ORIENTATION EFFECTS IN QSO SPECTRA

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ABSTRACT

The consequences of anisotropic continuum emission for the equivalent-width distribution of QSOs are investigated and compared with observations from a large QSO survey. Isotropic line emission is assumed, and a variety of continuum anisotropy models are investigated. Far fewer high equivalent width QSOs are observed than most models predict. Both thick and thin accretion disks are ruled out, unless their radiation is reprocessed into a more isotropic angular distribution, or an obscuring torus conceals the broad-line region of nearly edge-on QSOs.

Subject headings: accretion, accretion disks — quasars: general

1. INTRODUCTION

Accretion disks are an ingredient of most QSO models, but as yet there is little observational evidence for or against their presence. One possible observational signature is anisotropic continuum emission — the observed luminosity of any type of accretion disk is a strong function of the angle to the line of sight. If line radiation is relatively isotropic, a sample of identical QSOs viewed from a range of orientations will show a dispersion in its line-to-continuum ratios (equivalent widths) due to the continuum anisotropy.

Netzer and collaborators (Netzer 1985; Netzer, Laor, & Gondhalekar 1992) have modeled this equivalent width dispersion, and show that in a black-hole-mass limited sample, it can account for the most of the observed equivalent width dispersion. In addition, they show that an anticorrelation between continuum luminosity and equivalent width (the Baldwin effect [Baldwin 1977; Baldwin et al. 1988]) would be expected in such a sample. Existing surveys are, however, magnitude limited and will be strongly biased toward those QSOs that emit the bulk of their radiation toward us. In this paper the consequences of continuum anisotropy in such a sample are calculated and compared with observations.

The theory of orientation effects in magnitude-limited samples is developed in § 2, in § 3 the QSO sample and measurement techniques are described, and in § 4 the observations are compared with theory. Finally the results are discussed in § 5.

2. THEORY

Any magnitude-limited QSO sample will be biased toward those QSOs emitting most of their radiation toward us. In this section, luminosity function information is used to correct for this bias, and equivalent-width distributions are calculated for a wide variety of anisotropic continuum models.

2.1. Calculations

For the purposes of this paper, any QSO can be described by three parameters, its continuum luminosity $L_c$, its line luminosity $L_l$, and the angle between the line of sight and the normal to the accretion disk $\theta$. Due to the strong correlation between line and continuum luminosities, it will be convenient to use not the line luminosity, but the intrinsic line-to-continuum ratio $r = L_0/L_c$, where $L_c$ is defined to be the continuum luminosity viewed from the orientation that maximizes it. The angular dependence of the continuum luminosity is described by a function $f(\theta)$, with the observed luminosity $L_0$ of a QSO viewed at an angle of $\theta$ to its axis of symmetry given by $L_0 = L_c f(\theta)$.

The QSO population can be described by a distribution function $n(L_c, r, \theta)$, the number of QSOs per unit intrinsic continuum luminosity, and per unit angle and line-to-continuum ratio, but this is not an observable function. What can be observed is the distribution function $n(L_0, W)$, where $L_0$ is the observed luminosity and $W$ is the fraction of the observed radiation coming from the lines (i.e., $W$ is proportional to the total equivalent width of all emission lines). The calculations in this section show how $n(L_0, W)$ can be derived from $n(L_c, r, \theta)$.

To simplify the calculations, it will be assumed that the distributions of QSOs in angle, continuum luminosity and line luminosity are independent, i.e., that $n(L_c, r, \theta)$ can be written as $n_1(L_c) n_2(r) n_3(\theta)$. This is equivalent to saying that the QSOs have the same equivalent width distribution regardless of intrinsic continuum luminosity and that QSOs do not have any preferred orientation relative to the line of sight. It will be further assumed that all QSOs have the same value of $r = r_0$; i.e., that all QSOs have the same intrinsic equivalent widths and that all observed differences are due to orientation.

The physical and observed parameters are related by two equations

$$L_0 = L_c f(\theta) + L_l$$
$$W = L_l/[L_c f(\theta)]$$

A power-law luminosity function will be assumed, with $n_1(L_c) \propto L_c^p$. The consequences of a more realistic intrinsic luminosity function are discussed in § 2.3 below.

The intrinsic distribution function is thus

$$n(L_c, r, \theta) = L_0^p \delta(r - r_0) \sin(\theta),$$

where $\delta$ is a Dirac $\delta$-function. The $n_3(\theta) = \sin(\theta)$ term can be straightforwardly derived from the geometry of a sphere. The observed distribution function is

$$n(L_0, W) = n(L_c, \theta) \left[ \frac{dL_c}{dL_0} \frac{d\theta}{dW} \right].$$

1 Observations reported here were obtained with the Multiple Mirror Telescope, a facility operated jointly by the Smithsonian Institution and the University of Arizona, and with the Las Campanas Observatory, a facility of the Carnegie Institution of Washington.
Substituting from equations (1)–(3), the following result is obtained

\[
n(L_0, W) = \left(\frac{L_0}{r_0}\right)^{\beta} \sin(\theta) \frac{W^{\beta-1}}{(1 + W^{\beta+1})} \frac{1}{\mathcal{D}'(\theta)/d\theta}.
\]

The first factor in equation (5) is a power-law luminosity function—the observed luminosity function is, to a constant factor, identical to the intrinsic continuum luminosity function. This is only the case for pure power-law luminosity functions. The second factor [\sin(\theta)] is purely geometrical—if QSOs are randomly aligned, more will point perpendicular to the line of sight than along it. The third, \( W \), factor depresses the numbers of high equivalent width (edge-on) QSOs, for a given value of \( L_0 \). This can be seen as follows: say a QSO appears twice as bright when viewed from face-on as when viewed from edge-on. Then, to have the same observed luminosity as a face-on QSO, an edge-on QSO must have twice the intrinsic luminosity. But intrinsically bright QSOs are rarer than faint ones (i.e., \( \beta < 0 \)), so fewer edge-on QSOs will be observed at this given observed luminosity. Finally, the last term takes into account the radiation anisotropy pattern.

2.2. Luminosity Function

In the calculations above, a single power-law isotropic continuum luminosity function was assumed, and it was shown that given such an isotropic luminosity function, the observed luminosity function would also be a power-law with the same index. A more realistic observed luminosity function however consists of two power laws, a steep one \( [n(L) \propto L^{-3.9}] \) at high luminosities, and a shallower one \( [n(L) \propto L^{-1.6}] \) for less luminous QSOs (Boyle, Shanks, & Peterson 1988). What then is a realistic isotropic continuum luminosity function?

The observed luminosity function is the convolution of the intrinsic luminosity function with an orientation function, which describes the probability of a given QSO having a particular ratio between its face-on and its observed luminosities. The orientation function is determined by geometry and the accretion disk radiation pattern. The orientation function will smear out any departures from a power law in the intrinsic luminosity function. A key number is the width of the orientation function; the ratio of the observed luminosities of a QSO viewed from face and edge-on. The two QSO samples analyzed in this paper lie \( \sim 1.5 \) mag above (Large Bright QSO Survey) and 1.5 mag below (Boyle et al. 1990) the break in the luminosity function, so if the width of the orientation function is less than \( \sim 3 \) mag, the non-power-law nature of the luminosity function can be neglected.

Urry et al. (1991) show that for a thick accretion disk continuum source, orientation effects can affect the observed luminosity function over a very wide range of luminosities. Their result, however, did not include an isotropic line component to the luminosity, which decreases the width of the orientation function.

Line radiation is observed to be \( \sim 15\% \) of the total observed flux from a typical optically selected QSO in the UV-optical wavelength range (Francis et al. 1991). As shown below in Table 2, this is the observed line-to-continuum ratio that would be expected for most of the continuum models described in § 2.3, if the ratio \( r \) of line luminosity to the maximum observed continuum luminosity is \( \sim 0.1 \). Thus the ratio of face-on to edge-on luminosities will not exceed \( \sim 10 \) (2.5 mag).

For the purposes of this paper, therefore, a pure power-law intrinsic luminosity function will be used, with different indices for the two QSO samples. This approximation is not perfect, but the \( \beta = -1.6 \) and \( \beta = -3.9 \) cases straddle the range of possibilities.

2.3. Continuum Models

Accretion disk modeling is a complex and uncertain process, and no consensus has emerged as to the likely form of a QSO accretion disk. For this reason, a wide range of continuum anisotropy models are analyzed in this paper. The choice of models was guided by a desire to explore the parameter space of possible continuum anisotropy patterns. The angular radiation dependences of the models are shown in Figure 1, along with the resultant equivalent width distributions, calculated using equation (5).

Models A and B are thin accretion disk models taken from Figure 2 of Sun & Malkan (1989). Model B is the model for a frequency of \( 10^{15.3} \) Hz, which is roughly the wavelength observed. This angular luminosity dependence is similar to the cos(\( \theta \)) luminosity dependence used by Netzer et al. (1992). Model A is for a frequency of \( 10^{16.5} \) Hz. This is a much higher...
frequency that any of the observations, and was chosen as an example of continuum anisotropy strongly affected by general relativistic effects, which deflect light into the plane of the disk.

Models C and D are thick accretion disks from Madau (1988). Model D is for the observation wavelengths (frequencies of $\sim 10^{15.5}$ Hz). Model C is at the much higher frequency of $10^{16.5}$ Hz and shows a rapid decline in observed flux at angles of more than 15$^\circ$, the opening angle of the funnel of the thick disk.

Models E and F are for shrouded disks. To mimic an accretion disk surrounded by some form of scattering atmosphere, which reprocesses the continuum radiation into a more isotropic pattern, observed luminosities of the form $f(\theta) \propto 1 + k \cos(2\theta)$ have been used. Model E has a face-on flux 20% greater than the edge-on flux, while for model F the excess is a factor of 3.

Models G and H are for relativistic beaming. The continuum radiation comes from material moving at a uniform speed in both directions along the polar axis of the disk. The continuum anisotropy is caused by the relativistic aberration of the emitted light. Model G is for a velocity of 0.3c, while model H is for a velocity of 0.8c.

The resultant equivalent width distributions for the models are also shown in Figure 1, both for an intrinsic luminosity function of the form $n(L) \propto L^{-3.5}$, appropriate to luminous QSOs, and $n(L) \propto L^{-1.6}$, appropriate for less luminous QSOs (Boyle et al. 1988). An isotropic line flux equal to 10% of the peak continuum flux has been assumed. As shown in Table 2, this 10% ratio yields observed mean line-to-continuum flux ratios of $\sim 0.15$, consistent with observations (Francis et al. 1991).

The equivalent width distributions fall into two broad classes. When the ratio of face-on to edge-on luminosities is small, as in models E, F, and G, the equivalent width distribution is characterized by two sharp peaks joined by a concave curve. When the ratio of face-on to edge-on luminosities is large, however, the equivalent-width distributions have a single peak at $W = 0.1$, with a tail to higher equivalent widths. In addition, model C has a discontinuity in its equivalent width distribution, with large numbers of low equivalent width QSOs (those seen down the funnel), and relatively small numbers of QSOs with larger equivalent widths. The distributions for fainter QSOs show large numbers of high equivalent-width QSOs, as the flatter luminosity function decreases the bias toward low equivalent width QSOs.

3. THE OBSERVATIONS

The equivalent width measurements reported in this paper were obtained from the Large Bright QSO Survey (LBQS), which, due to its large size and broad-based selection criteria, is well suited to this project. The LBQS consists of data on more than 1000 QSOs, with redshifts $0.2 < z < 3.4$, and apparent magnitudes $16.0 \leq m_B \leq 18.7$. The survey is described in Foltz et al. (1987, 1989), Hewett et al. (1991), Chaffee et al. (1991), and Morris et al. (1991). The survey candidates were selected using both color and line detection algorithms, and hence should not be seriously incomplete for weak lined QSOs unless they are also extremely red [a continuum of the form $F(\nu) \propto \nu^{-2}$ or redder, so only the rare subclass of red BL Lacertae objects should be missed]. Radio observations are only available for a subset of the LBQS (Visnovsky et al. 1992)—the radio properties of the LBQS appear typical of optically selected QSO samples.

Equivalent widths were measured for the strongest broad emission lines; Ly$\alpha$ (1216 Å), C iv (1549 Å), C iii] (1909 Å), and Mg ii (2798 Å), using the continuum windows and integration limits listed in Table 1. All spectra whose wavelength coverage and redshift allowed the line in question to be measured were employed: 251 spectra showed Ly$\alpha$, 439 showed C iv, 606 showed C iii] and 551 showed Mg ii. The line fluxes were simply integrated above a straight line joining the continuum windows. The continuum windows were chosen with reference to a high signal-to-noise ratio composite QSO spectrum (Francis et al. 1991) to avoid as much line emission as possible, and the conservative line integration limits were chosen to minimize the contributions of blended lines, such as N v (1240 Å) in the red wing of Ly$\alpha$, and Al iii (1858 Å) in the blue wing of C iii]. This inevitably means that the measured equivalent widths underrepresent the true values, but for the purposes of this paper it is only necessary that the measured equivalent widths be proportional to the actual equivalent widths.

The results from the LBQS were compared with the much fainter published sample of Boyle et al. (1990). This consists of more than 400 color-selected QSOs with $B$ magnitudes of 21 or fainter, with redshifts similar to the LBQS QSOs. The main relevant selection effect applies at redshifts above 2.2: QSOs with high equivalent widths in Ly$\alpha$ will appear red and hence may be preferentially missed from the sample.

4. RESULTS

The measured equivalent-width distributions of the LBQS QSOs are shown in Figure 2. As the LBQS lies above the break in the QSO luminosity function, these observations should be compared with the second ($\beta = -3.9$) column of Figure 1.

Two qualitative conclusions can be drawn from the figures. First, the model equivalent width distributions are more sharply peaked than the observed distributions. In particular, all the model distributions have a sharp lower cutoff, whereas the observed distributions decline more gradually toward zero equivalent width. Second, some of the model distributions have a tail of high equivalent width QSOs stronger than that observed. Both these discrepancies are discussed below.

4.1. Distribution Widths

The calculated distributions shown in Figure 1 are clearly much more sharply peaked than the observed distributions. The broader peaks of the observed distributions are not surprising, as there are plenty of mechanisms for producing a dispersion in equivalent widths in addition to the range of viewing angles. Examples might include a range in covering factors, in the shape of the UV ionizing continuum or in the physical properties in the emitting clouds.

The standard deviations of the observed and model equivalent width distributions are shown in Table 2. The ratio of the distribution width to the mean equivalent-width (Table 4, below) is about 0.5 for the observations, and most of the
models predict ratios similar to or smaller than this. Models C and H, however, predict substantially wider distributions than are observed. This discrepancy is due to the tail of high equivalent-width QSOs, and is discussed in the following section.

4.2. High Equivalent Width QSOs

Many of the model distributions have a tail of very high equivalent-width QSOs. Is this consistent with the observations? To test this, the fraction of QSOs with equivalent-widths greater than 3 times the modal (peak) equivalent width was calculated (Table 2). The model predictions are compared with the observations in Table 3, and it can immediately be seen that far fewer high equivalent width QSOs are observed than many models predict. Models D and H are ruled out at a 99% confidence limit or better by all the lines, models B and C are ruled out at better than 99% by all the lines except Lyz, and model A is ruled out at the 99% confidence limit by the C m] and Mg II results. The confidence limits are derived comparing observed and predicted numbers of high equivalent width QSOs, assuming n^{12} errors.

The fraction of QSOs with equivalent-widths greater than 3 times the modal value was used as the measure of distribution tail strength because the mode of the distribution will be little affected by an intrinsic spread in QSO equivalent widths, and because few observed QSOs have equivalent widths this large.

<table>
<thead>
<tr>
<th>Model</th>
<th>(\beta = -3.9)</th>
<th>(\beta = -1.6)</th>
<th>(\beta = -3.9)</th>
<th>(\beta = -1.6)</th>
<th>(\beta = -3.9)</th>
<th>(\beta = -1.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.14</td>
<td>0.22</td>
<td>0.07</td>
<td>0.18</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>0.16</td>
<td>0.25</td>
<td>0.08</td>
<td>0.19</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>C</td>
<td>0.16</td>
<td>0.44</td>
<td>0.14</td>
<td>0.33</td>
<td>9</td>
<td>56</td>
</tr>
<tr>
<td>D</td>
<td>0.22</td>
<td>0.39</td>
<td>0.14</td>
<td>0.21</td>
<td>17</td>
<td>56</td>
</tr>
<tr>
<td>E</td>
<td>0.11</td>
<td>0.11</td>
<td>0.01</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>0.16</td>
<td>0.20</td>
<td>0.05</td>
<td>0.06</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G</td>
<td>0.14</td>
<td>0.15</td>
<td>0.03</td>
<td>0.03</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>0.20</td>
<td>0.45</td>
<td>0.15</td>
<td>0.33</td>
<td>12</td>
<td>54</td>
</tr>
</tbody>
</table>
The conclusions are, however, insensitive to the exact measure used. This was tested by using different multiples of the mode, or some multiple of the mean or median as the measure of the numbers of very high equivalent-width lines. In all cases the basic conclusions were the same: models A, B, C, D, and H overpredict the numbers of very high equivalent-width lined QSOs to a significant extent.

If an intrinsic spread in the equivalent widths of QSOs is introduced, as required to reproduce the broader peaks and gentle low equivalent-width cutoffs of the distributions, this will tend to increase the numbers of high equivalent-width QSOs, making the discrepancy worse.

A deficit in the observed number of QSOs with very high equivalent-width emission lines is unlikely to be a selection effect as such QSOs are the easiest to find in objective-prism surveys such as the LBQS. An increase in blended line emission contaminating continuum windows could diminish the equivalent widths, but as such blended line emission cannot amount to more than ~10% of the continuum flux (Francis et al. 1991), it cannot account for the discrepancy. Possible explanations are discussed in § 5.

4.3. Correlations with Luminosity: The Baldwin Effect

In the simple model outlined in this paper, the equivalent width distribution is independent of observed luminosity, as long as the isotropic luminosity function is a single power law. This is in contrast with the results of Netzer et al. (1992), whose Baldwin relation comes partially from the cutoff in black-hole mass and partially from a luminosity dependence of the ionizing continuum employed.

In actuality, the luminosity function of QSOs is steeper at large luminosities, so samples of luminous QSOs would be more strongly biased toward face-on disks. As face-on QSOs have lower equivalent widths, this implies that QSOs brighter than the break in the luminosity function will have lower mean equivalent widths than their fainter brethren. Predicted equivalent width distributions for faint ($\beta = -1.6$) and bright ($\beta = -3.9$) QSOs are shown in Figure 1: both have the same lower cutoff, but the distribution of faint QSOs has relatively more high equivalent width QSOs.

The predicted mean equivalent widths of both luminous ($\beta = -3.9$) and less luminous ($\beta = -1.6$) samples with the same line to isotropic continuum ratios $r$ are shown in Table 2. In all cases, less luminous QSOs have higher mean equivalent widths. The difference in mean equivalent width are parameterized in Table 4 by a Baldwin exponent $\gamma$, where $\gamma$ is defined by $W \propto L^{-\gamma}$, where $W$ is the mean equivalent width at a given observed luminosity. The parameterization assumes that the Baldwin effect is measured from a sample of QSOs with a 5 mag range of luminosities, centered on the break in the luminosity function. For models C, D, and H, the exponents lie within the range of published determinations of the slope of the Baldwin relation for C IV (e.g., Zamorani et al. 1992), while for the other models the predicted slopes are smaller than observed. If these models are correct, some additional anti-correlation between the equivalent width of C IV and the luminosity will be required to match the observations.

Note that this calculation of the expected anti-correlation between equivalent widths and luminosities applies to all emission-lines, not just C IV. Little or no correlation between the equivalent width of other lines and luminosity is seen, an observation which provides additional evidence against models C, D, and H.

The models predict a second trend with luminosity: the width of the distributions should be larger in faint QSO samples than in bright QSO samples. To test this, the widths of the equivalent-width distributions of the LBQS were compared with the published values for the less luminous sample of Boyle et al. (1990). As the equivalent widths were measured by different techniques, the ratio of the standard deviation of the equivalent widths to the mean was used. Results are shown in Table 4 and compared with the model predictions.

In general, the LBQS sample and the Boyle et al. sample show similar ranges of equivalent widths, while models A, B, C, D, and H predict much broader distributions of equivalent widths in the Boyle et al. sample. The discrepancy is particularly serious for Ly\alpha, where the measured width of the equivalent width distribution in the Boyle et al. sample is actually smaller than in the LBQS sample. As noted in § 3, however, there may be a selection effect against QSOs with very high equivalent width Ly\alpha in the color-selected Boyle sample.

5. Discussion

The key result of this work is that most of the continuum anisotropy models predict more high equivalent width QSOs than are observed. They also predict a greater difference between the equivalent width distributions of high- and low-luminosity QSOs than is observed.

The models that are ruled out are models A, B, C, D, and H. The feature they have in common is strong continuum aniso-
tropy: the continuum luminosity varies by a very large factor between edge-on and face-on orientations. Models E, F, and G, in contrast, have a relatively small ratio of face-on to edge-on fluxes, and therefore yield narrower equivalent width distributions, which when convolved with some intrinsic variation can match the observed distributions.

Could the line radiation be anisotropic? If a substantial part of the line radiation came from the accretion disk, it would share the anisotropy of the continuum radiation, and there would be little dispersion in equivalent width values due to differing orientations. While an accretion disk origin has been plausibly suggested for Mg II (Collin-Souffrin 1988), it is not likely that the higher ionization lines could come from such an environment, especially the intercombination line C III] with its low critical density. If line anisotropy arose due to the high optical depths in broad-line region clouds surrounding the accretion disk, line flux would be enhanced when observed from edge-on, increasing the predicted numbers of high equivalent width-lined QSOs and worsening the agreement with the observations. Thus line anisotropy alone cannot simply resolve the problem.

The discrepancies come primarily from edge-on disks, and so if, for some reason other than their low observed continuum luminosity, such objects are not observed, the data could be consistent with the model. If, for example, most QSOs are surrounded by a giant molecular torus, co-aligned with the accretion disk (as suggested for much lower luminosity AGN by Antonucci & Miller 1985, and for radio-loud QSOs by Barthel 1989), no edge-on QSOs will be observed, and the deficit of observed QSOs with very high equivalent widths is explained.

In the absence of such an obscuring torus, only models with moderate anisotropy are allowed—the ratio of face-on to edge-on fluxes can be no more than ~ 5. Thus if accretion disks are present in QSOs, their radiation must be reprocessed into a more spherically symmetric pattern.

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