The Realm of the First Quasars in the Universe: the X-ray View

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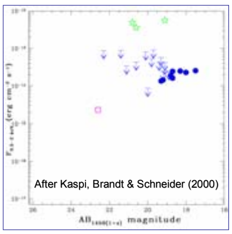
Quasars at z>4 provide direct information on the first massive structures to form in the Universe. Ground-based optical surveys (e.g., the Sloan Digital Sky Survey) have discovered a large number (≈1000) of quasars at z>4; the number of X-ray detections has increased from 6 in 2000 to more than 100 today, and has allowed probing of the inner regions of AGN when the Universe was less than 1 Gyr old. Here we review X-ray studies of the highest redshift quasars, focusing on the results obtained with *Chandra* and XMM-*Newton*. Overall, the X-ray and broad-band properties of high-redshift quasars and local quasars are reasonably similar, once luminosity effects are taken into account, suggesting that the small-scale X-ray emission regions of AGN are insensitive to the dramatic changes that occur at z≈0-6.

z>4 quasars: a progress report

An updated list of high-redshift AGN and quasars is available at http://www.astro.psu.edu/users/niel/papers/highz-xray-detected.dat



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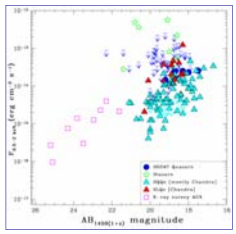

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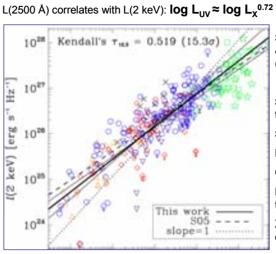
From the pioneering study by Kaspi, Brandt & Schneider (2000), the number of **X-ray detected z>4 QSOs** has increased significantly to **more than 100**, mostly thanks to exploratory observations with ***Chandra*** (Vignali et al. 2001, 2003, 2005; Brandt et al. 2002; Bassett et al. 2004; Lopez et al. 2006; Shemmer et al. 2006) and longer exposures with **XMM-*Newton*** (Brandt et al. 2001; Ferrero & Brinkmann 2003; Farrah et al. 2004; Grupe et al. 2004, 2006; Shemmer et al. 2005). At faint X-ray fluxes, **X-ray surveys** have provided detection of several AGN and quasars at z>4 (e.g., Schneider et al. 1998; Silverman et al. 2002, 2005; Vignali et al. 2002; Castander et al. 2003; Treister et al. 2004; Steffen et al. 2004; Eckart et al. 2006; Fontanot et al. 2006). All of these studies suggest that X-ray emission is a universal property of AGN at the highest redshifts.

α_{OX} studies

L(2500 Å) correlates with L(2 keV): **log L_{UV} ≈ log $L_X^{0.72}$**



See recent works by Vignali, Brandt & Schneider (2003), Strateva et al. (2005), and Steffen et al. (2006)

Sey 1: orange upward-pointing triangles

SDSS QSOs: blue circles

High-z QSOs: green boxes and stars

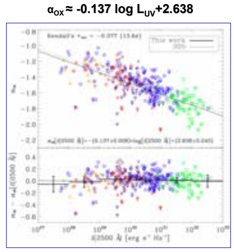
COMBO-17 AGN: red diamonds

BQS: violet downward-pointing triangles

X-ray selected AGN (for comparison): black crosses

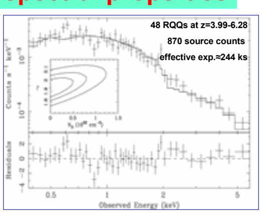
α_{OX} correlates with L(2500 Å), not with redshift:

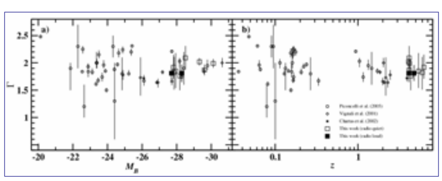
α_{OX} ≈ -0.137 log L_{UV}+2.638



Following X-ray studies of the early '80 and '90, we have investigated relations between X-ray and longer wavelength emission, by means of the point-to-point spectral slope between 2500 Å and 2 keV in the rest frame (α_{OX}). Any changes in the accretion mode over cosmic time might lead to changes in the fraction of total power emitted as X-rays. Using 333 AGN at z≈0-6.3 (88% X-ray detections), Steffen et al. (2006; figures on the left) confirmed that log $L_{2500\ Å}$ correlates with log $L_{2\ keV}$ (with an index <1) and α_{OX} depends upon $L_{2500\ Å}$ (with the slope perhaps depending on $L_{2500Å}$), and constrained the maximum evolution of AGN UV-to-X-ray flux ratios to be less than 30% (1 σ) out to z≈5.

X-ray spectral properties





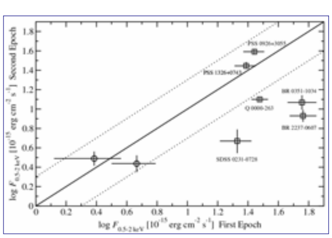
Vignali et al. 2005 [N=48 RQQs; z=3.99-6.28]:	Γ=1.93±0.10, N_H<5x10^{21} cm^{-2}
Lopez et al. 2006 [N=11 "moderate" RLQs, z=4.0-5.1]:	Γ=1.72±0.12, N_H<3x10^{22} cm^{-2}
Lopez et al. 2006 [N=3 blazars; z=3.5-5.1]:	Γ=1.47±0.13, N_H<2.8x10^{22} cm^{-2}
Shemmer et al. 2006 [N=15 RQQs, z>5]:	Γ=1.95±0.30, N_H<6x10^{22} cm^{-2}
Shemmer et al. 2005 [N=8 RQQs-**XMM**, z=4.1-5.4]:	Γ=1.97±0.05, N_H<10$^{22-23}$ cm^{-2}

For the high-redshift quasars, X-ray spectral results have been obtained primarily from *Chandra* stacked X-ray spectra (left-most figure) and some pointed X-ray observations, mostly with XMM-*Newton*. Overall, the X-ray spectral properties of high-redshift quasars are similar to those of local quasars, with no evidence for widespread absorption. A photon index of Γ≈1.9-2 for RQQs (Vignali et al. 2005; Shemmer et al. 2005), up to the highest redshifts (z>5; Shemmer et al. 2006), Γ≈1.7 for "moderate" RLQs, and Γ≈1.5 for RLQs and blazars (Lopez et al. 2006) is obtained. The photon index does not vary significantly with redshift/luminosity (right-most figure); recent results (Shemmer et al. 2006, ApJL) have shown that it depends primarily on the accretion rate (i.e., higher L/L_{EDD} sources have steeper X-ray slopes).

Furthermore, RLQs are ≈3-20 times brighter in the X-ray than RQQs of comparable UV luminosity.

Finally, no significant extended X-ray emission associated with kpc-scale X-ray jets is detected.

X-ray variability



Two-epoch Galactic-absorption corrected 0.5-2 keV fluxes for RQQs at z>4. The solid line indicated the 1:1 flux ratio, while the two dotted lines mark the 1:2 and 2:1 flux ratios; X-ray data come from *ROSAT*, *Chandra*, and XMM-*Newton*.

Over the last few years, it has been claimed that quasars (of matched luminosity) are more X-ray variable at higher redshift (Manners et al. 2002; Paolillo et al. 2004), possibly because of evolution in the X-ray variability mechanism, X-ray emitting region size, or accretion rate. X-ray variability studies represent an excellent probe for measuring black hole masses and sizes of the innermost regions of AGN. Recently, Shemmer et al. (2005) found variable X-ray emission in some z>4 quasars (figure on the left) on time scales of months-year.

Results in a nutshell

- X-ray emission as universal property of AGN
  No significant X-ray spectral evolution over cosmic time
  Similar accretion mechanisms at low and high redshift?
- QSOs at z>4 and z=0-3 have similar SEDs (after controlling for luminosity effects)

What's next?

- XMM-*Newton* observations of z>4 RLQs filling the observational gap between moderately radio-loud and extremely radio-loud quasars
- X-ray searches for increased variability at high z through multi-epoch monitoring
- "Peculiar" quasar populations at high z (broad-absorption line quasars, weak-line quasars,etc.)
  X-ray properties of faint AGN from X-ray surveys