

## NEW XMM-NEWTON SPECTROSCOPY OF THE MOST LUMINOUS AND DISTANT QUASARS

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### ABSTRACT

In the two parts of this contribution we describe two related *XMM-Newton* programs. The first part summarizes our study of the X-ray spectral properties and variability of  $z > 4$  quasars (Shemmer et al. 2005). The second part presents preliminary results from our ongoing *XMM-Newton* program to investigate the X-ray spectral properties and variability of luminous, high accretion-rate quasars at  $z \sim 2-3$ . We find that the X-ray photon index does not depend on luminosity or redshift, and there is suggestive evidence that it may depend on the accretion rate. None of our quasars is significantly absorbed, and none shows signatures of reflection. By jointly fitting high-quality spectra of eight radio-quiet  $z > 4$  quasars, including three from our *XMM-Newton* observations, we place tight constraints on the mean X-ray spectral properties of such sources. Most of our quasars are significantly X-ray variable on timescales of months–years, but none shows rapid ( $\sim 1$  hr timescale) variations.

### 1. XMM-NEWTON SPECTROSCOPY OF $Z > 4$ QUASARS

#### 1.1. Introduction

Quasars at  $z > 4$  are valuable cosmological probes of the physical environment in the  $\sim 1$  Gyr old Universe. In particular, the most distant quasars known, at  $z \sim 6$ , have enabled tracing of the physical conditions in the Universe at the end of the re-ionization epoch with implications for large-scale structure formation (e.g., Fan et al. 2002). The study of  $z > 4$  quasars therefore has become one of the main themes in astrophysics during the past few years. One of the lines of research in this field is to determine whether the energy production mechanism of quasars is sensitive to the significant large-scale evolution the Universe has experienced over cosmic time. A central question in this context is whether black holes (BHs) in distant quasars feed and grow in the same way as BHs in local active galactic nuclei (AGN). Recent radio–optical

observations of  $z > 4$  quasars have found that their spectral energy distributions (SEDs) are not significantly different from those of lower redshift sources implying no SED evolution, and hence no significant changes in the energy production mechanism of AGN are observed (e.g., see Carilli et al. 2001 and Petric et al. 2003 for radio observations; Pentericci et al. 2003 and Vanden Berk et al. 2001 for UV–optical observations).

X-rays from distant quasars are especially valuable for studying the energy production mechanism, since they provide information on the innermost regions of the central engine, where most of the nuclear energy is produced. Until fairly recently, only a handful of  $z > 4$  quasars were detected in X-rays, and the data only provided basic X-ray photometry. During the past five years over 100 quasars have been detected by *Chandra* and *XMM-Newton*, allowing reliable measurements of their mean X-ray spectral properties (e.g., Brandt et al. 2002; Bechtold et al. 2003; Grupe et al. 2004, 2006; Vignali et al. 2003a,b, 2005). However, the different X-ray studies of  $z > 4$  quasars often led to conflicting conclusions. For example, while Bechtold et al. (2003) reported that the X-ray power-law photon indices ( $\Gamma$ ) of  $z > 4$  quasars are *flatter* than those of nearby AGNs, Grupe et al. (2006) reported that their  $\Gamma$  are rather *steep*; Vignali et al. (2005) found that  $\Gamma$  does not undergo significant evolution and is not luminosity dependent.

The different conclusions, frequently based upon the same X-ray data, were reached mainly due to the small number of photons collected in the observations that were intended to detect  $z > 4$  quasars; this led to large uncertainties in the basic X-ray spectral properties and hence to several possible interpretations. This motivated us and other authors to solve the puzzle and obtain high-quality X-ray spectra of several X-ray bright  $z > 4$  quasars. High-quality X-ray spectra (with  $\gtrsim 500$  [ $\gtrsim 100$ ] photons obtained by *XMM-Newton* [*Chandra*]) are currently available for 10  $z > 4$  radio-quiet and radio-moderate quasars (Ferrero & Brinkmann 2003; Farrah et al. 2004; Grupe et al. 2004, 2006; Schwartz & Virani 2004; Shemmer et al. 2005, hereafter S05). Below we summarize the results of the recent set of five of those spectra, which are described in detail in S05.

## 1.2. High-Quality Spectra of $z > 4$ Quasars

We obtained high-quality *XMM-Newton* spectra of five  $z > 4$  quasars during *XMM-Newton* AO3; the detailed data-reduction and analysis procedures are described in S05. Each quasar was previously detected in *Chandra* snapshot observations (Vignali et al. 2001, 2003a,b). The basic properties of the quasars, as well as their measured X-ray properties, are given in Table 1. Three of the quasars are radio-quiet, one quasar, PSS 0121+0347, is radio loud ( $R=300$ ; Vignali et al. 2003a), and another quasar, SDSS 0210–0018, is radio moderate ( $R=80$ ; Vignali et al. 2001) following the radio-loudness definition of Kellermann et al. (1989). We detected  $\sim 500$ – $1500$  photons from each quasar in a net exposure time of  $\sim 20$ – $30$  ks per source. These exposures enabled accurate measurements of  $\Gamma$  (with  $\Delta\Gamma=0.15$ ) and upper limits on the intrinsic neutral column densities for each quasar. The *XMM-Newton* data, best-fit spectra, and residuals appear in Fig. 1. In Fig. 1 we also plot confidence contours in the  $\Gamma$ – $N_{\text{H}}$  plane for each quasar.

To extend our analysis, we added to our sample high-quality X-ray spectra of five additional  $z > 4$  radio-quiet quasars (RQQs) from the archive; these are Q 0000–263 (Ferrero & Brinkmann 2003), SDSS 1030+0524 (Farrah et al. 2004), BR 0351–1034 and BR 2237–0607 (Grube et al. 2004, 2006), from *XMM-Newton* observations, and SDSS 1306+0356 which was observed with *Chandra* (Schwartz & Virani 2004). The spectra of all 10  $z > 4$  quasars were reduced and analyzed uniformly to obtain the basic X-ray spectral properties for each source.

## 1.3. X-ray Spectral Properties of $z > 4$ Radio-Quiet Quasars

The best-fit X-ray spectral properties for our sources appear in Table 1. The photon indices and the upper limits on the neutral intrinsic absorption in each quasar were obtained by fitting the spectra with intrinsically (redshifted) absorbed power-law models, including Galactic absorption. The constraints we obtained on the intrinsic absorption in each quasar (Table 1) show that our  $z > 4$  RQQs are not significantly absorbed. In Fig. 2 we plot  $\Gamma$  (above 2 keV in the rest-frame) for samples of radio-quiet AGN, including our expanded sample of  $z > 4$  quasars, against optical luminosity and redshift. We find that  $\Gamma$  takes a typical value of  $\sim 1.9$ , and it does not depend significantly on either optical luminosity or redshift. We also note that there is no significant intrinsic dispersion in  $\Gamma$  values within our sample of eight  $z > 4$  RQQs.

We have also computed optical–X-ray spectral slopes ( $\alpha_{\text{ox}}$ , e.g., Tananbaum et al. 1979; see Table 1) for our sources and found that our measurements are consistent with the Strateva et al. (2005) and Steffen et al. (2006) conclusions that  $\alpha_{\text{ox}}$  strongly correlates with ultraviolet luminosity and does not evolve over cosmic time (out to  $z \sim 6$ ).

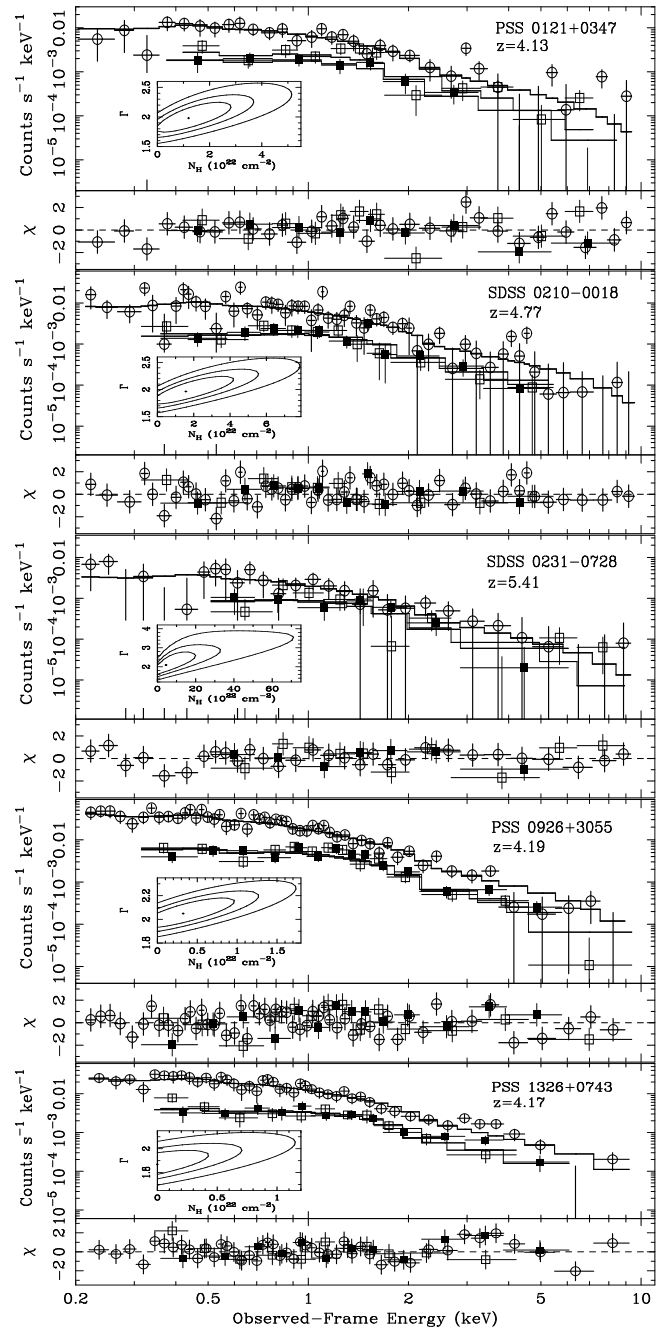


Figure 1. Data, best-fit spectra, and residuals for our new *XMM-Newton* observations of five  $z > 4$  AGNs. Open circles, filled squares, and open squares represent the pn, MOS1, and MOS2 data, respectively. Solid lines represent the best-fit model for each spectrum, and the thick line marks the best-fit model for the pn data. The  $\chi$  residuals are in units of  $\sigma$  with error bars of size 1. The inset in each panel shows 68%, 90%, and 99% confidence contours for the intrinsic absorption and photon index.

Table 1. Optical and X-ray properties of our  $z>4$  quasar sample.

Quasar	$z$	$M_B^a$	$\Gamma$	$N_H^b$ ( $10^{22} \text{ cm}^{-2}$ )	$\log L_{2-10 \text{ keV}}^a$ ( $\text{erg s}^{-1}$ )	$\alpha_{\text{ox}}$
PSS 0121+0347	4.13	-28.3	$1.81^{+0.16}_{-0.16}$	$\leq 2.91$	45.5	$-1.65^{+0.03}_{-0.03}$
SDSS 0210-0018	4.77	-27.7	$1.81^{+0.15}_{-0.14}$	$\leq 4.17$	45.3	$-1.54^{+0.03}_{-0.02}$
SDSS 0231-0728	5.41	-27.9	$1.85^{+0.33}_{-0.31}$	$\leq 19.90$	45.2	$-1.62^{+0.06}_{-0.06}$
PSS 0926+3055	4.19	-30.1	$1.99^{+0.08}_{-0.08}$	$\leq 1.02$	45.9	$-1.76^{+0.03}_{-0.01}$
PSS 1326+0743	4.17	-29.6	$1.87^{+0.10}_{-0.10}$	$\leq 0.47$	45.7	$-1.76^{+0.03}_{-0.02}$

<sup>a</sup>Luminosity distances were computed using the standard ‘‘concordance’’ cosmological parameters  $\Omega_\Lambda=0.7$ ,  $\Omega_M=0.3$ , and  $H_0=70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

<sup>b</sup>Neutral intrinsic column density.

To obtain the mean X-ray spectral properties of the RQQ population at  $z>4$ , we fitted jointly our new *XMM-Newton* spectra of three RQQs and the five archival high-quality spectra of  $z>4$  RQQs with several models; this is roughly equivalent to fitting a single mean spectrum composed of  $\sim 7000$  photons. The number of photons in our combined spectrum is larger by an order of magnitude than the number of photons previously used in such analyses (e.g., Vignali et al. 2005). By fitting the spectra jointly we obtained a mean photon index  $\Gamma=1.97^{+0.06}_{-0.04}$ . We also obtained the strongest constraint to date on the mean neutral intrinsic column density in such sources,  $N_H \lesssim 3 \times 10^{21} \text{ cm}^{-2}$  (Fig. 3), showing that optically selected RQQs at  $z>4$  are, on average, not more absorbed than their lower-redshift counterparts. All this suggests that the X-ray production mechanism and the central environment in radio-quiet AGN have not significantly evolved over cosmic time. We also used the combined spectrum to constrain the mean equivalent width of a putative neutral narrow Fe  $K\alpha$  line to  $\lesssim 190 \text{ eV}$ , and similarly to constrain the mean Compton-reflection component to  $R \lesssim 1.2$ ; these constraints are consistent with the expected strength of a reflection component given the high luminosities of our sources (e.g., Page et al. 2004).

#### 1.4. X-ray Variability of $z>4$ Radio-Quiet Quasars

We applied Kolmogorov-Smirnov tests to the photon arrival times in our new *XMM-Newton* observations to search for rapid ( $\sim 1 \text{ hr}$  timescale in the rest frame) variations, but none was detected.

To look for long-term (months–years) X-ray variations in our sample, we compared the fluxes of our sources in the observed-frame 0.5–2 keV band in the first epoch (*Chandra* snapshot observations) with those in the second epoch (*XMM-Newton* or *Chandra* observations). Seven  $z>4$  quasars from this study have high-quality

(i.e., *Chandra* or *XMM-Newton* data to minimize cross-calibration uncertainties) two-epoch X-ray data for our comparison. Using  $\chi^2$  statistics, we found that five of the seven quasars varied significantly between the two epochs (Fig. 4); the two sources that did not vary significantly between the two epochs are PSS 1326+0743 and SDSS 1030+0524.

While most quasars varied by no more than a factor of  $\approx 2$  between the two epochs, one source, SDSS 0231-0728, faded by a factor of  $\sim 4$  between the first observation (*Chandra*) and the second one (*XMM-Newton*). This flux change occurred over a rest-frame period of 73 d. This is the largest change in X-ray flux observed for a  $z>4$  RQQ. Given the UV–optical flux of the source, and using the Strateva et al. (2005) relation between UV luminosity and  $\alpha_{\text{ox}}$ , it is likely that this source was caught in an X-ray high state in the first epoch (Vignali et al. 2003b), since its X-ray flux in the second epoch (S05) agrees with the value predicted from its optical flux (assuming the optical flux is nearly constant). Vignali et al. (2003b) also noted that SDSS 0231-0728 was X-ray brighter than expected (see their Fig. 5). The spectral slope of the source also shows a possible indication of flattening from  $\Gamma=2.8^{+1.10}_{-0.95}$  to  $\Gamma=1.85^{+0.33}_{-0.31}$  between the two epochs, but the significance is only  $\sim 1 \sigma$  due to the limited number of counts ( $\sim 25$ ) in the first *Chandra* snapshot observation. This is a tentative indication for a transition from a soft/high state to a hard/low state in this source, as has been seen for a few local AGN (e.g., Guainazzi et al. 1998; Maccarone et al. 2003).

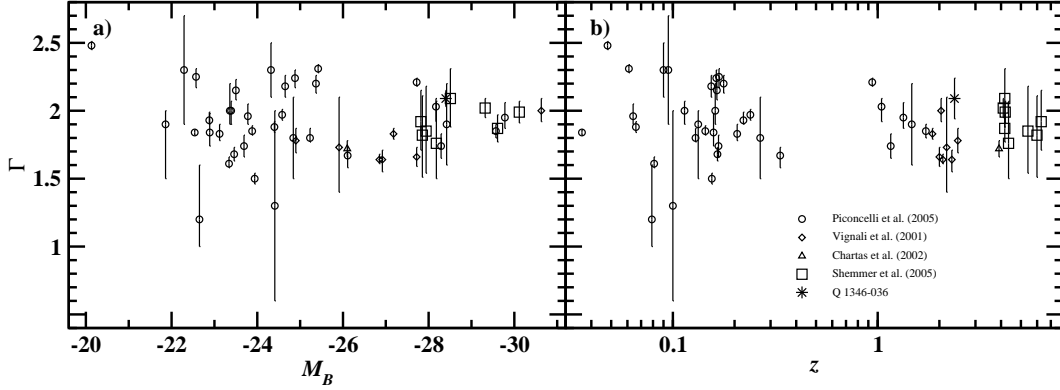


Figure 2. The X-ray photon index versus (a) absolute  $B$  magnitude and (b) redshift; adapted from S05. Note the lack of a clear dependence of the photon index on either luminosity or redshift, although considerable scatter in  $\Gamma$  is observed in local AGN. Our new XMM-Newton observation of Q 1346–036, a luminous, high accretion-rate quasar at  $z=2.37$  is represented by a star; our ongoing XMM-Newton observations of similar sources may determine whether  $\Gamma$  depends on the accretion rate (see § 2)

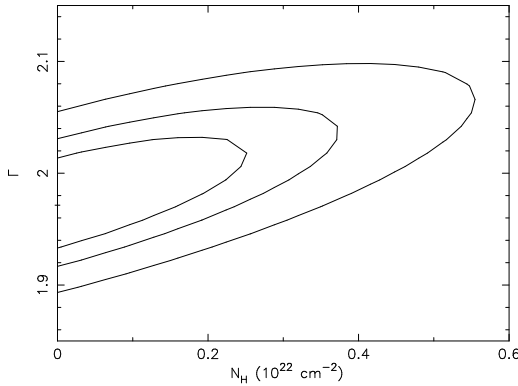


Figure 3. 68%, 90%, and 99% confidence regions for the photon index vs. intrinsic column density derived from joint spectral fitting of our sample of eight RQOs.

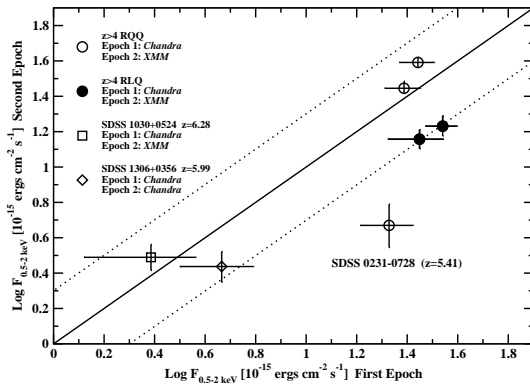


Figure 4. Two-epoch Galactic-absorption corrected 0.5–2 keV fluxes for seven of the  $z > 4$  quasars in our sample. The solid line marks the 1:1 flux ratio, and the two dotted lines mark 1:2, and 2:1 flux ratios, to guide the eye. SDSS 0231–0728 clearly varied by more than a factor of two between the two epochs. The second and third most variable sources, PSS 0121+0347 and SDSS 0210–0018, are radio loud and radio moderate, respectively, and are marked with filled circles.

## 2. XMM-NEWTON SPECTROSCOPY OF LUMINOUS, HIGH ACCRETION-RATE QUASARS AT REDSHIFT $\sim 2$ –3

### 2.1. Is $\Gamma$ an Accretion Rate Indicator?

In § 1 we have shown that the X-ray photon index in RQOs appears to be constant, with a typical value of  $\sim 1.9$ , regardless of redshift or luminosity. This result has also been confirmed and strengthened by other recent studies (e.g., Mateos et al. 2005; Page et al. 2005; Risaliti & Elvis 2005). However, inspection of Fig. 2 shows considerable scatter in  $\Gamma$ , in particular at low redshifts ( $z \lesssim 0.5$ ). This scatter may be attributed to a fundamental physical parameter, which controls the X-ray spectral shape in AGN.

Boller et al. (1996) have found that the soft (ROSAT band) X-ray power-law photon index is anti-correlated with FWHM( $H\beta$ ), and hence narrow-line Seyfert 1 (NLS1s) galaxies (which meet the FWHM( $H\beta$ )  $\lesssim 2000$  km s $^{-1}$  criterion of Osterbrock & Pogge 1985) have significantly steeper X-ray spectral slopes than broad-line Seyfert 1 galaxies. This trend is observed in the hard (ASCA) X-ray band as well (e.g., Brandt et al. 1997; Leighly 1999). Strong correlations between FWHM( $H\beta$ ) and the X-ray photon index in both the soft and hard bands are also exhibited by higher luminosity nearby ( $z \lesssim 0.5$ ) quasars (e.g., Laor et al. 1997; Porquet et al. 2004).

Brandt & Boller (1998) and Laor (2000) have suggested that the strong  $\Gamma$ –FWHM( $H\beta$ ) correlation may be a consequence of a fundamental correlation between  $\Gamma$  and the accretion rate, since FWHM( $H\beta$ ) is considered to be an accretion-rate indicator in AGN (e.g., Boroson & Green 1992; Porquet et al. 2004). Such a correlation may be expected if the bulk of the emitted optical–X-ray energy is shifted into higher energies for higher accretion rates.

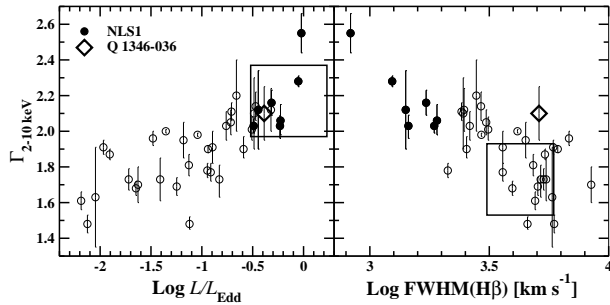


Figure 5. X-ray photon index in the rest-frame 2–10 keV band versus  $L/L_{\text{Edd}}$  (left) and  $\text{FWHM}(\text{H}\beta)$  (right). Circles mark AGN at  $z < 0.5$ . NLS1s are marked with filled symbols, and Q 1346–036, a luminous,  $z=2.37$  quasar from the S04 sample and recently observed by XMM-Newton, is marked with a diamond; it is the only high- $z$  source on this diagram. Both  $L/L_{\text{Edd}}$  and  $\text{FWHM}(\text{H}\beta)$  are significantly correlated with  $\Gamma$  for  $z < 0.5$  AGN. Boxes mark the expected positions of the S04 quasars on each correlation.

The use of  $\text{FWHM}(\text{H}\beta)$  as an accretion-rate indicator relies on reverberation-mapping studies that found a strong correlation between the broad-line region (BLR) size and luminosity in AGN (e.g., Kaspi et al. 2000). By assuming Keplerian motion of the BLR gas around the central BH and using the BLR size–luminosity relation, the BH mass becomes  $M_{\text{BH}} = c_1 [\lambda L_{\lambda}(5100)]^{c_2} [\text{FWHM}(\text{H}\beta)]^2$ , and the accretion rate (in terms of the Eddington ratio) is therefore  $L/L_{\text{Edd}} \propto [\lambda L_{\lambda}(5100)]^{1-c_2} [\text{FWHM}(\text{H}\beta)]^{-2}$ , where  $\lambda L_{\lambda}(5100)$  is the monochromatic luminosity at  $5100\text{\AA}$ ,  $L_{\text{Edd}}$  is the Eddington luminosity, and  $c_1$  and  $c_2$  are constants determined by reverberation mapping (e.g., Kaspi et al. 2000, 2005; see the specific equations in Shemmer et al. 2004, hereafter S04).  $\text{FWHM}(\text{H}\beta)$  is perhaps the best accretion-rate indicator, and the use of other emission lines as proxies to  $\text{H}\beta$ , such as C IV, can lead to spurious estimates of  $L/L_{\text{Edd}}$  (e.g., Baskin & Laor 2005). NLS1s are the highest accretion-rate sources among low-luminosity AGN, with  $L/L_{\text{Edd}}$  approaching, and in extreme cases even exceeding, unity.

## 2.2. X-ray Properties of Luminous, High Accretion Rate Quasars at High Redshift

The recent study of S04 has found that in at least two respects, accretion rate (determined from  $\text{H}\beta$ ) and metallicity, extremely luminous ( $L \gtrsim 10^{47}$  erg  $\text{s}^{-1}$ , where  $L$  is the bolometric luminosity) quasars at  $2 < z < 3.5$  resemble NLS1s with  $L \lesssim 10^{45}$  erg  $\text{s}^{-1}$ . Motivated by this study, we have initiated an XMM-Newton program to look for unusual X-ray properties in the S04 quasars and to determine whether they are the luminous, high- $z$  analogs of local NLS1s (frequently termed narrow-line type 1 quasars). Specifically, we intend to measure  $\Gamma$  accurately (to within  $\pm 0.15$ ) for these sources and to look for rapid (on a  $\sim 1$  hr rest-frame timescale) X-ray variations, since steep photon indices and rapid X-ray variations are two

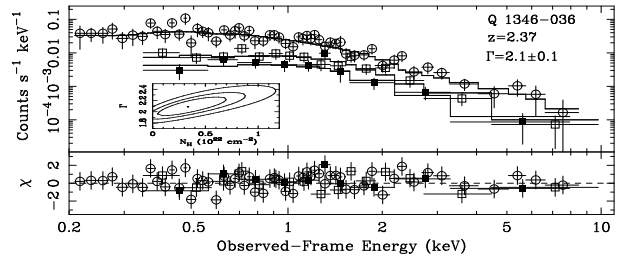


Figure 6. Data, best-fit spectrum, and residuals for our new XMM-Newton observation of Q 1346–036, a luminous  $z=2.37$  quasar from S04. Symbols are similar to those in Fig. 1. We find a photon index  $\Gamma=2.1\pm 0.1$ , which seems to support the hypothesis that the accretion rate is the underlying physical driver for steep X-ray spectra in AGN (see Fig. 5).

well-known NLS1 characteristics. The X-ray photon indices obtained for the S04 sources will allow us to test whether  $\Gamma$  can be considered a reliable accretion-rate indicator for all AGN, including luminous, high- $z$  quasars, with important implications for accretion disk and corona models in AGN (e.g., Haardt & Maraschi 1993).

This test is portrayed in Fig. 5, where we have plotted  $\Gamma$  versus  $\text{FWHM}(\text{H}\beta)$  and  $L/L_{\text{Edd}}$  (which is a combination of  $\text{FWHM}(\text{H}\beta)$  and  $L$ ). In this plot we consider archival data for AGN with high-quality X-ray spectra (obtained from Reeves et al. 1997; Reynolds 1997; George et al. 1998, 2000; Piconcelli et al. 2005) and with reliable  $\text{FWHM}(\text{H}\beta)$  measurements. All but one of the sources in Fig. 5, Q 1346–036, are AGN at  $z \lesssim 0.5$  (and therefore have low–moderate luminosities), since at higher redshift  $\text{H}\beta$  is not present in the optical band and near-IR measurements of  $\text{FWHM}(\text{H}\beta)$  are difficult to obtain. Although there are significant correlations between  $\Gamma$  and both  $\text{FWHM}(\text{H}\beta)$  and  $L/L_{\text{Edd}}$  for the nearby sources, the S04 quasars are predicted to have significantly different values of  $\Gamma$  in each case. Based on their  $\text{FWHM}(\text{H}\beta)$ , these quasars are expected to have a mean  $\Gamma$  of  $\sim 1.7$ , but when their high accretion rates are considered, the mean expected  $\Gamma$  is  $\sim 2.2$ , which is only observed in extreme NLS1s. The first S04 quasar observed in our ongoing XMM-Newton program, Q 1346–036, shows a moderately steep X-ray spectrum (see Fig. 6) and suggests that the  $\Gamma$ – $L/L_{\text{Edd}}$  correlation may still hold when luminous, high- $z$  quasars are included (Fig. 5).

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