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# Exploratory Chandra Observations of the Three Highest Redshift Quasars Known

William N. Brandt,[1] Donald P. Schneider,[1] Xiaohui Fan,[2] Michael A. Strauss,[3] James E. Gunn,[3] Gordon T. Richards,[1] Scott F. Anderson,[4] Daniel E. Vanden Berk,[5] Neta A. Bahcall,[3] J. Brinkmann,[6] Robert Brunner,[7] Bing Chen,[8] G.S. Hennessy,[9] Donald Q. Lamb,[10] Wolfgang Voges,[11] and Donald G. York[10]

## ABSTRACT

We report on exploratory *Chandra* observations of the three highest redshift quasars known ($z = 5.82$, 5.99, and 6.28), all found in the Sloan Digital Sky Survey. These data, combined with a previous *XMM-Newton* observation of a $z = 5.74$ quasar, form a complete set of color-selected, $z > 5.7$ quasars. X-ray emission is detected from all of the quasars at levels that indicate that the X-ray to optical flux ratios of $z \approx 6$ optically selected quasars are similar to those of lower redshift quasars. The observations demonstrate that it will be feasible to obtain quality X-ray spectra of $z \approx 6$ quasars with current and future X-ray missions.

*Subject headings:* galaxies: active — galaxies: nuclei — galaxies: quasars: general — galaxies: quasars: individual (SDSSp J083643.85+005453.3) — galaxies: quasars: individual (SDSSp J103027.10+052455.0) — galaxies: quasars: individual (SDSSp J130608.26+035626.3) — X-rays: galaxies

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[1]Department of Astronomy & Astrophysics, 525 Davey Laboratory, The Pennsylvania State University, University Park, PA 16802

[2]Institute for Advanced Study, Olden Lane, Princeton, NJ 08540

[3]Princeton University Observatory, Princeton, NJ 08544

[4]University of Washington, Department of Astronomy, Box 351580, Seattle, WA 98195

[5]Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510

[6]Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349-0059

[7]Astronomy Department, California Institute of Technology, Pasadena, CA 91125

[8]European Space Agency-Vilspa, Villafranca del Castillo, Apartado 50727, 28080 Madrid, Spain

[9]US Naval Observatory, 3450 Massachusetts Avenue NW, Washington, DC 20392-5420

[10]University of Chicago, Astronomy & Astrophysics Center, 5640 S. Ellis Ave., Chicago, IL 60637

[11]Max-Planck-Institut für Extraterrestrische Physik, Postfach 1603, Garching, D-85740, Germany

## 1. Introduction

One of the main themes in astronomy over the coming decades will be the study of the first generation of objects to form in the Universe. Due to their large luminosities, quasars are among the most accessible of these, particularly at high energies where stars produce little emission. X-ray studies of high-redshift quasars reveal the conditions in the immediate vicinity of their supermassive black holes. 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 about how the black hole is fed. The penetrating nature of X-rays allows even highly obscured black holes to be probed. While some very high-redshift quasars have been discovered via their X-ray emission (e.g., Henry et al. 1994; Zickgraf et al. 1997; Schneider et al. 1998; Silverman et al. 2002; A.J. Barger et al., in preparation), the vast majority of distant quasars were identified by optical observations.

Recently, the Sloan Digital Sky Survey (SDSS; York et al. 2000) discovered the three highest redshift quasars known to date: SDSSp J083643.85+005453.3 at $z = 5.82$, SDSSp J103027.10+052455.0 at $z = 6.28$, and SDSSp J130608.26+035626.3 at $z = 5.99$ (Fan et al. 2001; hereafter these quasars will be referred to through their abbreviated names). The SDSS uses a CCD camera (Gunn et al. 1998) on a dedicated 2.5 m telescope at Apache Point Observatory in New Mexico to obtain images in five broad optical bands ($u$, $g$, $r$, $i$, $z$; Fukugita et al. 1996; Stoughton et al. 2002); the images of all three of these quasars have extremely red colors in the SDSS system. All three quasars are luminous and, by the Eddington argument (see §1.2 of Frank, King, & Raine 1992; Fan et al. 2001), have central black holes with masses of several times $10^9\ M_\odot$ that formed within a billion years of the Big Bang.

We have begun a project to determine the X-ray properties of the highest redshift quasars utilizing both the new generation of X-ray observatories and archival data (Kaspi et al. 2000; Brandt et al. 2001; Vignali et al. 2001). Thus far we have mostly been making short, exploratory observations designed to define the basic X-ray properties of these quasars and to identify good candidates for future X-ray spectroscopy. Aside from addressing the scientific issues mentioned above, this project is also laying groundwork for future X-ray observatories focused on studying the high-redshift X-ray Universe (e.g., *Constellation-X*, *XEUS*, and *Generation-X*). After the discoveries of SDSS 0836+0054, SDSS 1030+0524, and SDSS 1306+0356, we requested Director's Discretionary Time in 2001 August for exploratory *Chandra* observations of these quasars. This request was approved, and the observations were performed in 2002 January. Here we present the results of the observations.

We adopt $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\rm M} = 1/3$, and $\Omega_\Lambda = 2/3$ throughout.

## 2. Observations and data analysis

The basic properties of the observed quasars, along with the observation dates and exposure times, are given in Table 1. We have also included in Table 1 the $z = 5.74$ Broad Absorption Line (BAL) quasar SDSSp J104433.04–012502.2 (Fan et al. 2000; Maiolino et al. 2001; Goodrich et al. 2001; hereafter SDSS 1044–0125); this quasar has not been observed by *Chandra*, but it has been detected by *XMM-Newton* (Brandt et al. 2001). We have included SDSS 1044–0125 in this paper because it and the other three quasars form a complete $z \gtrsim 5.7$ color-selected sample down to a $z$ magnitude of $\approx 20$ over about 1500 deg$^2$ (Fan et al. 2001). SDSS 0836+0054 has a 20 cm radio detection of 1.2 mJy in the FIRST survey (Becker, White, & Helfand 1995) and is radio intermediate ($R = 8.5$; see Table 1 for the definition of $R$). The other quasars lack radio detections and could be either radio quiet or radio intermediate (see Table 1 for their $R$ parameters).

All targets were observed at the aimpoint of the S3 back-illuminated CCD in the *Chandra* Advanced CCD Imaging Spectrometer (ACIS; G.P. Garmire et al., in preparation). Given previous X-ray studies of $z > 4$ quasars and the superb source detection capability of *Chandra*, these quasars were expected to be detectable with relatively short 6–8 ks *Chandra* observations. Faint mode was used for the event telemetry format, and *ASCA* grades 0, 2, 3, 4 and 6 were used in all analysis; this grade set choice is a standard one that, in general, optimizes signal-to-noise ratio.[12] We have searched for background flares that occurred during the observations and found none. We have inspected the photon arrival times for the X-ray sources described below, and there is no evidence for transient spurious phenomena affecting the data.

We created images around the quasar positions in each of the four standard bands defined in Table 2, and we show adaptively smoothed full-band images for each of the quasars in Figure 1. Note that in the rest frame we are probing the $\approx$ 2–60 keV emission from these quasars. Source detection was performed with WAVDETECT (Freeman et al. 2002). For each image, we calculated wavelet transforms (using a Mexican hat kernel) with wavelet scale sizes from 1–4 pixels. Those peaks whose probability of being false were less than the threshold of $10^{-5}$ were taken as real. All of the quasars were detected in at least two of the standard bands (see Table 2). The photometry in Table 2 was performed using circular apertures with radii of $2''$; errors on the photometry due to background subtraction are negligible. In all cases, the full-band X-ray centroid positions lie within $1''$ of the precise optical positions of the quasars; this is within plausible errors considering the limited number of counts. Given the positional coincidence, the probability of an unrelated, confusing counterpart for even our X-ray faintest quasar (SDSS 1030+0524) is only $\sim 1 \times 10^{-4}$.

Since our observations do not have sufficient counts for spectral fitting, we have calculated the quasars' fluxes and luminosities adopting a nominal power-law model with a photon index of $\Gamma = 2$ (at energy $E$ the photon density $N(E) \propto E^{-\Gamma}$; e.g., Reeves & Turner 2000) and the Galactic

[12]See §6.3 of the *Chandra* Proposers' Observatory Guide at http://asc.harvard.edu/udocs/docs/docs.html for a discussion of grades.

absorption column densities in Table 1. This spectral model is consistent with the observed hardness ratios of our targets, although the constraints on the hardness ratios are poor due to the limited numbers of counts. Using the *Chandra* X-ray Center Portable Interactive Multi-Mission Simulator (PIMMS; Mukai 2001), we find the absorption-corrected 0.5–2.0 keV fluxes given in Table 2. In Table 2 we also present the derived luminosities in the 3.5–14.0 keV rest-frame band; this rest-frame band is well matched to the observed 0.5–2.0 keV band for our objects. Note that for a $\Gamma = 2$ power law the rest-frame 3.5–14.0 keV and 0.5–2.0 keV luminosities are the same.

We have calculated $\alpha_{\rm ox}$, the slope of a nominal power law between 2500 Å and 2 keV in the rest frame [$\alpha_{\rm ox} = 0.384 \log(f_{2\ \rm keV}/f_{2500\ \text{Å}})$ where $f_{2\ \rm keV}$ is the flux density at 2 keV and $f_{2500\ \text{Å}}$ is the flux density at 2500 Å], for each of our targets (see Table 2). We again adopt $\Gamma = 2$ for the X-ray continuum, and we use an optical power-law slope of $\alpha_{\rm o} = -0.5$ ($f_\nu \propto \nu^{\alpha_{\rm o}}$; e.g., Schneider et al. 2001; Vanden Berk et al. 2001) to estimate the flux density at 2500 Å in the rest frame. We have used the observed soft-band fluxes to find $f_{2\ \rm keV}$ in the $\alpha_{\rm ox}$ calculations, so the derived $\alpha_{\rm ox}$ values are actually based on the relative amount of X-ray emission in the $\approx$ 3.5–14.0 keV rest-frame band; 2 keV in the rest frame corresponds to $\approx$ 0.3 keV in the observed frame for these quasars, and this energy is poorly sampled by ACIS for these faint sources.

## 3. Discussion

These three short *Chandra* observations provide the highest redshift X-ray detections to date, demonstrating the power of *Chandra* for probing the high-redshift X-ray Universe efficiently. Figure 2 shows a redshift histogram of the known $z > 4$ quasars; the X-ray detections are indicated in the figure.[13] Together with SDSS 1044–0125, the highest redshift X-ray detection obtained previously, the quasars studied here form a small but complete $z \gtrsim 5.7$ color-selected sample that should be representative of the luminous, optically selected quasar population at $z \approx 6$ (we recognize that optically selected $z \approx 6$ quasars may not be representative of the entire $z \approx 6$ quasar population, but these quasars are the only ones available for study at present).

In Figure 3 we plot the Galactic absorption-corrected 0.5–2.0 keV flux versus $AB_{1450}$ magnitude for the quasars in Table 1 as well as for other $z > 4$ quasars (e.g., Kaspi et al. 2000; Vignali et al. 2001; Silverman et al. 2002). While the BAL quasar SDSS 1044–0125 is notably X-ray weak (probably due to intrinsic X-ray absorption; see Brandt et al. 2001), the $z \approx 6$ quasars observed by *Chandra* appear to lie within the locus of points for other $z > 4$ quasars. The spectral region around the C IV line at rest-frame 1549 Å has been observed in both SDSS 1030+0524 and SDSS 1306+0356; neither shows evidence for BALs (Fan et al. 2001; Pentericci et al. 2002). The integrated column density of the intergalactic medium to these quasars, including both ionized and neutral material,

[13]The data used to construct this figure are available from http://www.astro.caltech.edu/~george/z4.qsos and http://www.astro.psu.edu/users/niel/papers/highz-xray-detected.dat.

is almost certainly too small to produce significant X-ray absorption (e.g., Weinberg et al. 1997; Miralda-Escudé 2000). This is especially true given the intergalactic medium's low metallicity.

Figure 4 shows that there is no strong evolution in $\alpha_{\rm ox}$ for optically selected, radio-quiet quasars (RQQs) out to $z \approx 6$ (despite the strong changes in quasar number density over the redshift range shown in this figure; see §5.3 of Fan et al. 2001 and references therein). The central X-ray power sources of quasars do not appear to evolve strongly out to this redshift, and there is no indication that strong intrinsic obscuration of the X-ray emission generally occurs at $z \approx 6$. This result 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; our data suggest that these objects are likely to be luminous X-ray emitters. Furthermore, this result helps to validate the bolometric correction factor adopted by Fan et al. (2001) when estimating the black hole masses of these objects via the Eddington argument. Some studies have found evidence that $\alpha_{\rm ox}$ depends upon quasar luminosity, with more luminous quasars generally having larger negative values of $\alpha_{\rm ox}$ (e.g., Green et al. 1995 and references therein). The $z \approx 6$ quasars under study here have comparable luminosities at 2500 Å to those of the typical $z \approx$ 4–5 quasars studied by Vignali et al. (2001; see their Figure 5 noting the different cosmology). Therefore, we do not expect luminosity effects upon $\alpha_{\rm ox}$ to affect our conclusions materially (see §4.2 of Vignali et al. 2001 for further discussion).

The observations presented here are consistent with the statement that the majority of optically selected quasars at redshifts of near six possess similar X-ray properties to those of their low-redshift counterparts. X-ray observations have now reached what appears to be the redshift regime of the reionization of the intergalactic medium (Becker et al. 2001; Djorgovski et al. 2001). The *Chandra* observations also indicate that X-ray spectroscopy with *XMM-Newton* will be feasible for a significant fraction of $z \approx 6$ quasars (with $\approx 100$ ks exposures), and high-quality X-ray spectroscopy of this class of objects will be possible with *Constellation-X*, *XEUS*, and *Generation-X*.

This work would not have been possible without the enormous efforts of the entire *Chandra* team. We thank H.D. Tananbaum for kindly allocating the time for these observations, and we thank S.N. Virani for help with observation planning. We thank S.C. Gallagher, S. Kaspi, C. Vignali, and an anonymous referee for helpful discussions. We gratefully acknowledge the financial support of NASA LTSA grant NAG5-8107 (WNB), NSF grant AST-9900703 (DPS, GTR), and NSF grant AST-0071091 (MAS).

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Table 1. Basic Quasar Properties and Observation Log

| Name | $z$ | $AB_{1450}$ | $f^{a}_{2500\ \mathrm{Å}}$ | $M_{1450}$ | $R^{b}$ | Galactic $N_{\mathrm{H}}$ ($10^{20}$ cm$^{-2}$)[c] | Obs. Date | Exp. Time (ks) |
|---|---|---|---|---|---|---|---|---|
| SDSS 0836+0054 | 5.82 | 18.81 | 14.2 | −27.9 | 8.5 | 4.4 | 2002 Jan 29 | 5.7 |
| SDSS 1030+0524 | 6.28 | 19.66 | 6.5 | −27.2 | $< 7.5$ | 2.7 | 2002 Jan 29 | 8.0 |
| SDSS 1306+0356 | 5.99 | 19.55 | 7.3 | −27.2 | $< 8.7$ | 2.1 | 2002 Jan 29 | 8.2 |
| SDSS 1044–0125[d] | 5.74 | 19.21 | 9.8 | −27.5 | $< 8.5$ | 4.6 | 2000 May 28 | 40.0 |

[a]Observed flux density at $\lambda_{\mathrm{obs}} = 2500(1+z)$ Å in units of $10^{-28}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$. If rest-frame values are desired, divide the listed numbers by $(1+z)$ following §3.5.1 of Weedman (1986); this is the "bandpass" correction.

[b]Radio-loudness parameter. $R = f_{6\ \mathrm{cm}}/f_{4400\ \mathrm{Å}}$ where $f_{6\ \mathrm{cm}}$ is the rest-frame flux density at 6 cm and $f_{4400\ \mathrm{Å}}$ is the rest-frame flux density at 4400 Å (e.g., Kellermann et al. 1989). $f_{6\ \mathrm{cm}}$ has been calculated using data from FIRST (Becker et al. 1995), and $f_{4400\ \mathrm{Å}}$ has been calculated using data from Fan et al. (2001).

[c]From Stark et al. (1992).

[d]This quasar was not observed by *Chandra*, but it has been detected by *XMM-Newton* (Brandt et al. 2001). We have included information on it here because it and the other three quasars form a complete color-selected sample at $z \gtrsim 5.7$. The observation date and exposure time apply to the *XMM-Newton* observation.

Table 2. X-ray Counts and Properties

| | Counts[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Ultrasoft | Soft | Hard | Full | | | | |
| Name | 0.3–0.5 keV | 0.5–2.0 keV | 2.0–8.0 keV | 0.5–8.0 keV | $F^{\mathrm{b}}_{0.5-2.0}$ | $f^{\mathrm{c}}_{2\ \mathrm{keV}}$ | $L^{\mathrm{d}}_{3.5-14.0}$ | $\alpha^{\mathrm{e}}_{\mathrm{ox}}$ |
| SDSS 0836+0054 | $< 6.4$ | $16.9^{+5.2}_{-4.1}$ | $3.8^{+3.1}_{-1.9}$ | $20.7^{+5.6}_{-4.5}$ | 10.29 | 10.5 | 45.6 | $-1.58^{+0.05}_{-0.05}$ |
| SDSS 1030+0524 | $< 4.8$ | $5.9^{+3.6}_{-2.4}$ | $< 3.0$ | $5.8^{+3.6}_{-2.3}$ | 2.43 | 2.6 | 45.1 | $-1.68^{+0.08}_{-0.09}$ |
| SDSS 1306+0356 | $< 4.8$ | $11.8^{+4.5}_{-3.4}$ | $4.9^{+3.4}_{-2.1}$ | $16.8^{+5.2}_{-4.1}$ | 4.63 | 4.8 | 45.3 | $-1.60^{+0.05}_{-0.06}$ |
| SDSS 1044–0125[f] | ··· | ··· | ··· | ··· | 1.22 | 1.2 | 44.7 | $-1.88^{+0.04}_{-0.05}$ |

[a] Errors on the counts have been calculated following Gehrels (1986) for $1\sigma$. Upper limits have been calculated following Kraft, Burrows, & Nousek (1991) for 95% confidence.

[b] Galactic absorption-corrected flux in the 0.5–2.0 keV observed-frame band in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$.

[c] Observed flux density at $E_{\mathrm{obs}} = 2/(1+z)$ keV in units of $10^{-32}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$. If rest-frame values are desired, divide the listed numbers by $(1+z)$ following §3.5.1 of Weedman (1986); this is the "bandpass" correction.

[d] Logarithm of the Galactic absorption-corrected luminosity in the 3.5–14.0 keV rest-frame band. This rest-frame band is well matched to the observed 0.5–2.0 keV band for our objects.

[e] $\alpha_{\mathrm{ox}}$ is calculated between 2500 Å and 2 keV. The error bars on $\alpha_{\mathrm{ox}}$ represent the statistical uncertainty associated with the observed number of counts.

[f] The quantities reported here are derived from the *XMM-Newton* observation using the revised redshift and the same spectral assumptions made for the other quasars; see Table 1 for further information.

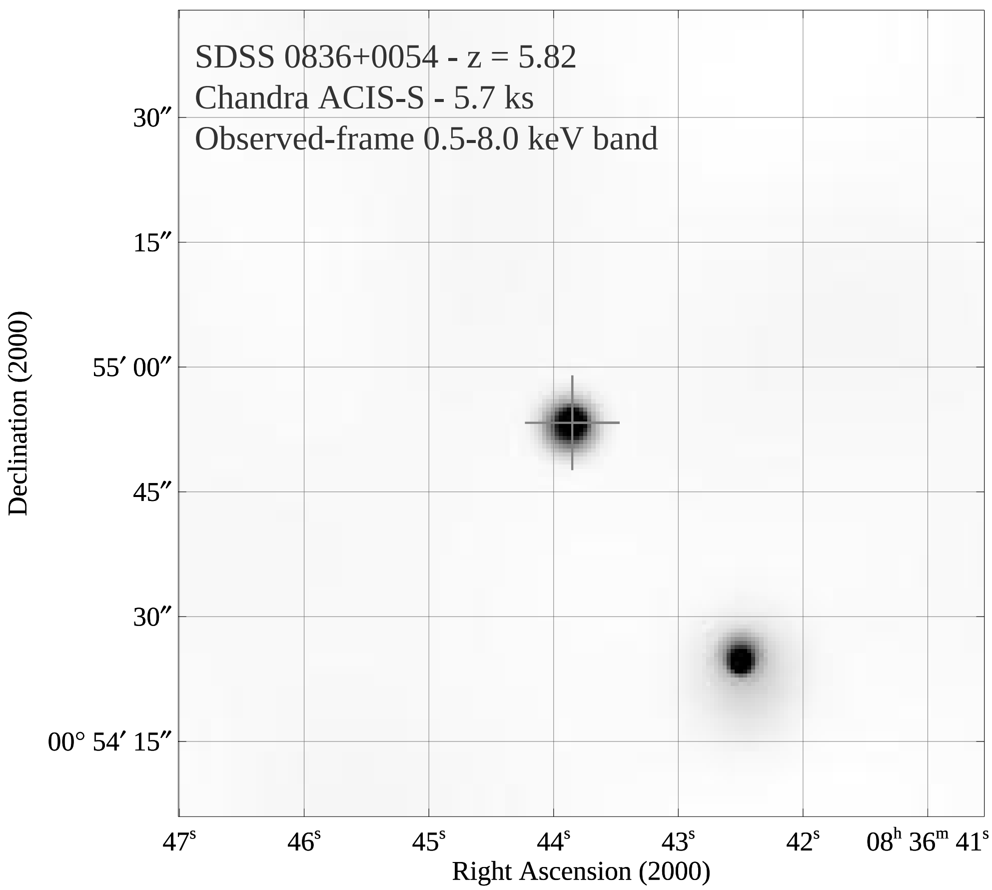
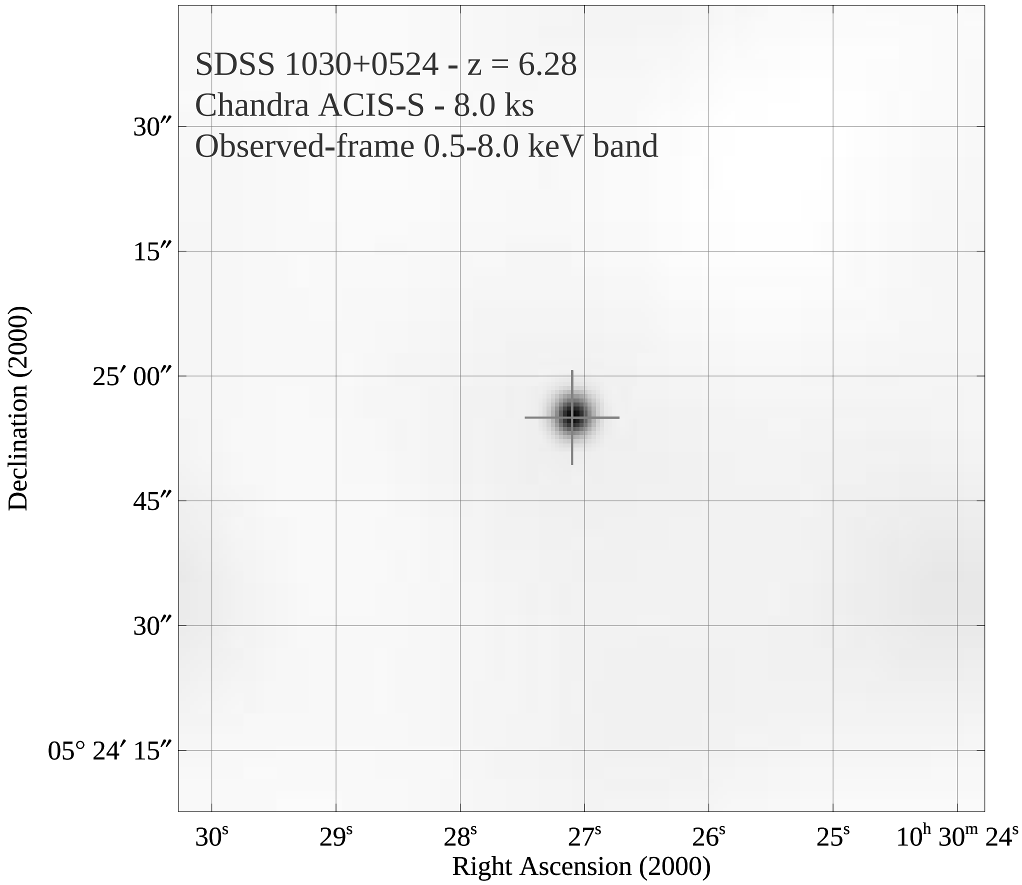
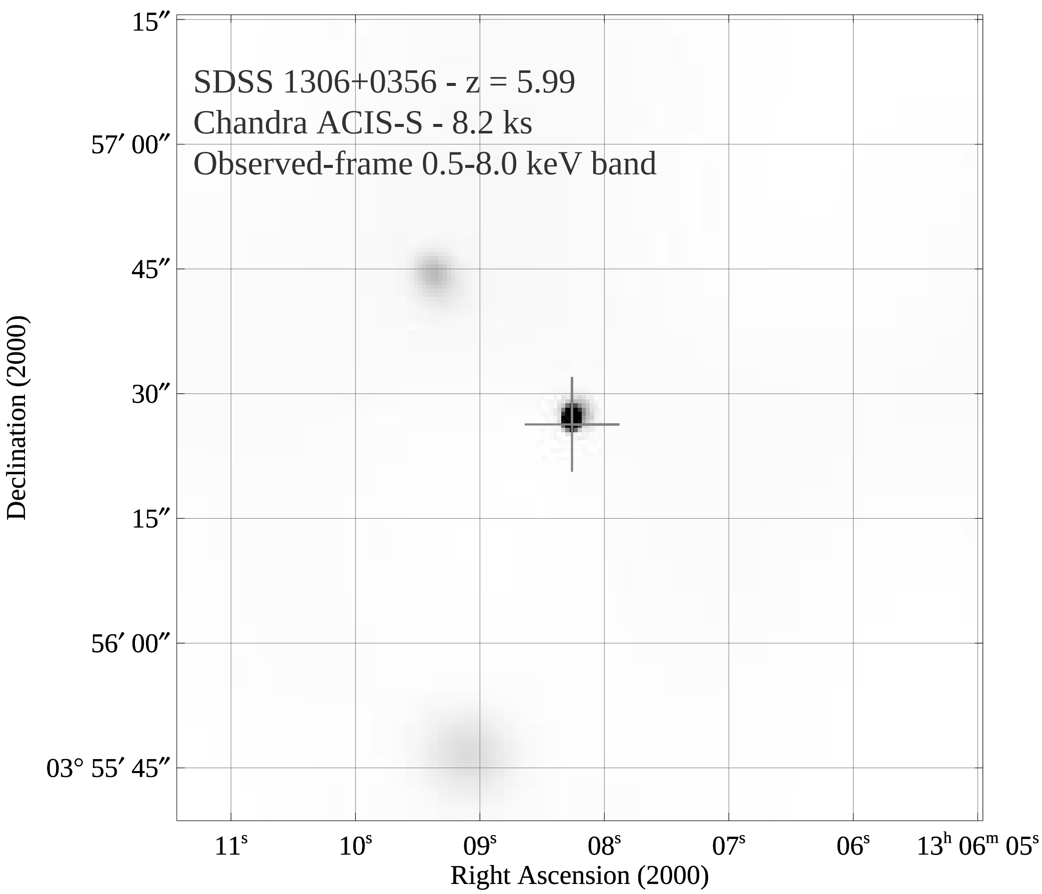



Fig. 1.— Full-band ACIS S3 images of the three target quasars. The images have been adaptively smoothed at the $2\sigma$ level using the algorithm of Ebeling, White, & Rangarajan (2002). The gray scales are linear. Crosses mark the optical positions of the quasars (accurate to $\approx 0\farcs1$ in each coordinate).


SDSS 1030+0524 - z = 6.28
Chandra ACIS-S - 8.0 ks
Observed-frame 0.5-8.0 keV band
30″
15″
25′ 00″
45″
30″
05° 24′ 15″
Declination (2000)
30s
29s
28s
27s
26s
25s
10h 30m 24s
Right Ascension (2000)


SDSS 1306+0356 - z = 5.99
Chandra ACIS-S - 8.2 ks
Observed-frame 0.5-8.0 keV band
Declination (2000)
15″
57′ 00″
45″
30″
15″
56′ 00″
03° 55′ 45″
11s
10s
09s
08s
07s
06s
13h 06m 05s
Right Ascension (2000)

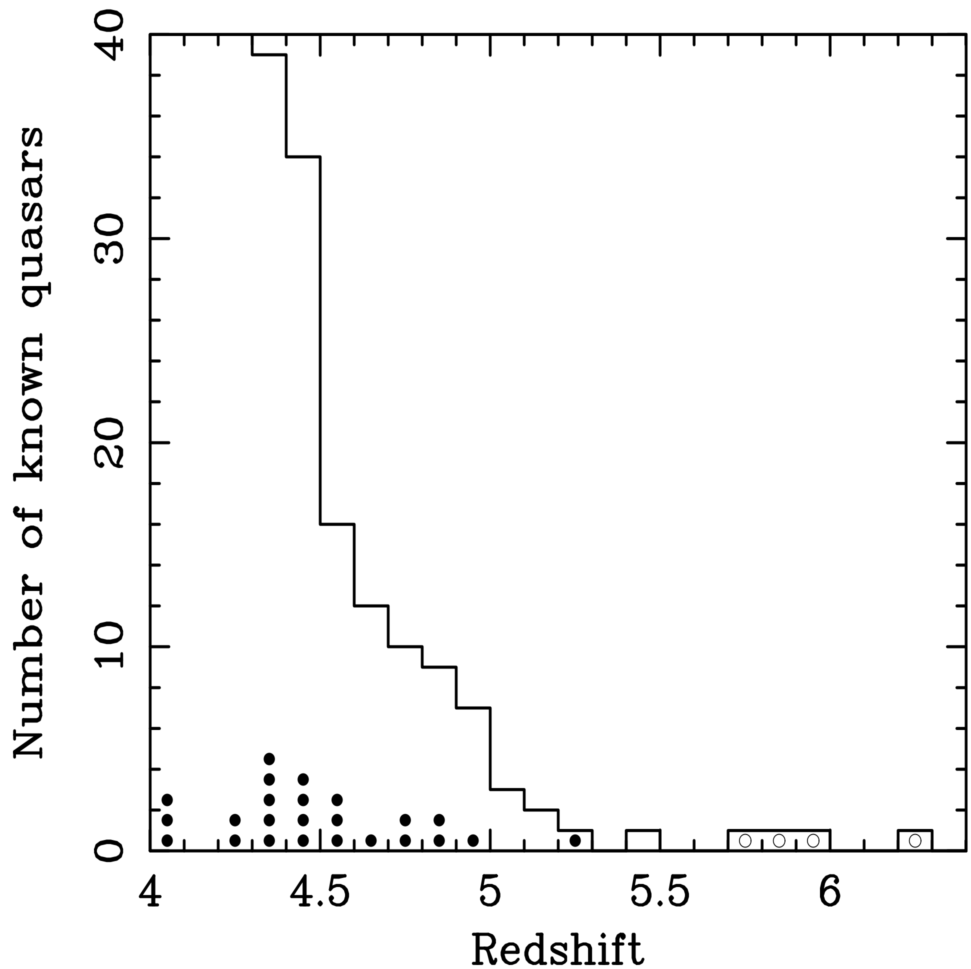



Fig. 2.— Redshift distribution of known $z > 4$ quasars. The dots indicate quasars detected in X-rays previously, and the open circles indicate the four quasars under study here including SDSS 1044–0125. Note that most of the known $z \approx 4$–5 quasars do not have X-ray observations at present.

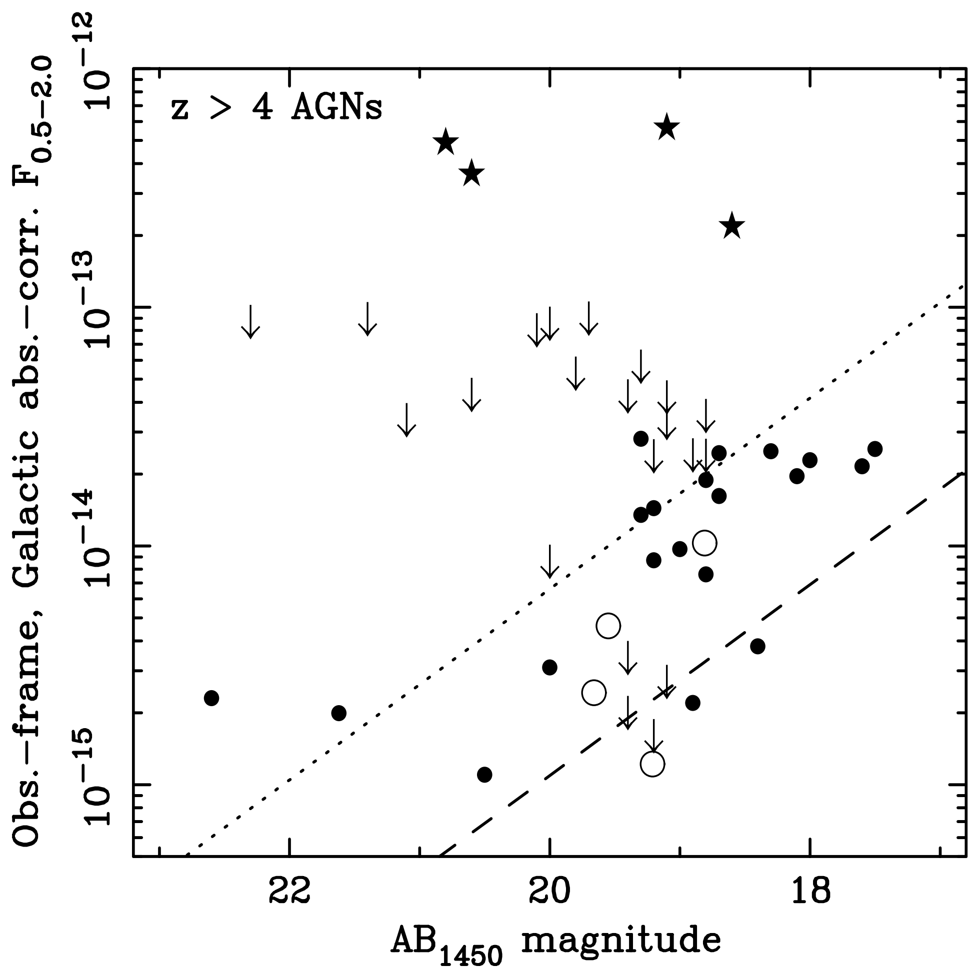



Fig. 3.— Observed-frame, Galactic absorption-corrected 0.5–2.0 keV flux versus $AB_{1450}$ magnitude for $z > 4$ AGNs; the units of the ordinate are erg cm$^{-2}$ s$^{-1}$. The dots and arrows show $z > 4$ detections and upper limits, respectively, from Kaspi et al. (2000), Vignali et al. (2001), and Silverman et al. (2002). Blazars at $z > 4$ are shown as stars. The open circles show the quasars studied here including SDSS 1044–0125. The slanted lines show $z = 6.0$ loci for $\alpha_{\rm ox} = -1.5$ (dotted) and $\alpha_{\rm ox} = -1.8$ (dashed).

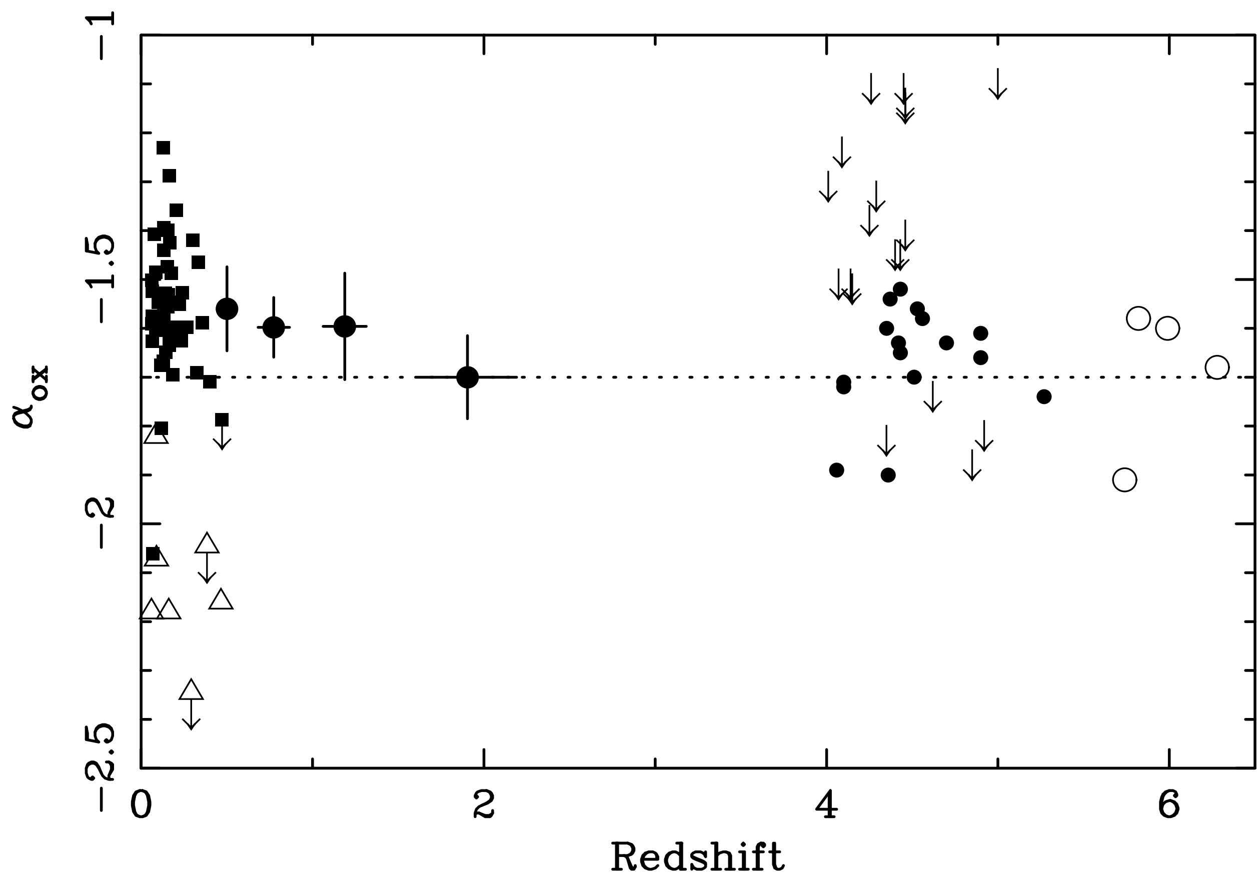



Fig. 4.— $\alpha_{\rm ox}$ versus redshift for optically selected RQQs. The open triangles are for seven luminous, absorbed Bright Quasar Survey (BQS; Schmidt & Green 1983) RQQs, and the solid squares are for the other 46 luminous BQS RQQs (from Brandt, Laor, & Wills 2000). The large solid dots with 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) and Vignali et al. (2001). The open circles show the quasars studied here including SDSS 1044–0125. A horizonal line has been drawn at $\alpha_{\rm ox} = -1.7$ to guide the eye.