Structure and Kinematics of Quasar Broad Line Regions
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SEDs vs. Emission-Line Correlations in Low Redshift Quasars

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Abstract. We investigate the relations between the observed emission line strengths, widths and continuum properties of a sample of low redshift quasars for which contemporaneous IR-soft-X-ray spectral energy distributions (SEDs) are available. This includes investigating correlations between optical/UV lines with both the luminosity and the shape of the quasars' continua, as well as correlations between the various lines. Our data do not favor a model in which changes in continuum shape (due to e.g., the ionization parameter decreasing with luminosity) cause the "Baldwin effect". The data can instead be explained by an accretion disk (AD) model in which limb darkening and the projected surface area of an optically thick, geometrically thin disk combine to cause a viewing-angle dependent apparent opt./UV luminosity and a more isotropic X-ray luminosity. The scatter in our correlations is larger than that expected from this AD model, suggesting the presence of dust, which reddens both the continuum and the broad emission lines.

1. Introduction

The strong, broad emission lines which characterize quasar spectra are generally believed to be generated in a large number of small gas clouds photoionized by the central continuum source of a quasar. To date photoionization models have been reasonably successful in predicting the average emission line properties of a quasar using an average continuum shape. However, it has become clear that, while the emission line properties are largely similar from quasar to quasar, the observed spectral energy distributions (SEDs) are not (Elvis et al. 1994). If photoionization models are generally applicable, we would expect systematic relations between the observed lines and continuum in different objects (Krolik & Kallman 1988) and, at first glance at least, the dichotomy between continuum and the line behavior looks surprising. We will show that this behavior can be explained by an accretion disk model, surrounded by a dusty torus, with the addition of small amounts of dust reddening both the lines and the continuum.

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2. Sample

We have obtained a small sample of uniform, high quality continuum and emission line data. The sample consists of 41 low redshift ($z < 1$) quasars, among which 18 are radio-loud, selected to have high-quality X-ray data in the Einstein archives. We have obtained far-infrared (IR) through soft X-ray (100 μm – 3.5 keV) continuum data and low-resolution (5-20Å) optical (our observations) and ultraviolet spectra (IUE archives). We have measured all the line and continuum parameters ourselves to minimize the scatter generally introduced by combining datasets from different techniques and different analysis. The range in shapes of the IR–ultraviolet continuum is large even in this small, low-redshift sample, allowing investigation of whether the range in continuum shapes produces any corresponding range in the emission line properties. The X-ray selection results in a bias towards low α_{ox} quasars.

3. Analysis and Results

We investigate the relations between various emission line parameters (fluxes, equivalent widths (EW) and full-width at half maximum intensity (FWHM) of all the prominent optical and UV emission lines) and continuum parameters (L_{opt}, L_X, decade and octave luminosities, broad-band luminosities: L_{UVOIR}, L_{BOL}, Lycon, L_{Ion} and spectral slopes: α_{ox}, α_x, α_{OUV}). We use the ASURV statistical package (Isobe, Feigelson, & Nelson 1986) which includes allowance for the presence of upper limits in the sample. Specifically we applied the following tests to each pair of parameters: the Generalized Kendall Rank and the Spearman Rank test, which is insensitive to outlying points. We considered a correlation real only if the probability of it occurring by chance was <2% in *both* of these tests.

We find anti-correlations between the equivalent-width (EW) and various opt./UV luminosities for the Lyα and Hβ lines (Fig. 1a,b) and a marginal anti-correlation for CIII]. The exclusion of seven narrow line, low luminosity AGN reveals similar relation for both CIII] and CIV lines (Fig. 1c). This suggests that NL S1s have systematically low carbon line EW for their luminosity.

A significant anti-correlation with α_{ox} is seen for the EW of CIV line (Fig. 1d), and a marginal anti-correlation for Hβ and OVI. We do not find any correlations between lines and the X-ray luminosity or X-ray slope. The FeII optical multiplet also does not show a simple relationship with luminosity or continuum slope, however there is a tendency for objects with flat X-ray spectra and/or strong X-ray luminosities to have weak FeII.

4. Discussion

4.1. The Baldwin Effect

The inverse correlation between the emission line equivalent widths and the UV luminosity is commonly known as the Baldwin effect. It indicates that the line flux is increasing more slowly than the local continuum (e.g., is constant) with increasing quasar luminosity. It has been shown that the Baldwin effect in CIV

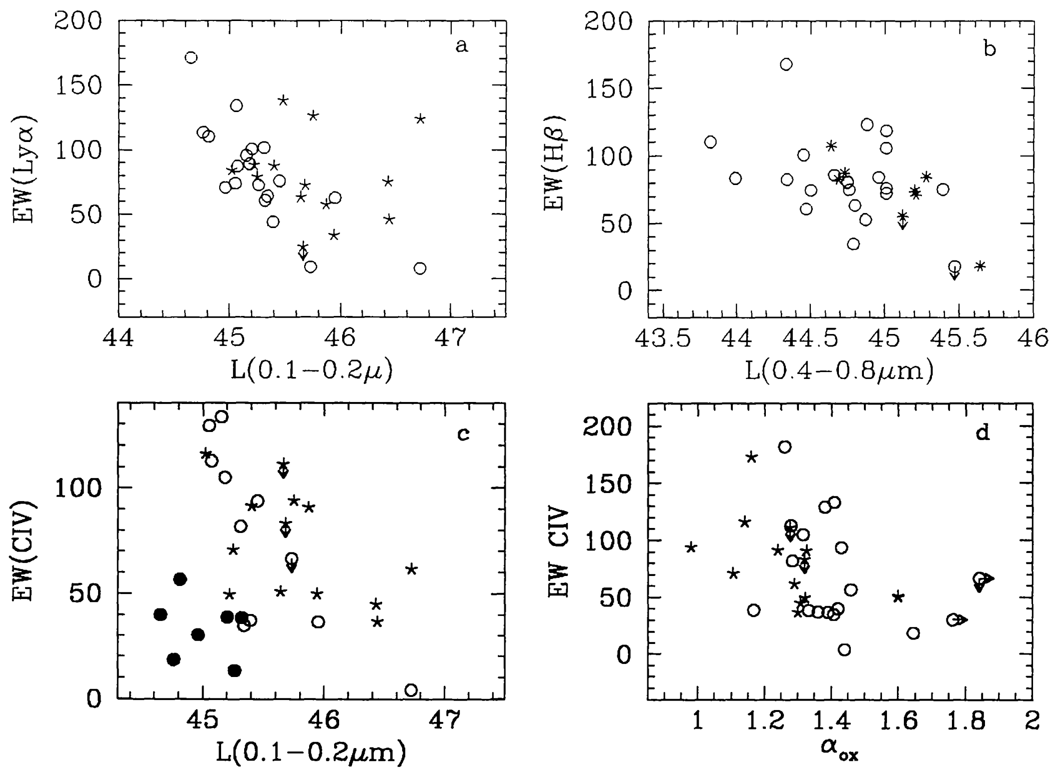

Figure 1. a, b, c – Correlations between line equivalent widths and luminosity. Radio-loud quasars are indicated by stars and radio-quiet by circles; upper limits by arrows. In Fig. 1c filled circles denote NL S1 objects which spoil the CIV Baldwin effect. d - Correlation between CIV equivalent width and α_{ox}.

and Lyα lines covers 7 orders of magnitude in quasar luminosity (Kinney et al. 1990). In comparison our sample covers $\sim$ 2 orders of magnitude and shows a steeper slope in the $W_\lambda(L)$ relation. There have been a number of explanations suggested:

Zheng & Malkan (1993) — explain the Baldwin effect as due to the shift of the big blue bump towards lower energies with increasing luminosity. Hence the higher luminosity quasars have a lower fraction of higher energy ionizing photons. This causes the equivalent widths of high ionization emission lines sensitive to the X-ray continuum (CIV and HeII) to decrease at high luminosities relative to lower-ionization emission lines (Lyα, CIII], and the Balmer lines). The scenario thus predicts a stronger and more easily detectable Baldwin effect for higher-ionization lines. Our data do not favor this model as we see the Baldwin effect equally for both high and low-ionization lines.

Mushotzky & Ferland (1984) – explain the Baldwin effect as due to a systematic decrease in ionization parameter, U, as the luminosity increases. As the ionization parameter depends on the number of ionizing photons, U depends on the continuum shape.

The model predicts the Baldwin effect for the CIV line only, as the CIV line luminosity increases rapidly with increasing U (decreasing UV luminosity and α_{ox}). The Lyα, CIII], Hα, and Hβ do not show any Baldwin effect in this scenario. Additionally equivalent widths of Lyα, CIII], CIV should be, according to the model, relatively independent of both α_{ox} and α_x as the lines do not originate in the X-ray heated zones deep in the emission-line clouds. The model is not consistent with our data.

The Accretion Disk (AD) Model - Netzer (1985,1987,1992) If the optically thick accretion disk, in the center of an AGN, is geometrically thin, then limb darkening and change in projected surface area will result in a range of apparent opt./UV luminosities if the disk is viewed from different angles. The UV emission is strongest when the disk is viewed face-on, while the X-ray emission is more isotropic. The BELR also radiates isotropically as the clouds are at distances greater than the size of the UV-emitting part of the disk. The differing angular dependence of the lines and the continuum results in an anti-correlation of line equivalent widths with opt./UV luminosity and α_{ox}. For the more isotropic X-ray emission, such correlations are not expected. The predictions of this model are consistent with our data.

The AD model predicts both the slope of the line/driving continuum correlations and scatter around the mean. Both are dependent on the range of disk inclination angles seen by the observer.

If we assume that the accretion disk is hidden by a dusty torus with a standard opening angle of $\sim 60°$ then the AD model predicts, for a random selection of objects differing only in disk inclination between 0° and 60° (at larger angles the BLR is assumed to be obscured by the dusty torus), a variation in opt./UV luminosity of a factor of 2 (0.3 in log or 0.3/2= 0.15 around the mean in log). This modifies the slope α, of the line luminosity vs. driving continuum correlations in the following way:

$$\alpha = 1 - 0.3/(logF_{cont}^{max} - logF_{cont}^{min})$$

Most of the lines have slopes as predicted by the model, with the exception of CIV and CIII], which have much flatter slopes.

The scatter around the mean slope in our sample is larger than that expected from the model which could be due to random obscuration of lines and continuum by dust lying outside the BLR.

The role of dust Several properties of our sample suggest the presence of dust:

1. we see larger Balmer decrements than the canonical "case B" value

2. the primary correlations between lines and continua are *not* with their driving continuum

To check how dust can change the primary correlations and how much scatter it can produce, we have constructed a hypothetical sample of objects, having a range in bolometric luminosity matching our real sample, and reddened by a random amount of dust (maximum reddening was based on the difference in the strength of the strongest and weakest big blue bump (BBB) objects in the real sample). Before being reddened each hypothetical object was assumed to have a spectral energy distribution matching the quasar with the largest BBB in the real sample. We have chosen two extinction curves: the standard Galactic extinction curve (Seaton 1979) and the Small Magellanic Cloud (SMC) extinction curve (Prévot et al. 1984), which corresponds well to the extinction by dust dominated by small amorphous carbon grains (Czerny et al. 1995). Two lines widely separated in wavelength, Lyα and Hβ, were studied. We found that the hypothetical sample randomly reddened by dust lying outside the BLR, with the maximum extinction in $E(B-V)=0.2$ and following the SMC extinction curve, has the same primary correlations for Lyα and Hβ lines as the real sample. The scatter in the line/driving continuum correlations is comparable to the additional scatter required in comparing our results with the accretion disk model.

We conclude that the Netzer AD disk model surrounded by an optically thick dusty torus, with addition of small amounts of dust outside the BLR fits well into our line-continuum correlations.

4.2. Outstanding problems

The CIII] and CIV lines have the line/driving continuum slopes too flat and the scatter too large to fit into the AD+dust scenario. Possible explanations include:

- larger than 60° opening angle of the torus; this would however affect all the emission lines
- contamination of the carbon lines by FeII and FeIII multiplets, this would however effect mostly the CIII] line
- distinct carbon emitting region - not a generally excepted point of view.

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