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Emission Lines and the Spectral Energy Distributions of Quasars

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Abstract. Many years of study have failed to establish conclusively relationships between a quasar's spectral energy distribution (SED) and the emission lines it is thought to produce. This is at least partially due to the lack of well-observed SEDs. We present initial results from a line–SED study for a sample of 43 quasars and active galaxies for which we have optical and ultraviolet spectra and far-infrared–X-ray SEDs. We present the results of tests for correlations between line equivalent widths and SED luminosity and slope parameters and compare these results to those from earlier studies. We find that the Baldwin effect is weaker when the luminosity is defined close to the ionizing continuum of that line and conclude that the detailed SED is likely to be important in making further progress.

1. Introduction

It is generally believed that the strong, broad emission lines which characterize quasar spectra are generated in gas photoionized by the central continuum source. While this implies an intimate relationship between the lines and the SED, many years of study have failed to conclusively establish such relations. Indeed there is a general dichotomy between our qualitative viewpoints of the emission lines and SEDs of quasars which belies a strong relation between the two. The emission lines are thought to be similar from object to object, and a single-zone model for the broad emission-line region (BELR) was used with success for many years (Netzer 1990). In contrast the SEDs, including the ionizing UV-soft X-ray continuum, vary a good deal from one object to another (Elvis et al. 1994). Possible explanations for this dichotomy include:

- The BELR gas sees the primary continuum, which has a fairly constant shape, while our view is dominated by reprocessing in regions of the quasar exterior to the BELR as well as along the line of sight.
- A quasar's continuum is anisotropic so that the BELR sees a different continuum from that seen by us.
- Our viewpoints on the emission lines and SEDs of quasars are incomplete and dominated by selection effects.

- There exists a balance between the BELR gas and the continuum such that the prominent emission lines have a small range in relative strengths.
- The emission lines are not emitted in photoionized gas.

Our sample of 43 quasars with complete SED and emission line information allows us to address these possibilities. Here we present preliminary results using standard single-band luminosities and slopes.

2. The Sample

Our sample consists of 43 quasars observed by the *Einstein* X-ray satellite with sufficient counts to define the X-ray spectral shape. It is a heterogeneous sample, about half of which is radio-loud, and is biased toward objects with relatively strong X-ray emission. The multi-wavelength observations of the sample are described in detail in Elvis et al. (1994).

For the purpose of this paper, ultraviolet (UV) spectra are taken from the Lanzetta, Turnshek & Sandoval (1993) compilation of *IUE* spectra of quasars. The optical spectra were obtained by ourselves on the MMT over the period 1985–1990 and will be presented by Wilkes et al. (in preparation). Continuum luminosities L_{opt}, L_x and $\alpha_{\rm ox}$ are taken from Wilkes et al. (1994), optical-UV slopes ($\alpha_{\rm ouv}$) from Kuhn (1996) and X-ray slopes ($\alpha_{\rm x}$) from Elvis et al. (1994) and Wilkes & Elvis (1987). The UV and optical spectra were measured using automated routines described by Green (1996). No deconvolution of heavily blended features was attempted.

3. Results and Discussion

We investigated the relation between the equivalent width (EW) of all the prominent UV and optical emission lines and the gross continuum parameters: L_{opt}, $\alpha_{\rm ox}$, L_x, $\alpha_{\rm x}$, $\alpha_{\rm ouv}$. In order to avoid biases introduced by weak or non-detected lines, we use survival analysis techniques to include upper limits. We applied the following tests for a significant correlation using the ASURV package (LaValley, Isobe, & Feigelson 1992): Cox Proportional Hazard Model, Generalized Kendall's Tau, Spearman's Rho. The average probabilities of a chance correlation derived from the results of these tests are presented in Table 1. Values < 0.03 are considered significant.

We find no correlation between the emission-line EWs and the slopes of either the X-ray or optical-UV continua. We find significant correlations between $\alpha_{\rm ox}$ and the UV lines Lyα+N V, O VI+Lyβ, and C IV, but not with C III], Mg II, or the Balmer lines. Correlations with the continuum luminosities are seen for all lines except C IV. The traditional Baldwin effect (EW inversely related to L_{opt}, Baldwin 1977) is the primary correlation for Lyα+N V, Mg II, and the Balmer lines while a similar correlation with L_x is primary for C III] and Fe II λ4570. O VI+Lyβ has too few data points (14, including 8 upper limits) to assess the correlations. Similar results have been reported by Green (1996), Zheng, Kriss, & Davidson (1995) and Corbin & Boroson (1996), respectively.

The pattern of EW–luminosity correlations found here may perhaps be understood if we refer to the part of the continuum believed to be responsible

Table 1. Average Correlation Coefficients

Line	L_{opt}	L_x	α_{ox}	α_x	α_{ouv}	IC[a]
O VI+Lyβ	NS[b]	0.06	0.03	NS	NS	X
Lyα+N V	0.006	NS	0.02	NS	NS	O+X,X
C IV	NS	NS	0.007	NS	NS	O+X
C III]	0.04	0.015	NS	NS	NS	O
Mg II	0.02	NS	NS	NS	NS	X
Hδ	0.04	NS	NS	...	...	O+X
Hγ+[O III]	0.04	NS	NS	...	...	O+X
Fe II λ4570	NS	0.01	NS	NS	NS	X
Hβ	NS	NS	NS	NS	NS	O+X
[O III] λ5007	0.09	NS	NS	NS	NS	

[a] Ionizing Continuum (Krolik & Kallman 1988)

[b] NS - correlation not significant, average probability of a chance correlation > 0.1

for ionizing each emission line. The final column of Table 1 indicates, very roughly, the spectral region to which a line/blend is sensitive according to Krolik & Kallman (1988). We define the divide between optical (O) and X-ray (X) to be 0.01 eV, and find that, with the exception of the Fe II feature, the *EW*–luminosity inverse correlation is weaker with respect to the luminosity defined closer to the ionizing continuum for that line. This confirms a similar result found by Green (1996) for a largely different sample of quasars and implies that the ionizing continuum is indeed important in determining the strength of an emission line. A more detailed investigation, including continuum luminosities defined over narrower continuum bands, is likely to provide information on the nature of this continuum in each case. These results argue against a purely geometric explanation for the Baldwin effect (e.g., Netzer 1987) and in favor of scenarios involving variations in the shape of the SED (e.g., Mushotzky & Ferland 1984).

A notable exception to this general trend is Fe II λ4570. It is believed to originate in X-ray heated gas deep inside the BELR clouds and so should be sensitive to hard X-rays, although photoionization models generally under-predict the line strengths, calling their results into question. A relation between the soft X-ray slope and the Fe II equivalent width, such that softer sources have stronger Fe II, in contrast to photoionization model predictions, has been debated for a number of years (Bergeron & Kunth 1984, Wilkes, Elvis, & McHardy 1987, Boroson 1989, Zheng & O'Brien 1990). Recent studies have suggested a complex set of relations which also include line width and the strength of [O III] λ5007 (Boroson & Green 1992; Laor et al. 1994, 1996; Boller et al. 1996; Lawrence et al. 1996). The presence of an inverse *EW*(Fe II)–L_x correlation, which perhaps suggests that the X-rays are not responsible for generating Fe II, along with the absence of a simple Fe II–α_x correlation in the current sample, is intriguing and will be followed up in more detail.

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