mu}{\int^\mu_0 d\mu \frac{\partial^2 N}{\partial F_s \partial \mu}} = R \frac{\int^\mu_0 d\mu f^{\alpha-2}(\mu)}{\int^\mu_0 d\mu f^{\alpha-1}(\mu)},
\]

so that

\[
\frac{\langle F_r/F_s \rangle_{\text{BAL}}}{\langle F_r/F_s \rangle_{\text{all}}} = \frac{1}{f_{\text{BAL}}} \frac{\int^\mu_0 d\mu f^{\alpha-2}(\mu)}{\int^\mu_0 d\mu f^{\alpha-2}(\mu)}.
\]

If either of the two models for \( f(\mu) \) used in § 1 is assumed with a value of \( \mu_5 \) that gives an observed BAL fraction of ~0.1, \( \langle F_r/F_s \rangle_{\text{BAL}} \) is enhanced relative to the mean ratio for all quasars by ~2.
2.3. Scattering Contributions to Emission Lines

Many people have considered possible contributions to the broad emission lines due to resonance scattering in BAL gas (Surdej & Hutsemekers 1987; Turnshek 1988; Hamann, Korista, & Morris 1993; Hamann & Korista 1996). Indeed, some (e.g., Turnshek 1988 and Hamann et al. 1993) have tried to limit the covering fraction by constraints on these contributions. However, several special features arise in this model that change the character of these arguments: the large covering fraction enhances the magnitude of the scattering contributions, although the limb darkening partially counteracts this, and the width of the scattered line is diminished both by the preference for discovering face-on quasars and by the relatively greater equivalent width of the intrinsic emission line as seen by the scattering gas.

2.3.1. Emission-Line Equivalent Width

If we consider an isolated resonance line (e.g., C iv λ1549), the limb darkening by itself can modulate the equivalent width of the intrinsic emission line by factors of several (as would similarly occur for isolated nonresonance lines such as Hβ or CII λ1909). However, the combination of scattering and absorption diminishes the range of observed emission equivalent widths. Scattering increases the equivalent width of emission lines seen from the polar direction, which would otherwise be the direction in which the equivalent width was least, while absorption, of course, removes line flux from the equatorial direction.

The quantitative character of these effects depends strongly on details of the geometry and kinematics. It matters whether the emission region is very small compared with the absorption region or whether it nearly fills it. The scattered line profile also depends on the velocity gradients within the scattering gas and on the direction of the flow (helical outflow, as predicted by Murray et al. 1995, has different properties from radial, for example).

To qualitatively explore scattering effects, consider an extremely simplified model: suppose that the emission-line region is far inside the absorption region, the velocity of the absorbing gas is purely radial, and the absorbing gas is black across some range of velocities $\beta_{\min} \leq \beta \leq \beta_{\max}$ but is transparent otherwise. With these simplifying assumptions, the scattered luminosity in the direction $\hat{n}$ is

$$\frac{dL}{d\Omega} = \int_{\beta_{\min}}^{\beta_{\max}} d\beta \int_{-\pi}^{\pi} d\phi' \int_0^{2\pi} d\mu' g(\hat{n},\hat{n}') \frac{dL'}{d\Omega'} \delta(\beta - \beta_*), \quad (5)$$

where the primed quantities refer to the intrinsic spectrum. Photons of initial frequency $\nu'$ and direction $\hat{n}'$ are scattered with probability $g(\hat{n},\hat{n}')$ into direction $\hat{n}$ and frequency $\nu$ by material with speed $\beta_*$, defined by the pair of equations

$$\nu' = \nu \frac{1 + \beta_*}{1 - \beta_*}, \quad (6)$$

$$\nu' = \nu \frac{1 - \beta_* \cdot \hat{n'} \cdot \hat{n}}{1 - \beta_*}, \quad (7)$$

for rest-frame resonance frequency $\nu_\circ$.

When $\mu_*=0.5$, $\beta_{\min}=0$, and $\beta_{\max}=0.05-0.1$, the observed emission equivalent width of an isolated resonance line seen in a non-BAL direction is typically enhanced by tens of percent relative to what it would be without scattering, and ranges over a factor of roughly 2 from the polar to the equatorial directions. Part of this enhancement in the equivalent width is due to low broad wings. Depending on how the equivalent width is measured, in practice only a portion of these wings may actually be counted toward the emission-line equivalent width, with the rest being absorbed into the apparent continuum. Interestingly, if the maximum velocity in the absorbing gas is $\sim 0.1c$, the extent of the wings is comparable to the extent of the “very broad line” component identified by Brotherton et al. (1997).

If attention is restricted to the red half of the emission line, this model predicts a greater contrast between BAL and non-BAL quasars. The emission equivalent width in BALQSOs should be some 50% stronger, on average, than similar lines in unabsorbed quasars. Weymann et al. (1991) found no strong differences between the emission-line properties of quasars with and without broad absorption; however, the dispersion of properties in each sample is large. An additional effect that might mask possible differences is that the intrinsic emission might be blueshifted relative to the systemic velocity of the quasar, so that non-BALQSOs appear to have greater red-side flux. The investigation of such effects will have to await more sophisticated modeling of line profiles in limb-darkened BALQSOs.

2.3.2. Ratio of Absorption to Emission Equivalent Width

The ratio of the absorption equivalent width to the emission equivalent width is sometimes taken as an indicator of the intrinsic covering fraction, because scattering by itself would result in these being equal if the covering fraction were unity (e.g., Hamann et al. 1993). It is, of course, reduced by any true absorption. The observed range of this ratio in BALQSOs is $\approx 5-0.5$, with a median value of $\approx 2$ (Hamann et al. 1993). In the simple model defined in the preceding paragraph, this ratio also depends on both the intrinsic emission equivalent width and the range of velocities in the absorbing matter, decreasing for greater intrinsic equivalent width and increasing for increasing $\beta_{\max}$. For $\mu_* = 0.5$, it is $2-4$ when $\beta_{\max} = 0.1$ and $W_{c}/\lambda = 0.01-0.015$.

2.3.3. Emission-Line Profiles

Hamann et al. (1993) argued that if the covering fraction of scattering gas were large, the resulting emission-line profile (in the non-BAL view) would be too broad. However, if the intrinsic emission-line flux is originally isotropic while the continuum radiation is limb-darkened, this story changes. A wind in an equatorial wedge with a covering factor of 0.5 can intercept half of the isotropic line photons while intercepting a much smaller fraction of the limb-darkened continuum. The scattered C iv profile that results is then not much broader than the original line because the contribution from scattered line photons dominates that from scattered continuum photons. Scattering in the radial outflow can only reduce a photon’s frequency in the rest frame of the photon source.

We have explored this effect using the very simple model of scattering described above. Suppose, for example, that the absorption profile is generated by pure isotropic scattering, $\beta_{\max} = 0.05$, and $\mu_* = 0.5$. Let us further assume that the continuum limb darkening is given by $f_\lambda(\mu)$, and that the intrinsic C iv emission line, emitted by a point source at the center, is Gaussian with a dispersion of 0.01c and a peak-to-continuum ratio of 1.5 when viewed along the pole. The resulting C iv
profile, when viewed over a variety of non-BALQSO lines of sight, has an FWHM of $0.015c$, a peak-to-continuum ratio of $\sim 2$, and a shape parameter $S \equiv (FWHMA_{\text{max}} - FWHM)/FWHMA_{\text{max}} \approx 1.0$. All these numbers compare favorably with the C iv line-shape parameters measured by Wills et al. (1993) for quasars in the same redshift range as the bulk of the Weymann et al. (1991) sample. The red sides of the model C iv profiles have similar shapes but somewhat higher peak-to-continuum ratios ($\sim 2.5$) because the continuum is substantially limb-darkened.

2.3.4. Enhancement of N v $\lambda 1240$

The pair of lines Ly$\alpha$ and N v $\lambda 1240$ constitutes a special case. Because the absorbing gas sees the intrinsic emission redshifted, and the intrinsically strong Ly$\alpha$ emission line is blueward of N v $\lambda 1240$ by only $\approx 6000$ km s$^{-1}$, the flux available to scatter in the N v feature is substantially magnified relative to the pure continuum. For this reason, scattering can increase the N v $\lambda 1240$ emission equivalent width by factors of several (Surdej & Hutsemakers 1987), provided that the covering factor is greater than 0.3 (Hamann et al. 1993).

To quantify this effect, we again use the simple model already described. In this case, because N v $\lambda 1240$ and Ly$\alpha$ are always blended, one cannot measure the equivalent width of the observed N v $\lambda 1240$ line by integrating across the profile after subtracting off a fixed continuum level. Instead, we defined the flux in each of the two lines by a least-squares fit to a model of two Gaussians, one centered at 1240 A and the other at 1216 A. Specific numbers for the relative strength of the apparent N v emission due only to scattering depend on parameters, but only weakly. For $\mu = 0.5$, the limb-darkening law $f_2(\mu)$, $\beta_{\text{min}} = 0$, $\beta_{\text{max}} = 0.05-0.1$, and a Ly$\alpha$ equivalent width from 40 to 140 A (a range taken from Baldwin, Wamplar, & Gaskell 1989), the scattered N v $\lambda 1240$ flux is 0.4-0.5 times the Ly$\alpha$ flux. This ratio—with no contribution from intrinsic N v emission—is right in the middle of the range found by Baldwin et al. (1989) for their sample of quasars with $z \approx 1.7-2.5$.

Strong enhancement of the N v $\lambda 1240$ line is of particular interest in view of the fact that its flux, relative to both C iv $\lambda 1549$ and He ii $\lambda 1640$, increases on average by a factor of 2-3 when comparing AGNs at $z \sim 0.1$ with those at $z = 2-4$ (Hamann & Ferland 1992, 1993). If the incidence of BALQSOs also increases sharply with increasing redshift (as anecdotal evidence suggests), the scattering contribution may explain this systematic change in line ratios. Further support for this idea that the strength of N v $\lambda 1240$ is due to scattering in the BAL gas is given by the principal component analysis of quasar spectra by Francis et al. (1992), which show that broad absorption is related to excess N v emission and broader C iv emission.

3. CONCLUSIONS

We have shown that if anisotropy in the continuum emission of quasars is correlated with the direction toward broad absorption line gas, optical flux–limited samples of quasars would be severely biased with respect to the discovery of broad absorption line quasars. If, as the simplest models suggest, quasar continua are limb-darkened at the selection wavelengths, BALQSOs are severely underrepresented in such samples. The inferred covering fraction of broad absorption gas could well be nearer to $<0.5$ than to the usual estimate of $<0.1$.

Such large covering fractions of absorbing gas would have numerous consequences: hard X-ray surveys may discover roughly twice as many quasars as would be predicted on the basis of soft X-ray surveys; the ASCA survey may already have done just this. The fact that BALQSOs are somewhat stronger radio sources than the average radio-quiet quasar would also be explained. In addition, resonance scattering in the broad absorption gas could contribute to the emission lines. N v $\lambda 1240$, because it is just 6000 km s$^{-1}$ redward of Ly$\alpha$, would be strongly enhanced, providing an alternative explanation (i.e., other than elevated N abundance; Hamann & Ferland 1992, 1993) for the strength of this line in high-redshift quasars.

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