The ionizing continuum of quasars

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Abstract. The ionizing continuum shape of quasars is generally not directly observable, but indirect arguments, based on photoionization models and thin accretion disk models suggest that it should peak in the extreme UV, and drop steeply into the soft X-ray regime. However, recent observations of very soft X-ray emission in low $z$ quasars, and far UV emission of high $z$ quasars, suggest that the ionizing continuum of quasars does not peak in the extreme UV, and may extend as a single power law from $\sim 1000$ Å to $\sim 1$ keV. If true, that has interesting implications for photoionization models and for accretion disk models. The proposed revised continuum shape will be tested directly in the near future with FUSE.

1. Introduction

What is the shape of the ionizing continuum (1~10 Rydbergs) of quasars? This question is interesting because this is where quasars’ continuum emission peaks (e.g. Sanders et al. 1989; Elvis et al. 1994), and it therefore provides an important clue to the nature of the continuum emission mechanism. It is also interesting because this spectral shape controls the H to He photoionization ratio, and the heating per ionization of the ionizing continuum, and is thus important for understanding the physical parameters of the photoionized gas in quasars.

The best guess mechanism for the continuum emission mechanism in quasars is accretion of gas into a massive black hole (e.g. Rees 1984). The most detailed models calculated are for thin accretion disks. One can thus use theoretical accretion disk spectra to predict the ionizing continuum shape based on the observed optical-UV emission. The implied shape tends to peak in the extreme UV (EUV, e.g. Laor 1990). One can also constrain the EUV spectral shape using the He II $\lambda$1640 equivalent width. This line is presumably a pure recombination line, and thus it can be used as a rather accurate measure of the number of He II ionizing photons. Mathews & Ferland (1987) used this argument to deduced an ionizing continuum which peaks at a few Rydbergs. Thus, it appeared that both accretion disks and photoionization models indicate that the ionizing continuum peaks in the EUV.

However, these arguments are indirect, and one would like to get the best possible observational constraints on the ionizing spectral shape. To address this question we carried out a large program with the ROSAT position sensitive
proportional counter (PSPC). The results were surprising, as further described below (for more details see Laor et al. 1994; 1997).

2. How to Observe?

The large Galactic opacity prevents a direct observation of the EUV in quasars. One alternative is to observe the UV spectra of very high redshift quasars. The other alternative, adopted in our study, is to go to the other side of the Galactic opacity barrier and to observe low redshift quasars in very soft X-rays.

X-ray observations below 1 keV prior to ROSAT indicated a spectral steepening, or equivalently an excess emission, relative to the flux predicted by an extrapolation of the hard X-ray power-law (e.g. Arnaud et al. 1985; Wilkes & Elvis 1987; Turner & Pounds 1989). In some objects the excess could be described as a very steep and soft component, which is consistent with the Wien tail of a hot thermal component dominating the UV emission. However, these studies were limited by the low signal to noise ratio (S/N) and energy resolution of the *Einstein* IPC, and the *EXOSAT* LE detectors, in particular in the crucial energy range below 0.5 keV. This prevented an accurate determination of the soft X-ray emission spectrum of quasars. Furthermore, the objects studied do not form a complete sample, and these results are likely to be biased by various selection effects which were not well defined a priori. In particular, most studied objects are nearby, intrinsically X-ray bright, AGNs.

The PSPC detector aboard *ROSAT* had a significantly improved sensitivity, energy resolution \( \frac{E}{\Delta E} = 2.4 \left( \frac{E}{1 \text{ keV}} \right)^{1/2} \text{ FWHM} \), and spatial resolution below \( \sim 2 \text{ keV} \), compared with previous detectors (Trümper 1983). We used this detector to make an accurate determination of the soft X-ray properties of a well defined, complete, and otherwise well explored, sample of quasars.

3. What to Observe?

We found the BQS sample, a subset of the PG survey defined by Schmidt & Green (1983), to be particularly suitable for our purpose for the following reasons: 1. These objects are selected only by their optical properties, thus they are not directly biased in terms of their X-ray properties. 2. This sample has already been studied extensively, and in a uniform manner in other parts of the spectrum, including the radio (Kellerman et al. 1989; Miller, Rawlings & Saunders 1993), the mid- to far-infrared (Sanders et al. 1989), and the near-infrared to optical (Neugebauer et al. 1987). High quality optical spectroscopy was obtained by Boroson & Green (1992), *HST* FOS spectroscopy was obtained by Wills et al. (1998, these proceedings), and *ASCA* and *SAX* X-ray spectra were obtained by George et al. (1998) and Fiore et al. (1998). These studies of the PG quasars provide us with the most complete and coherent picture of the emission properties of bright AGNs, and allow us to make a detailed study of possible correlations between the soft X-ray properties and various other emission properties. 3. This sample includes a large fraction of the brightest known quasars, thus rather high S/N spectra could be obtained within a reasonable amount of spacecraft time.
The complete PG sample includes 114 AGNs, of which 92 are quasars (i.e. \( M_B < -23 \)). We selected a subsample of the PG quasars which is optimally suitable for soft X-ray observations by the following two selection criteria: 1. \( z \leq 0.400 \). This prevents the rest-frame 0.2 keV from being redshifted beyond the observable range. 2. \( N_{\text{Gal}}^{\text{HI}} < 1.9 \times 10^{20} \text{ cm}^{-2} \), where \( N_{\text{Gal}}^{\text{HI}} \) is the H I Galactic column density as measured in 21 cm. This low \( N_{\text{Gal}}^{\text{HI}} \) cutoff is critical for minimizing the effects of Galactic absorption. This cutoff implies an upper limit on the Galactic optical depth in our sample of \( \tau_{0.2 \text{keV}} < 1.6 \) (Morrison & McCammon 1983). Even with this low \( N_{\text{Gal}}^{\text{HI}} \) cutoff, no photons below 0.15 keV can be detected. This is because the opacity of the Galaxy increases as \( E^{-3} \), giving \( \tau_{0.1 \text{keV}} = N_H/1.77 \times 10^{19} \), while the effective area of the PSPC drops rapidly below 0.15 keV. As a result practically no photons below 0.15 keV can be detected from the quasars (although the formal lower limit of the usable channels on the PSPC is 0.1 keV). These criteria limited our sample to 23 quasars, which should be representative of the low-redshift, optically-selected quasar population.

Accurate values of \( N_{\text{Gal}}^{\text{HI}} \) are crucial, even for our low \( N_{\text{Gal}}^{\text{HI}} \) sample, in order to make an accurate determination of the intrinsic soft X-ray spectrum. The \( N_{\text{Gal}}^{\text{HI}} \) values were taken from Elvis, Lockman & Wilkes (1989), Savage et al. (1993), Lockman & Savage (1995), and the recent extensive measurements by Murphy et al (1996). All these measurements of \( N_{\text{Gal}}^{\text{HI}} \) were made with the 140 foot telescope of the NRAO at Green Bank, WV, using the “bootstrapping” stray radiation correction method described by Lockman, Jahoda, & McCammon (1986), which provides an angular resolution of 21', and an uncertainty of \( \Delta N_{\text{Gal}}^{\text{HI}} = 1 \times 10^{19} \text{ cm}^{-2} \) (and possibly lower for our low \( N_{\text{H}} \) quasars). This uncertainty introduces a flux error of 10% at 0.2 keV, 30% at 0.15 keV, and nearly a factor of 2 at 0.1 keV. Thus, with our accurate \( N_{\text{Gal}}^{\text{HI}} \) reasonably accurate fluxes can be obtained down to \( \sim 0.15 \text{ keV} \).

### 3.1. The Soft X-ray Continuum

All the objects in our sample were detected with the PSPC, and high quality spectra were obtained for most objects. The spectra of 22 of the 23 quasars are consistent, to within \( \sim 30\% \), with a single power-law model at rest-frame 0.2–2 keV. There is no evidence for significant soft excess emission with respect to the best fit power-law. We place a limit (95% confidence) of \( \sim 5 \times 10^{19} \text{ cm}^{-2} \) on the amount of excess foreground absorption by cold gas for most of our quasars. The limits are \( \sim 1 \times 10^{19} \text{ cm}^{-2} \) in the two highest S/N spectra.

Significant X-ray absorption (\( \tau > 0.3 \)) by partially ionized gas (“warm absorber”) in quasars is rather rare, occurring for \( \leq 5\% \) of the population, which is in sharp contrast to lower luminosity Active Galactic Nuclei (AGNs), where significant absorption probably occurs for \( \sim 50\% \) of the population.

For the complete sample we find \( \langle \alpha_{\text{ox}} \rangle = -1.55 \pm 0.24 \), and \( \langle \alpha_x \rangle = -1.62 \pm 0.45 \). This may appear to suggest that \( \langle \alpha_{\text{ox}} \rangle \simeq \langle \alpha_x \rangle \), as proposed by Brunner et al. (1992) and Turner, George & Mushotzky (1993). However, this relation does not hold when the sample is broken to the RQQ where \( \langle \alpha_{\text{ox}} \rangle = -1.56 \pm 0.26 \), and \( \langle \alpha_x \rangle = -1.72 \pm 0.41 \), and to the RLQ where \( \langle \alpha_{\text{ox}} \rangle = -1.51 \pm 0.16 \), and \( \langle \alpha_x \rangle = -1.15 \pm 0.27 \).

A significantly flatter \( \langle \alpha_{\text{ox}} \rangle \) is obtained when the three X-ray weak quasars (see Laor et al. 1997), and the absorbed quasar PG 1114+445, are excluded.
Thus, “normal” RQQ quasars in our sample have $\langle \alpha_{ox} \rangle = -1.48 \pm 0.10, \langle \alpha_x \rangle = -1.69 \pm 0.27$, while for the RLQ $\langle \alpha_{ox} \rangle = -1.44 \pm 0.12, \langle \alpha_x \rangle = -1.22 \pm 0.28$, where the ± denotes here and above the dispersion about the mean, rather than the error in the mean.

3.2. The EUV Continuum

Zheng et al. (1997) have constructed a composite quasar spectrum based on HST spectra of 101 quasars at $z > 0.33$. They find a far-UV (FUV) slope (1050-350 Å) of $\langle \alpha_{FUV} \rangle = -1.77 \pm 0.03$ for RQQs and $\langle \alpha_{FUV} \rangle = -2.16 \pm 0.03$ for RLQs, with slopes of $\sim -1$ in the 2000-1050 Å regime. The Zheng et al. mean spectra, presented in Figure 6, together with the PSPC mean spectra, suggest that the FUV power-law continuum extends to the soft X-ray band. In the case of RQQs there is a remarkable agreement in both slope and normalization of the soft X-ray and the FUV power-law continua, which indicates that a single power law continuum component extends from $\sim 1000$ Å to $\sim 1 - 2$ keV. RLQs are predicted to be weaker than RQQs at $\sim 100$ eV by both the FUV and the PSPC composites. It thus appears that there is no extreme UV sharp cutoff in quasars, and no steep soft component below 0.2 keV. This implies that the fraction of bolometric luminosity in the FUV regime may be significantly smaller than previously assumed.

The UV to X-ray continuum suggested in Figure 1 is very different from the one predicted by thin accretion disk models and suggested by photoionization models. In particular, it implies about a four times weaker FUV ionizing continuum compared with the Mathews & Ferland continuum that was deduced based on the He II $\lambda$1640 recombination line equivalent width.

4. What does it Mean?

4.1. Photoionization models

Korista, Ferland & Baldwin (1997) discuss possible ways to reconcile the revised ionizing spectral shape with photoionization models. They find that there is no way to adjust the BLR parameters to produce the observed strength of He II together with the other UV emission lines, and so they conclude that either the ionizing continuum is anisotropic, and the BLR sees a harder continuum than what we see, or that the interpolation between the FUV and soft X-ray emission is wrong, and there is an EUV peak near 4 Rydbergs.

An anisotropic ionizing continuum is naturally produced by thin accretion disks, as the radiation from the hottest inner parts of the disk is deflected towards low inclination angles by the combined effect of Doppler beaming and gravitational deflection (e.g. fig.8 in Laor & Netzer 1989). Unified models of AGNs (e.g. Antonucci 1993), as well as X-ray spectroscopy of the Fe Kα line (Nandra et al. 1997), indicate that quasars are generally seen not too far from face-on. Thus, the BLR is most likely spread at high inclination angles, together with the rest of the obscuring gas, and the observed continuum will always be softer than the one incident on the BLR.

The other possibility of an EUV peak may have a physical explanation as a bound-free He II emission edge produced in the disk’s atmosphere (Hubeny &
Figure 1. Composite optical-soft X-ray spectrum for the RQQs and RLQs in the Laor et al. sample (thick solid line). Note that despite the fact that RLQs are brighter at 2 keV, they are fainter at 0.2 keV. The Mathews & Ferland (1987) spectral shape assumes a hard X-ray power law down to 0.3 keV and a very steep component below 0.3 keV. This spectral shape is inconsistent with the PSPC results. The Zheng et al. composites for RLQs and RQQs are plotted in a thin solid line. They suggest that the FUV power law extends into the soft X-ray regime, with no extreme UV spectral break and no steep soft component below 0.2 keV.
Hubeny 1997, 1998). The problems with this explanation is that a strong He II emission edge requires fine tuning of the disk model parameters. It also requires fine tuning of the spectral shape so that the emission shortward of the EUV peak will look like a smooth extension of the emission longward of the peak.

4.2. Accretion disk models

Accretion disks inevitably produce a spectral shape which rises slowly with frequency and then drops steeply above some cutoff frequency. This just reflects the fact that the disk is powered by gravity, and that the dissipated energy is radiated locally (and that it has an inner edge). The revised ionizing continuum drops much more slowly than possible with any form of simple thin accretion disk models (e.g. Fig. 7 in Laor et al. 1997). This slow drop may reflect a drop in the disk radiation efficiency at small radii, either due to the disk becoming optically thin, so that the viscous infall time is shorter than the gas cooling time, or if the optical depth remains large, the radiative efficiency may drop due to trapping of the outgoing radiation in the disk, and its advection beyond the black hole event horizon. Alternatively, part of the dissipation may occur in a warm corona above the disk, which will turn the disk exponential tail EUV emission passing through it into a power law tail (e.g. Czerny & Elvis 1987).

5. Possible Caveats

5.1. Is the PSPC well calibrated at low energy?

Both EINSTEIN and ASCA observations of quasars generally suggest a flatter soft X-ray power-law emission. This raises the possibility that the PSPC may be badly calibrated, and that the FUV - soft X-ray match may just be a coincidence. A proper evaluation of the calibration of these X-ray telescopes is well beyond the scope of this contribution. It is sufficient to say that there is no consensus about this issue in the X-ray community.

However, the following result suggests that the PSPC is most likely well calibrated below 0.5 keV. Figure 2 compares the Galactic $N_H$ deduced from the accurate 21 cm measurements with the best fit X-ray column deduced using $N_H$ as a free parameter (Laor et al. 1997). In most objects the two columns agree to within $\sim 1\sigma$. Two objects, PG 1116+215 and PG 1226+023, have a very high S/N PSPC spectrum, and for these $N_H$(X-ray) is very well determined (to within $0.8 - 1 \times 10^{19}$ cm$^2$), yet this column is still consistent with $N_H$(21 cm), indicating that both methods agree to 5-7%. This remarkably good match implies that the PSPC is very unlikely to be have a significantly biased calibration below $\sim 0.5$ keV, where the ISM absorption becomes significant. The $N_H$(X-ray) vs. $N_H$(21 cm) match also has various interesting physical implications, as further discussed in Laor et al. (1997).

It is also likely that the PSPC is well calibrated above 0.5 keV. Laor et al. (1994, 1997) fitted each object above 0.5 keV, to look for spectral curvature by comparing this fit to the fit to the whole PSPC band (their fit 3). They found that the mean spectral slope above 0.5 keV is not significantly different from the mean slope over the whole PSPC band. This suggests that the PSPC is also well calibrated above 0.5 keV. Otherwise, the PSPC calibration above 0.5 keV
needs to be biased in such a way so as to just compensate for an intrinsic slope change above 0.5 keV.

5.2. Is it dust reddening?
Zheng et al. corrected their individual quasar FOS spectra for Galactic extinction and also made a statistical correction for absorption by the Lyman forest. However, no correction was applied for reddening intrinsic to the quasars. The Galactic extinction curve rises steeply below 2000 Å and relatively small extinction in the optical may induce significant reddening in the FUV. If quasars have dust with a Galactic extinction curve one may worry that the observed steepening below 1000 Å is induced by dust.

The dust opacity for a variety of grain compositions peaks at $\sim 700 - 800$ Å and drops steeply at shorter wavelengths, to about 1/3 of the peak opacity at $\sim 300$ Å (see Fig.6 in Laor & Draine 1993). Thus, if the observed steepening below 1000 Å was due to dust extinction, then the spectrum at $\lambda < 700$ Å should have flattened back due to the decreasing extinction. Since the observed composite does not show such a recovery, it is not likely that the steepening is due to intrinsic dust absorption, whether it is Galactic dust or dust of other compositions.

5.3. Are we comparing apples and oranges?
The Zheng et al. sample includes only $z > 0.33$ quasars, and their composite FUV slope is based mostly on $z \geq 1$ quasars, while our sample is limited to $z \leq 0.4$ quasars only. Thus the two samples are practically disjoint. If the FUV to soft X-ray spectral shape is redshift dependent then we are not comparing similar objects, and the apparent agreement of the FUV and soft X-ray composites would be just a coincidence.

One clearly needs to explore the FUV to soft X-ray spectral shape in samples with similar redshifts. A stronger test is to explore whether the mean FUV and soft X-ray continua agree in a given sample, and the strongest test is to explore whether they agree for each object in the sample. A large program was recently approved for the FUSE mission (PI Anuradha Koratkar) to obtain high quality FUV spectra for all our sample of 23 quasars. The spectra will be obtained down to the Galactic Lyman limit cutoff, i.e. typical rest frame $\lambda \sim 750$ Å, which is well below the 1000 Å break. This will allow us to clearly determine for each object whether the FUV and soft X-ray continua agree.

6. The EUV in Other Types of AGNs
Seyfert galaxies show flatter $\alpha_{ox}$ than quasars, but they also show a flatter $\alpha_x$ than in quasars. This raises the possibility that these objects may also have a single power law component extending from the FUV to $\sim 1$ keV, as was suggested by Zheng et al. (1995) for Mrk 335. FUSE observations of a large sample of Seyfert galaxies having high quality PSPC spectra are required in order to address this possibility, although given the low $z$ of Seyferts, it will be possible to probe their continuum slope only down to rest frame $\lambda 850$ Å.
Figure 2. The H I column determined by 21 cm measurements versus the best fit H I column determined by a power-law fit to the quasars PSPC spectrum. The assumption that both values are equal, indicated by the straight line, is acceptable at the 8% level. Note, in particular, the two highest S/N objects, which deviate from the straight line by less than $1 \times 10^{19}$ cm$^{-2}$. The agreement between the two measures of $N_H$ indicates a lack of intrinsic cold gas absorption in quasars, and that H I/He ~ H/He in the ISM at high Galactic latitudes.
BALQSOs appear to have a steep FUV slope (Korista et al. 1992; Arav et al. 1998), and they also generally show a steep $\alpha_{ox}$ (Green & Mathur 1996), most likely due to strong X-ray absorption (Mathur, Elvis, & Singh 1995). Again, this raises the possibility that their FUV extrapolates to the soft X-ray flux level. *HST* and *FUSE* observations of a larger sample of $z \sim 1-2$ BALQSOs can address this possibility. If the FUV of BALQSOs is indeed generally very steep that would exacerbate the energy budget problem, which is already significant in normal quasars. Since the weakness of the soft X-ray emission is most likely due to absorption, the steep FUV spectra may also be due to (a wavelength dependent) absorption.

Some AGNs must clearly have an EUV continuum which is very different from a simple power law. In particular, Puchnarewicz et al. (1994, 1995a, b) find a number of AGNs with an extremely strong soft X-ray component, much above the UV component. However, these AGNs were selected from the most luminous soft X-ray sources known, and are thus most likely extreme cases. Other AGNs have a rather steep UV continuum, but flat $\alpha_{ox}$ (Puchnarewicz & Mason 1998), possibly due to extinction of the optical continuum and absorption of the soft X-ray continuum.

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