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Chandra and XMM-Newton Observations of the Highest Redshift Quasars: X-rays from the Dawn of the Modern Universe

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Abstract. We review X-ray studies of the highest redshift ($z > 4$) quasars, focusing on recent advances enabled largely by the capabilities of *Chandra* and *XMM-Newton*. Included are discussions of basic X-ray population studies, X-ray spectroscopy, high-redshift AGN in X-ray surveys, and future prospects.

1. Introduction

One of the main themes in astronomy over the coming decades will be the exploration of the dawn of the modern Universe, when the first massive black holes, galaxies, and stars formed.[1] X-ray astronomy missions such as *Chandra*, *XMM-Newton*, *Constellation-X*, *XEUS*, and *Generation-X* can play a crucial role in this investigation by allowing studies of warm and hot objects in the early Universe. They will thereby complement high-redshift studies with observatories such as *ALMA*, *GSMT*, *Herschel*, *NGST*, and *SIRTF*, which will generally focus on cooler objects. For example, X-ray observations will permit study of the first massive black holes to form in the Universe; such black holes can plausibly form at $z \gtrsim 10$ (e.g., Haiman & Loeb 2001).

X-rays reveal the conditions in the immediate vicinity of the supermassive black hole. Measurements of the X-ray continuum's shape, amplitude relative to longer wavelength radiation, and variability can provide information about the inner accretion disk and its corona and thus ultimately offer insight into how the black hole is fed. The X-ray continua of quasars could plausibly change at the highest redshifts. For example, the rapid growth of such quasars could occur if they are accreting matter near the Eddington limit where accretion-disk instabilities and "trapping-radius" effects (e.g., Begelman 1978) can arise.[2] There have been some claims of X-ray continuum shape evolution with redshift that require further investigation (e.g., Vignali et al. 1999; Blair et al. 2000).

The penetrating nature of X-rays allows even highly obscured black holes to be studied, and X-ray absorption measurements can be used to probe the environments of high-redshift quasars. Changes in the amount of X-ray absorption with redshift have been discussed by many authors (e.g., Fiore et al. 1998; Elvis et al. 1998; Reeves & Turner 2000). The fraction of radio-loud quasars (RLQs) with heavy X-ray absorption appears to rise with redshift, with column densities of $\gtrsim 2 \times 10^{22}$ cm^{-2} being seen at $z \gtrsim 3$. The absorbing gas may be circumnuclear, located in the host galaxy, or entrained by the radio jets. The situation for the more common radio-quiet quasars (RQQs) is less clear due to a general lack of RQQ X-ray spectra at $z \gtrsim 2.5$. RQQs definitely show less of an absorption increase with redshift than do RLQs (e.g., Fiore et al. 1998), but the constraints on an absorption/redshift connection are quite loose and require improvement.

Our understanding of the X-ray emission from $z > 4$ quasars has advanced rapidly over the past few years, enabled largely by the capabilities of *Chandra* and *XMM-Newton*. Furthermore, ground-based surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) have discovered many new $z > 4$ quasars that are excellent X-ray targets. The number of published X-ray detections at $z > 4$ has increased to almost 30 (see Fig. 1).[3] This in-

[1] See, for example, the National Research Council 2000 Decadal Report at http://books.nap.edu/catalog/9839.html.

[2] Note that even models with relatively short quasar growth times suggest that accretion rates, relative to the Eddington rate, are likely to increase with redshift (e.g., see Fig. 10 of Kauffmann & Haehnelt 2000).

[3] See http://www.astro.psu.edu/users/niel/papers/highz-xray-detected.dat for a regularly updated list of $z > 4$ X-ray detections. The only $z > 4$ non-AGN detected in the X-ray band is the $z = 4.50$ gamma-ray burst GRB 000131 (Andersen et al. 2000).

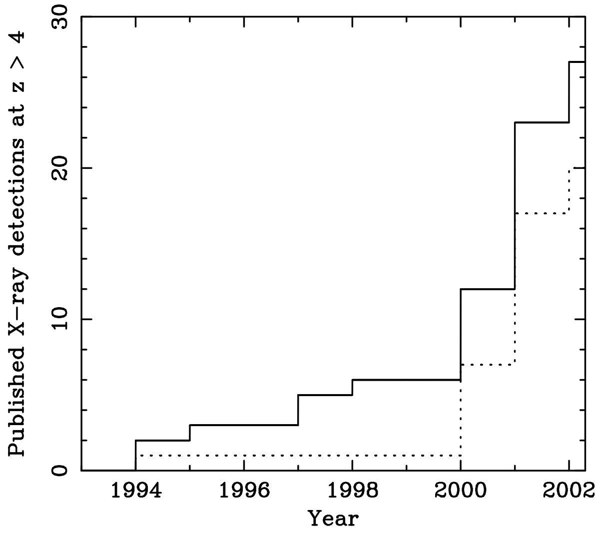

Fig. 1. Cumulative number of published X-ray detections of $z > 4$ quasars as a function of publication year. The solid line is for all quasars, while the dotted line is for optically selected RQQs. Note the dramatic rise from 2000–2002.

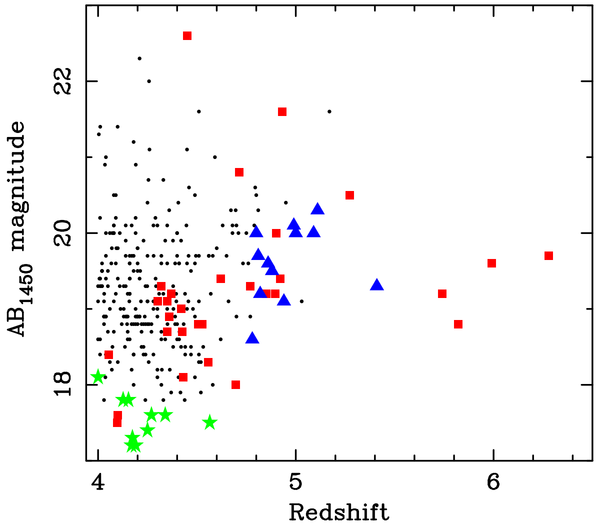

Fig. 2. AB_{1450} magnitude versus redshift for $z > 4$ quasars (small dots). Solid squares indicate quasars that have published X-ray detections or tight upper limits at present. Triangles and stars indicate SDSS and PSS quasars, respectively, that we are observing during *Chandra* Cycle 3.

crease has allowed the first reliable X-ray population studies of $z > 4$ quasars. It has also been possible to achieve X-ray detections at redshifts above five. Prior to 2001 the highest redshift X-ray detection was GB 1428+4217 at $z = 4.72$ (Fabian et al. 1997), while today there are nine published X-ray detections with $z = 4.77$–6.28 (see Fig. 2; e.g., Vignali et al. 2001; Brandt et al. 2002).

The rapid advances of late should continue for the next several years. By 2004 it is plausible that there will be $\gtrsim 100$ X-ray detections and $\gtrsim$ 10–15 *XMM-Newton* X-ray spectra of $z > 4$ objects.

Throughout this paper we will adopt $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 1/3$, and $\Omega_\Lambda = 2/3$.

2. Current Status and Some Recent Results

2.1. First X-ray Population Studies at $z > 4$ via Exploratory Observations

Prior to 2000 there were only six published $z > 4$ X-ray detections (see Fig. 1), and these were for a heterogeneous mixture of objects not suitable for population studies. They included three radio-loud blazars (Mathur & Elvis 1995; Fabian et al. 1997; Zickgraf et al. 1997), two X-ray selected RQQs (Henry et al. 1994; Schneider et al. 1998), and only one optically selected RQQ (Bechtold et al. 1994). The blazars were notable for their large X-ray fluxes that allowed moderate-quality X-ray spectroscopy (see Fig. 3; Moran & Helfand 1997; Fabian et al. 1998; Boller et al. 2000; Yuan et al. 2000; Fabian et al. 2001a; also see Fabian et al. 2001b for the X-ray spectrum of a recently discovered $z > 4$ blazar). All of the four $z > 4$ blazars currently detected in the X-ray regime appear to have their emission dominated by jets. Three of the four show evidence for low-energy spectral flattening that may be due to intrinsic absorption, in line with the findings for lower redshift RLQs described in §1. While these blazars have been wonderful targets for study, they are not representative of the majority quasar population at $z > 4$ (e.g., Stern et al. 2000). Furthermore, due to the strength of the X-ray emission from the jet, it is difficult to observe the accretion disk and the immediate vicinity of the black hole.

With the 2000–2002 studies, optically selected RQQs, the majority quasar population, now dominate the number of $z > 4$ X-ray detections (see Fig. 1). There are 20 such detections published at present. Six of these were obtained in an archival study of *ROSAT* data by Kaspi, Brandt, & Schneider (2000), and an additional 12 were obtained via exploratory (2–10 ks) *Chandra* observations (e.g., Vignali et al. 2001; Brandt et al. 2002; Mathur, Wilkes, & Ghosh 2002; Schwartz 2002b).[4] We have ongoing *Chandra* programs designed to obtain additional detections; *Chandra* is extremely effective at this and, near the Advanced CCD Imaging Spectrometer (ACIS; G.P. Garmire et al., in preparation) aim point, can detect quasars with as few as 2–3 counts! As shown in Fig. 2, we are focusing on $z > 4.8$ quasars from the SDSS and optically bright quasars from the Palomar Digital Sky Survey (PSS; e.g., Djorgovski et al. 1998).[5] We have obtained a

[4] The other two optically selected RQQs with published X-ray detections are Q0000–2619 (Bechtold et al. 1994; detected by *ROSAT*) and SDSS 1044–0125 (Brandt et al. 2001a; detected by *XMM-Newton*).

[5] See http://www.astro.caltech.edu/~george/z4.qsos for a listing of the PSS quasars.

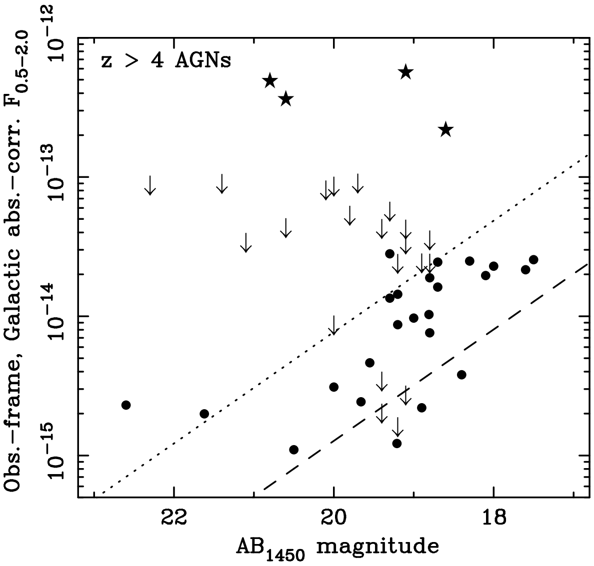

Fig. 3. Observed-frame, Galactic absorption-corrected 0.5–2 keV flux versus AB_{1450} magnitude for $z > 4$ AGNs; the units of the ordinate are erg cm^{-2} s^{-1}. The dots and arrows show $z > 4$ detections and upper limits, respectively, from Kaspi et al. (2000), Brandt et al. (2001a), Vignali et al. (2001), Silverman et al. (2002), and Brandt et al. (2002). Blazars at $z > 4$ are shown as stars. The slanted lines show $z = 5.0$ loci for $\alpha_{\rm ox} = -1.5$ (dotted) and $\alpha_{\rm ox} = -1.8$ (dashed).

significant number of new detections, and these will be published shortly (C. Vignali et al., in preparation).

The exploratory observations have defined the typical X-ray fluxes and luminosities of $z > 4$ quasars. As shown in Fig. 3, these quasars are typically faint X-ray sources, and even the brightest non-blazars generally have 0.5–2 keV fluxes $\lesssim 3 \times 10^{-14}$ erg cm^{-2} s^{-1}. The practical implication of this is that X-ray spectroscopy of $z > 4$ quasars will generally be a challenging endeavor (see §2.2 for details). There is a clear correlation between X-ray flux and AB_{1450} magnitude, although there is significant scatter around this correlation (see Fig. 3; Vignali et al. 2001 give the results of correlation tests). The scatter makes it risky to attempt long spectroscopic observations before an X-ray flux has been established via exploratory observations. The 2–10 keV rest-frame luminosities of the observed quasars range from $\approx 2 \times 10^{44}$ erg s^{-1} to $\approx 4 \times 10^{45}$ erg s^{-1}.

The exploratory observations have also allowed a basic assessment of the contribution of X-ray emission to the broad-band spectral energy distributions (SEDs) of $z > 4$ quasars. Fig. 4, for example, shows the quantity $\alpha_{\rm ox}$ plotted versus redshift for optically selected RQQs; $\alpha_{\rm ox}$ is the slope of a nominal power law between 2500 Å and 2 keV in the rest frame [$\alpha_{\rm ox} = 0.384 \log(f_{2\ {\rm keV}}/f_{2500\ {\rm Å}})$ where $f_{2\ {\rm keV}}$ is the flux density at 2 keV and $f_{2500\ {\rm Å}}$ is the flux density at 2500 Å].[6] There is no evidence for strong changes in $\alpha_{\rm ox}$ with redshift, despite the large changes in quasar number density over the redshift range shown in Fig. 4 (see §5.3 of Fan et al. 2001 and references therein). Some quasars at $z > 4$ may have slightly more negative $\alpha_{\rm ox}$ values, perhaps due to X-ray absorption by the large amounts of gas in their primeval host galaxies (see Vignali et al. 2001 for further discussion). However, the $\alpha_{\rm ox}$ constraints at $z > 4$ (and especially at $z \gtrsim 4.8$) require improvement via further observations before small $\alpha_{\rm ox}$ changes can be considered significant. The lack of strong changes in $\alpha_{\rm ox}$ with redshift is generally consistent with the lack of strong spectral evolution at other wavelengths. For example, the ultraviolet rest-frame spectra of $z > 4$ quasars are only subtly different from those at lower redshifts (e.g., Schneider, Schmidt, & Gunn 1989; Constantin et al. 2002), and the fraction of RLQs does not appear to change significantly with redshift (e.g., Stern et al. 2000).

Fig. 4 has several important implications. First of all, it supports the idea that X-ray emission is a universal property of quasars at all redshifts; this result had already been established for low-redshift quasars ($z \lesssim 0.5$; e.g., Avni & Tananbaum 1986; Brandt, Laor, & Wills 2000). Most of the X-ray nondetections in Fig. 4 with $\alpha_{\rm ox} < -1.8$ are Broad Absorption Line (BAL) QSOs or mini-BALQSOs; there is now evidence that these quasars indeed produce X-rays at a typical level but that this emission is absorbed (e.g., Gallagher et al. 2001; Green et al. 2001; Gallagher et al. 2002). Thus, Fig. 4 bodes well for attempts to detect the first massive black holes to form in the Universe ($z \approx$ 8–20) with deep X-ray surveys; the current data suggest that these objects are likely to be luminous X-ray emitters. Secondly, the fact that $\alpha_{\rm ox}$ does not change strongly with redshift helps to validate the bolometric correction factor usually adopted (e.g., Fan et al. 2001) when estimating the black hole masses of high-redshift quasars via the Eddington argument. The derived masses of $\approx (1\text{–}5)\times10^9$ $M_\odot$ place constraints on theories of cosmic structure formation (e.g., Efstathiou & Rees 1988; Turner 1991). Thirdly, the X-ray emission of high-redshift quasars is expected to affect the heating and ionization of the intergalactic medium (e.g., Venkatesan, Giroux, & Shull 2001).[7] The data in Fig. 4 suggest that, at least to first order, the SEDs of local quasars may be adopted

[6] For the $z > 4$ quasars in Fig. 4 we have generally calculated $f_{2\ {\rm keV}}$ from the observed-frame 0.5–2 keV flux (assuming an X-ray power-law photon index of $\Gamma = 2$); this is required because ACIS has limited spectral response below 0.5 keV. Thus, the derived $\alpha_{\rm ox}$ values are actually based on the relative amount of X-ray flux in the $0.5(1 + z)$ keV to $2(1 + z)$ keV rest-frame band.

[7] Due to its low metallicity and relatively low integrated column density, the intergalactic medium should not prevent the X-ray detection of quasars even to very high redshift (e.g., Aldcroft et al. 1994; Weinberg et al. 1997; Miralda-Escudé 2000).

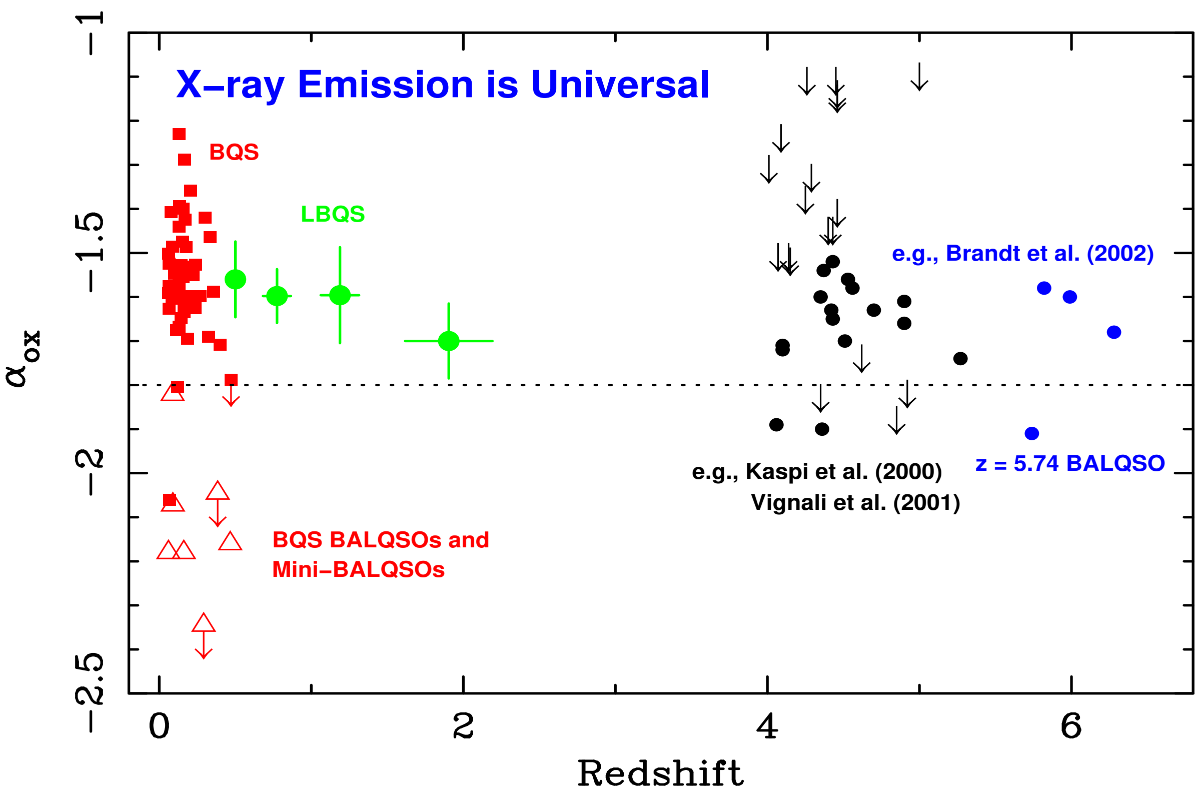

Fig. 4. The parameter $\alpha_{\rm ox}$ versus redshift for optically selected RQQs. The open triangles are for seven luminous, absorbed Bright Quasar Survey (BQS; Schmidt & Green 1983) RQQs, and the solid squares are for the other 46 luminous BQS RQQs (from Brandt et al. 2000). The large solid dots with error bars show stacking results for Large Bright Quasar Survey (LBQS; Hewett, Foltz, & Chaffee 1995) RQQs from Figure 6d of Green et al. (1995). The small solid dots and plain arrows show $z > 4$ detections and upper limits, respectively, from Kaspi et al. (2000), Brandt et al. (2001a), Vignali et al. (2001), and Brandt et al. (2002). A horizontal line has been drawn at $\alpha_{\rm ox} = -1.8$ to guide the eye.

when trying to compute the effects of early quasars upon the intergalactic medium.

Some studies have found evidence that $\alpha_{\rm ox}$ depends upon quasar optical luminosity, with more luminous quasars generally having more negative values of $\alpha_{\rm ox}$ (e.g., Avni, Worrall, & Morgan 1995; Green et al. 1995; but see Yuan, Siebert, & Brinkmann 1998 for an alternative point of view). We have searched for such a trend using the RQQs shown in Fig. 4; BALQSOs and mini-BALQSOs have been removed since their $\alpha_{\rm ox}$ values are affected by absorption. A weak trend is possible, but additional observations (of a well-defined RQQ sample) will be required to determine if one is present since there is significant scatter in $\alpha_{\rm ox}$ ($\approx \pm 0.2$) at all optical luminosities (see §4.2 of Vignali et al. 2001 for details). It is worth noting that $\approx$ 5–30% of $z \approx$ 4–6 quasars are expected to suffer from strong flux amplification (by a factor of $\gtrsim 2$) due to gravitational lensing (e.g., Wyithe & Loeb 2002). Such an effect will confuse studies of the dependence of $\alpha_{\rm ox}$ upon luminosity; $\alpha_{\rm ox}$ will probably not be changed by gravitational lensing, but the true luminosity will differ from that assumed.

Finally, exploratory observations of $z > 4$ quasars allow searches for extended X-ray emission associated with jets. Schwartz (2002a) has argued that X-ray jets can serve as cosmic beacons. If the X-ray emission from jets is produced via the Compton scattering of cosmic microwave background (CMB) photons by relativistic electrons, then it should be detectable to high redshift; the increase in the CMB energy density with redshift compensates for cosmological surface-brightness dimming. Schwartz (2002b) has recently identified a possible jet from the quasar SDSS 1306+0356; notably, this quasar is not a strong radio source. Further observations are required to check this possibility, and exploratory observations of a large number of $z > 4$ quasars should allow a search for an overdensity of "companion" X-ray sources that could be radio jets.

2.2. X-ray Spectral Analyses at $z > 4$

Aside from the four blazars mentioned near the start of §2.1, detailed X-ray spectral analyses of $z > 4$ quasars have not been performed at present. Such analyses are important to search for changes in the X-ray power-law photon index and X-ray absorption (neutral or ion-

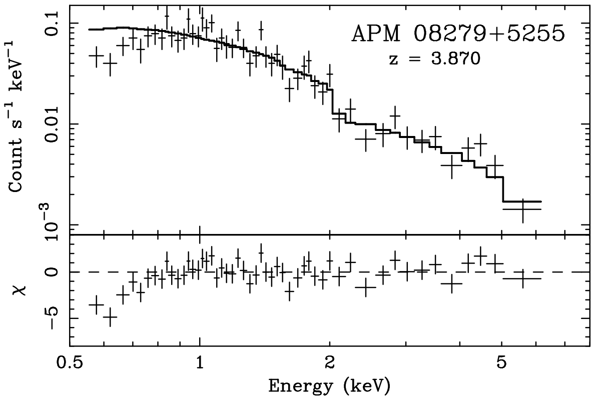

Fig. 5. Observed-frame *Chandra* ACIS spectrum of the $z = 3.87$ gravitationally lensed BALQSO APM 08279+5255. The spectrum has been fit above rest-frame 5 keV with a power-law model that has then been extrapolated back to lower energies. The lower panel shows fit residuals in units of σ with error bars of size one. The systematic residuals below observed-frame 1 keV are thought to be due to intrinsic absorption ($N_{\rm H} \approx 6 \times 10^{22}$ cm^{-2}) associated with the BAL wind. Adapted from Gallagher et al. (2002).

ized) with redshift. To our knowledge, the highest redshift RQQ with X-ray spectral constraints of reasonable quality is the $z = 3.87$ gravitationally lensed BALQSO APM 08279+5255 (see Fig. 5; Gallagher et al. 2002). This object has a power-law photon index of $\Gamma = 1.86^{+0.26}_{-0.23}$ (for the rest-frame 5–25 keV band), consistent with those seen for lower-redshift RQQs (e.g., George et al. 2000; Reeves & Turner 2000).

The lack of quasar X-ray spectroscopy at $z > 4$ is largely due to their low X-ray fluxes which limit the number of photons that can be gathered (see §2.1). Basic hardness ratios for several objects appear consistent with those of low-redshift quasars (e.g., Vignali et al. 2001), but even these have large errors. With 40–100 ks exposures, *XMM-Newton* can obtain moderate-quality ($\approx$ 1000–2000 count) $\approx$ 1–50 keV spectra of $z > 4$ quasars with 0.5–2 keV fluxes of $\gtrsim 1.5 \times 10^{-14}$ erg cm^{-2} s^{-1} (see Fig. 3).[8] Furthermore, stacking the counts from quasars observed by *XMM-Newton* (as well as those with exploratory *Chandra* observations) can provide tight average spectral constraints and allow searches for spectral features such as iron Kα lines. Effective X-ray spectroscopy of quasars with 0.5–2 keV fluxes of $\lesssim 1.5 \times 10^{-14}$ erg cm^{-2} s^{-1} will require future missions such as *Constellation-X*, *XEUS*, and *Generation-X*; populating Fig. 3 with further detections will allow optimum planning of these missions.

[8] These data can also be used to search for X-ray variability. At present, highly significant X-ray variability at $z > 4$ has only been detected from the blazars PMN J0525–3343 (Fabian et al. 2001b), GB 1428+4217 (Fabian et al. 1999; Boller et al. 2000), and GB 1508+5714 (Moran & Helfand 1997). There are tentative claims that quasar X-ray variability increases with redshift (e.g., Manners, Almaini, & Lawrence 2002).

2.3. *AGN at $z > 4$ in X-ray Surveys*

At present, there are four published $z > 4$ quasars that were selected based upon their detection in X-ray surveys: RX J1759+6638 (Henry et al. 1994), RX J1028–0844 (Zickgraf et al. 1997), RX J1052+5719 (Schneider et al. 1998), and CXOMP J213945.0–234655 (Silverman et al. 2002). The Lockman Hole source RX J1052+5719 is notable due to its low luminosity (it is the point furthest to the left in Fig. 3), and CXOMP J213945.0–234655 is the highest redshift X-ray selected quasar published to date ($z = 4.93$). Follow-up studies of sources from the *Chandra* Deep Field-North survey (Brandt et al. 2001c) have recently discovered a still higher redshift quasar at $z = 5.18$ (A.J. Barger et al., in preparation).[9] This object's spectrum is notable for its relatively narrow Lyman α line.

The radio-selected AGN VLA J1236+6213 has also been detected in the *Chandra* Deep Field-North survey (Brandt et al. 2001b); this object has a likely redshift of $z = 4.424$ (Waddington et al. 1999). VLA J1236+6213 is a very faint source in both the optical and X-ray bands with $AB_{1450} \approx 25.2$ and a 0.5–2 keV flux of $\approx 9 \times 10^{-17}$ erg cm^{-2} s^{-1} (compare with Fig. 3). Its rest-frame 2–10 keV luminosity is $\approx 2 \times 10^{43}$ erg s^{-1}, comparable to those of the local Seyfert galaxies NGC 3516, NGC 3783, and NGC 5548. This is by far the lowest luminosity X-ray source known at $z > 4$, and its detection demonstrates that *Chandra* is achieving the sensitivity needed to study Seyfert-luminosity AGN at high redshift.

A large population of Seyfert-luminosity AGN at $z \approx$ 4–10 has been postulated by Haiman & Loeb (1999). These "proto-quasars" would represent the first massive black holes to form in the Universe, and they would play an important role in galaxy formation. One of NASA's long-term goals for X-ray astronomy is to understand such objects (e.g., White 2002), and ultradeep *Chandra* exposures are one of the few ways that they might be found at present. With a 5–10 Ms exposure, *Chandra* can achieve sensitivities comparable to those discussed for missions such as *XEUS* (see Fig. 6). A 5 Ms *Chandra* observation could detect a $z = 10$ proto-quasar down to a rest-frame 5.5–22 keV luminosity of $\approx 8 \times 10^{42}$ erg s^{-1} (after a plausible bolometric correction, this is the X-ray luminosity expected from an $\approx 10^6$ M$_\odot$ black hole radiating near the Eddington limit). At $z = 10$ *Chandra* provides rest-frame sensitivity up to $\approx$ 90 keV, and such high-energy X-rays can penetrate a substantial amount of obscuration. *Chandra* positions are likely to be the best available for at least 15–20 years, and precise positions will be essential for reliable identification of proto-quasars.[10]

[9] See http://www.astro.wisc.edu/~barger/hizq.jpg for a plot of the spectrum.

[10] *Generation-X* is planned to have an angular resolution comparable to or better than that of *Chandra* (see Fig. 6). However, it is not expected to launch until $\approx$ 2020, and its construction will require challeng-

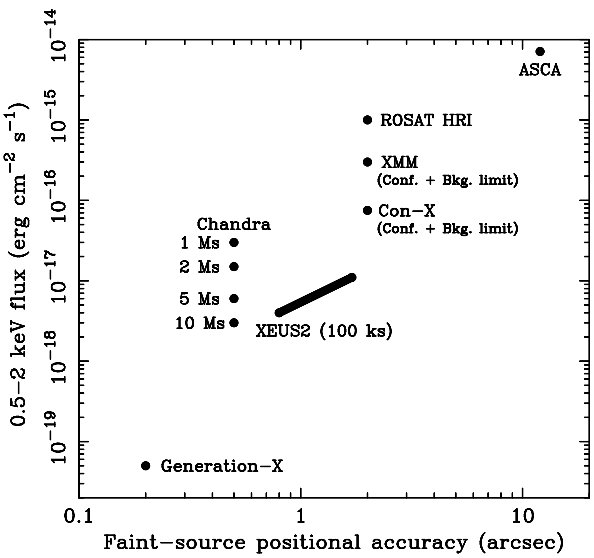

Fig. 6. Soft-band flux limit versus faint-source positional accuracy for some past, present, and future X-ray missions. Note that the locations in the diagram for future missions should be taken as approximate, and that *Constellation-X* is focused on high-throughput spectroscopy rather than deep surveys. Both *XMM-Newton* and *Constellation-X* are background limited and suffer from source confusion at approximately the positions shown. With sufficient exposure, *Chandra* can achieve sensitivities comparable to those discussed for future missions such as *XEUS*. Furthermore, *Chandra* positions are likely to be the best available for at least 15–20 years.

At $z \gtrsim 6.5$ an AGN should appear optically blank; the Lyman α forest and Gunn-Peterson trough will absorb essentially all of the flux through the I band. Thus, an upper limit on the space density of proto-quasars can be set simply by counting the number of X-ray sources that lack any optical counterpart.[11] Effective application of this method, however, requires exceptionally deep optical imaging to prevent confusion between truly optically blank sources at extreme redshift and very optically faint sources at moderate redshift (e.g., objects like the $I = 25.8$, $z \approx 2.75$ AGN CXOHDFN J123651.7+621221; Brandt et al. 2001b and references therein). At present, the *Chandra* Deep Field-North data suggest that there is $\lesssim 1$ AGN detected at $z \gtrsim 6.5$ per ≈ 12 arcmin^2 (Alexander et al. 2001; down to a 3.75–15 keV luminosity limit at $z = 6.5$ of $\approx 2 \times 10^{43}$ erg s^{-1}). This limit should soon be tightened substantially via improved ground-based imaging and the Great Observatories Origins Deep Survey (GOODS).[12]

A 5–10 Ms *Chandra* exposure should also allow normal and starburst galaxies at $z > 4$ to be studied via count stacking analyses. Such analyses using the 1 Ms data for the *Chandra* Deep Field-North have recently been used to determine the basic X-ray properties of $z = 2$–4 Lyman break galaxies (Brandt et al. 2001d).

3. Some Future Prospects

Further *Chandra* and *XMM-Newton* observations can significantly improve our understanding of $z > 4$ quasars, thereby laying the groundwork for future high-redshift X-ray efforts. Some important studies include the following:

1. Exploratory *Chandra* observations of additional $z \gtrsim 4.8$ quasars will allow a better search for any dependence of $\alpha_{\rm ox}$ upon redshift (see Fig. 4) or luminosity. The SDSS is expected to find ≈ 50–100 quasars with $z > 5$ and ≈ 10 quasars with $z > 6$; it can find quasars up to $z \approx 6.5$ (e.g., Fan et al. 2001). Additional quasar surveys are being implemented to search for quasars up to $z \approx 7.2$ (e.g., Warren & Hewett 2002).
2. Exploratory *Chandra* observations of the optically brightest $z > 4$ quasars known (see Fig. 2) can identify further targets appropriate for *XMM-Newton* spectroscopy.
3. The SDSS has identified some unusual quasars lacking emission lines (e.g., Fan et al. 1999; Anderson et al. 2001). The nature of these objects is mysterious, and defining their basic X-ray properties may provide insight. The one object observed thus far (SDSS 1532–0039) was not detected and appears to be fairly X-ray weak (Vignali et al. 2001).
4. The X-ray properties of $z > 4$ BALQSOs are poorly understood. There has been speculation that the X-ray absorption in BALQSOs may increase with redshift (e.g., §4.3 of Vignali et al. 2001), but better $\alpha_{\rm ox}$ constraints and X-ray observations of more BALQSOs are required. A large negative value of $\alpha_{\rm ox}$ can help to identify a BALQSO when BALs cannot be identified due to limited rest-frame ultraviolet spectral coverage (e.g., Brandt et al. 2001a; Goodrich et al. 2001; Maiolino et al. 2001).
5. The X-ray properties of $z > 4$ RLQs are poorly defined. There are few X-ray observations of $z > 4$ quasars that are intermediate in radio loudness between RQQs and highly radio-loud blazars (see Fig. 3). Filling this radio-loudness gap is important, and some of these radio-loud objects may be bright enough for *XMM-Newton* spectroscopy.

ing improvements in lightweight precision X-ray optics. See the *Generation-X* white paper by Zhang et al. at http://universe.gsfc.nasa.gov/docs/roadmap/submissions.html.

[11] Of course, this method requires the assumption that proto-quasars be X-ray luminous. The best available data suggest that this should be the case (see §2.1).

[12] See http://www.stsci.edu/science/goods/ for a description of GOODS.

6. *XMM-Newton* can obtain moderate-quality ($\approx$ 1000–2000 count) $\approx$ 1–50 keV spectra of $z > 4$ quasars with 0.5–2 keV fluxes of $\gtrsim 1.5 \times 10^{-14}$ erg cm^{-2} s^{-1} (see Fig. 3). These observations will constrain changes in the X-ray power-law photon index and X-ray absorption (neutral or ionized) with redshift. Furthermore, stacking the counts from quasars observed by *XMM-Newton* (as well as those with exploratory *Chandra* observations) can provide tight average spectral constraints and allow searches for spectral features such as iron Kα lines.
7. A 5–10 Ms *Chandra* survey can effectively search for the first massive black holes to form in the Universe (see Fig. 6).

In the more distant future, *Constellation-X*, *XEUS*, and *Generation-X* should allow detailed X-ray studies of the highest redshift quasars (see §5 of Vignali et al. 2001 for some simulations).

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