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CHANDRA DETECTION OF HIGHEST REDSHIFT ($z \sim 6$) QUASARS IN X-RAYS

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ABSTRACT

We report on *Chandra* observations of the three quasars SDSSp J083643+005453, SDSSp J103027+052455, and SDSSp J130608+035626 at redshifts 5.82, 6.28, and 5.99, respectively. All three sources are clearly detected in the X-ray band, up to rest-frame energies of ∼55 keV. These observations demonstrate the unprecedented sensitivity of *Chandra* to detect faint sources in relatively short exposure times (5.7–8.2 ks). The broadband X-ray properties of these highest redshift quasars do not appear to be any different from their lower redshift cousins, implying little or no evolution for these few sources out to $z \sim 6$, at redshifts where the optical space density is falling. Spectra of the sources could not be determined with only a few counts detected. Observations with *XMM-Newton* will be able to constrain the spectral shapes, if they are simple. Determination of complex spectra in a reasonable amount of time, however, will have to await the next generation of X-ray missions.

Subject headings: galaxies: active —
quasars: individual (SDSSp J083643+005453, SDSSp J103027+052455,
SDSSp J130608+035626) — X-rays: galaxies

1. INTRODUCTION

The highest redshift (z) quasars are of interest not only for their "record-setting" quality but also because they can tell us about the formation of quasars and about conditions in the first few percent of the age of the universe. The discovery of $z \sim 6$ quasars (Fan et al. 2001, hereafter Paper I) was remarkable, as it showed that luminous quasars with massive black holes had formed when the universe was less than a gigayear old. Quasars SDSSp J083643+005453, SDSSp J103027+052455, SDSSp J104433−012502, and SDSSp J130608+035626 at $z = 5.82$, 6.28, 5.80, and 5.99, respectively, were discovered as a part of the Sloan Digital Sky Survey (SDSS; York et al. 2000) imaging multicolor observations. Follow-up spectroscopy revealed rich quasar spectra with a strong Lyα forest. The importance of these observations was amplified by the realization that the neutral hydrogen fraction of the intergalactic medium increases drastically around $z \sim 6$, marking it the epoch of the end of reionization (Becker et al. 2001; Fan et al. 2002; Pentericci et al. 2002).

Observations of high-redshift quasars are also important to understand quasar evolution and the associated possible growth of massive black holes. While the evidence for the evolution of the quasar luminosity function is clear (Boyle et al. 2000), we still do not know *how* the quasars evolve, i.e., which of the observed properties of quasars exhibit change with time. Mathur (2000) suggested that the accretion rate relative to the Eddington limit is likely to be a function of time, in which case properties related to accretion, such as those contributing to "eigenvector 1" (Boroson 2002) would be expected to change. X-ray studies of high-redshift quasars are important as the X-ray slope changes with accretion rate and so may give us information about the evolution. The overall spectral energy distribution of quasars also changes with accretion rate. While small changes are difficult to see, the extreme cases, e.g., advection-driven accretion flows, show clearly different spectral energy distributions, including that in the X-ray band (Narayan, Mahadevan, & Quataert 1998 and references therein). So the hope of X-ray studies of high-redshift quasars is that they may give us some clue about the early accretion process, and so, about their evolution.

This goal has not been achieved yet, because X-ray detections of high-redshift quasars have been rare. Prior to the *Chandra* and *XMM-Newton* era, only a handful of $z > 4$ quasars were detected in X-rays (Kaspi, Brandt, & Schneider 2000 and references therein). Thanks to the sensitivity of the *Chandra* observatory, the total number of X-ray–detected $z > 4$ quasars is now over two dozen (Silverman et al. 2002; Vignali et al. 2001, hereafter Paper II, and references therein). At redshifts greater than 5, however, the numbers are very sparse, both in optical and X-ray bands. The $z = 5.8$ quasar SDSSp J104433−012502 was detected with *XMM-Newton* (Brandt et al. 2001a; Mathur 2001), and a $z \sim 5.2$ quasar is reported to be detected with *Chandra* (Brandt et al. 2001b). (A $z = 5.27$ quasar, SDSSp J120823.82+001027.7, is also reported to be detected by Vignali et al. in Paper II, but with only two counts, this is questionable.) In spite of these small numbers, there have been tantalizing suggestions of changes of X-ray properties of quasars with redshift (e.g., Paper II and references therein). Vignali et al. (Paper II) found suggestive evidence that *Chandra*-detected, optically selected high-redshift ($z > 4$) quasars are fainter in X-rays compared to those detected earlier with *ROSAT*. Mathur (2001) found that the $z = 5.8$ quasar SDSSp J104433−012502 is likely to have a steep X-ray slope. While these suggestions need to be confirmed with better observations, the trends are encouraging. In this Letter, we report the *Chandra* detections of three $z \sim 6$ SDSS quasars.

2. OBSERVATIONS AND DATA ANALYSIS

The subarcsecond angular resolution and very low background makes *Chandra* ideal for detecting faint sources such as high-redshift quasars. The $z \sim 6$ quasars SDSSp J083643+005453, SDSSp J103027+052455, and SDSSp J130608+035626 were observed with the *Chandra X-Ray Observatory* on 2002 January 29 with director's discretionary time. The data were made available to the astronomical community immediately. Observational details are given in Table 1.

All three observations were performed using the detector

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TABLE 1

Chandra Observations of $z \sim 6$ Quasars

Source	R.A.	Decl.	z	N_H[a] ($\times 10^{20}$ atoms cm^{-2})	$AB_{(1450)}$[b]	Observation Date	Sequence Number	Exposure (s)
SDSS 0836+0054	08 36 43.90	+00 54 53.30	5.82	4.12	18.81	2002 Jan 29	700605	5687.06
SDSS 1030+0524	10 30 27.10	+05 24 55.00	6.28	3.12	19.66	2002 Jan 29	700606	7955.57
SDSS 1306+0356	13 06 08.30	+03 56 26.30	5.99	2.07	19.55	2002 Jan 29	700607	8157.78

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Galactic column density calculated using HEASARC tool NH.

[b] From Paper I.

Advanced CCD Imaging Spectrometer for spectroscopy (ACIS-S; Nousek et al. 1998). The sources were observed at the nominal aim point on the back-illuminated CCD S3. Analysis was performed in a standard manner using the software *Chandra* interactive analysis of observations (CIAO version 2.2.1; M. Elvis 2002, in preparation).[3]

Virtually all the source counts are contained in the 2″.9 (5.75 pixels) radius extraction aperture that was centered on the X-ray source centroid. Background counts were estimated from an annulus with inner and outer radii of 10 and 30 pixels, respectively. The background counts expected in the source extraction region are between 0.2 and 0.3 for the three sources, so we ignore the background in the rest of the analysis. All three sources are clearly detected in the broad band (0.5–8.0 keV; Fig. 1). To determine the centroid position of the sources, we used the CIAO tool WAVDETECT (Freeman et al. 2002). The X-ray positions of all three sources are within 1″ of the optical positions (Table 2). We also extracted source counts in the soft (0.5–2.5 keV) and hard (2.5–8 keV) bands separately. The spatial distribution of the 6 counts for SDSSp J103027+052455 appears elongated (Fig. 1). However, with so few counts a comparison with the expected point source response does not show a significant difference (95% probability of a difference; Kolmogorov-Smirnov test). Further observations are needed.

We calculated the probability of serendipitous source detections using the observed source flux distribution of Hasinger et al. (1998). Assuming the 0.5–2.5 keV flux limit of 1×10^{-15} ergs cm^{-2} s^{-1} for the faintest of the three sources, and a detection cell of 2″.9 radius, the expected number of sources is 2.4×10^{-3} for each of the observations. So it is highly unlikely that the detected sources are unrelated to the quasars. We therefore conclude that SDSS sources observed by *Chandra* are detected.

Using the observed count rate, the broadband flux was determined assuming a power-law slope of $\alpha_X = 1.0$ and the Galactic N_H-values for each source (Table 2; both optical and X-ray spectral slopes are defined as $f_\nu \propto \nu^{-\alpha}$). The rest-frame luminosity was calculated for two different cosmologies: $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ for consistency with earlier work and also with $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. The observed X-ray properties of all three sources are presented in Table 2.

3. DISCUSSION

The detections of $z \sim 6$ quasars in X-rays demonstrates the power of *Chandra* to detect such faint sources. The sources are detected up to rest-frame energies of ∼55 keV. With only a few counts detected, however, detailed source information is difficult to obtain. Nevertheless, we can learn about the overall broadband spectral energy distributions by determining the optical–to–X-ray ratio α_{ox} [defined as $-\log(f_X/f_{opt})/\log(\nu_X/\nu_{opt})$, where f_X and f_{opt} are monochromatic flux densities at 2 keV and 2500 Å, respectively, in the rest frame of a quasar; Tananbaum et al. 1979]. We calculated the optical monochromatic luminosity at rest-frame 2500 Å using the observed optical flux (Paper I) and assuming a power-law optical continuum slope with $\alpha_o = 0.5$. The use of $\alpha_o = 0.5$ is appropriate for the observed continuum in Paper I. In the X-ray band, the observed energy range of 0.5–8.0 keV corresponds to the rest-frame range of ∼3.5–56 keV. So, the monochromatic luminosity at rest-frame 2 keV was calculated assuming a power-law slope $\alpha_X = 1$. The re-

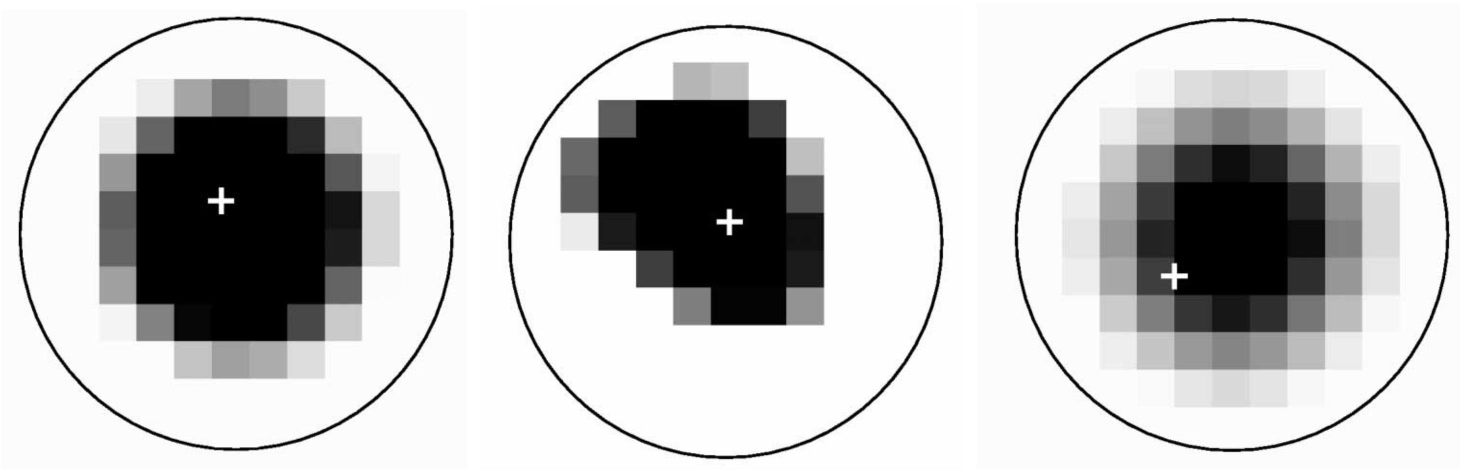

Fig. 1.—ACIS-S images of the SDSS sources, smoothed by 2 pixels. Each image is 20″ × 20″, and the circle is centered on the X-ray position with radius 2″.9. The cross marks the optical position of each source. *Left*, SDSSp J083643+005453; *middle*, SDSSp J103027+052455; *right*, SDSSp J130608+035626.

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[3] See also the *Chandra* data processing threads at http://cxc.harvard.edu/ciao/documents_threads.html.

TABLE 2

Properties of $z \sim 6$ Quasars

Source	X-Ray Position		Detected Counts			f_X[a]	L_X[b]	α_{ox}[c]	HR[d]
	R.A.	Decl.	Broad	Soft	Hard	($\times 10^{-14}$ ergs s^{-1} cm^{-2})	($\times 10^{45}$ ergs s^{-1})		
SDSS 0836+0054	08 36 43.9	+00 54 52.9	21 ± 4.6	19 ± 4.4	2 ± 1.4	2	6.1, 2.7	1.59 ± 0.04	$0.8^{+0.2}_{-0.3}$
SDSS 1030+0524	10 30 27.1	+05 24 54.7	6 ± 2.4	6 ± 2.4	<2	0.4	1.4, 0.64	1.72 ± 0.06	$1.0^{+0.0}_{-0.6}$
SDSS 1306+0356	13 06 08.3	+03 56 26.9	18 ± 4.2	14 ± 3.7	4 ± 2	1.2	4.2, 1.8	1.56 ± 0.03	$0.6^{+0.3}_{-0.3}$

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Broadband flux-corrected for Galactic absorption.

[b] Luminosity in the rest-frame 0.5–8 keV band. For each source, the first number corresponds to $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ while the second line assumes $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

[c] Errors reflect uncertainty in the observed number of counts.

[d] Statistical errors based on errors on observed number of counts.

sulting α_{ox}-values are 1.59 ± 0.04, 1.72 ± 0.06, and 1.56 ± 0.03 for SDSSp J083643+005453, SDSSp J103027+052455, and SDSSp J130608+035626, respectively (Table 2). These are within the range observed for normal lower redshift quasars (e.g., Green et al. 1995). This is consistent with the Silverman et al. results and contrary to the Vignali et al. claim that *Chandra* quasars appear to populate preferentially the region of low (negative) α_{ox}-values (i.e., more X-ray faint).[4] Note, however, that if the true α_X for these high-redshift quasars is significantly different than 1, then the implied values of α_{ox} would also be different and may not be similar to the low-redshift average.

For comparison with earlier work (Silverman et al. 2002; Paper II), in Figure 2 we have plotted the observed X-ray fluxes of $z > 4$ quasars versus their $AB_{1450(1+z)}$ magnitudes (Paper I) along with those reported here. The $z \sim 6$ quasars do not occupy any conspicuously different region on this plot. As discussed in § 1, Vignali et al. suggested that *ROSAT*-detected, optically selected sources are systematically brighter than the *Chandra* sources for the same optical brightness. No obvious selection effect (or any other effect) could explain this trend (Paper II). However, such a trend is not apparent in Figure 2 (see also Silverman et al. 2002). In Figure 3, we have plotted the X-ray–to–optical flux ratio of $z > 4$ X-ray–detected quasars as a function of redshift. The dashed line corresponds to the low-redshift average of $\alpha_{ox} = 1.6$ (Green et al. 1995). Again, no obvious trend with redshift is apparent.

X-ray astronomers have traditionally used hardness ratios (HRs) to extract spectral information when observed counts are too few to perform spectral analysis (Mathur 2001 and references therein). The HR is defined as HR = (soft − hard)/(soft + hard), where "soft" and "hard" are the counts in energy bands 0.5–2.5 and 2.5–8.0 keV, respectively. (We prefer HR over the band ratio BR = soft/hard sometimes used in the literature. HR is bounded well between −1 and 1 for detected sources, compared to the 0 to infinity range of BR.) In these high-redshift sources, we are observing rest-frame energies above ~3.5 keV so that only highly absorbed sources would show evidence for absorption, and we expect to be observing the pure continuum

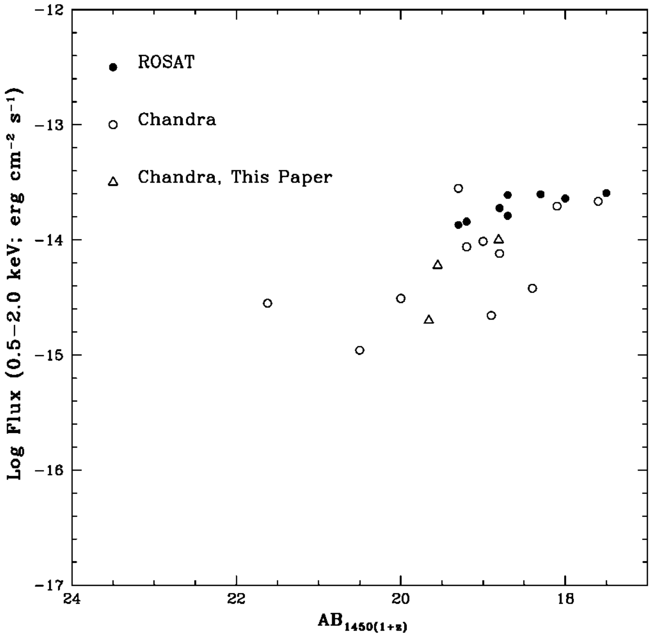

Fig. 2.—For comparison with earlier work, observed frame, Galactic absorption–corrected, soft-band X-ray flux is plotted against $AB_{1450(1+z)}$ for $z > 4$ quasars. Only detected sources are plotted. Data are from Paper II, Silverman et al. (2002), and this Letter. Optical magnitudes of the SDSS quasars are from Paper I. The $z \sim 6$ quasars do not occupy any conspicuously different region on this plot.

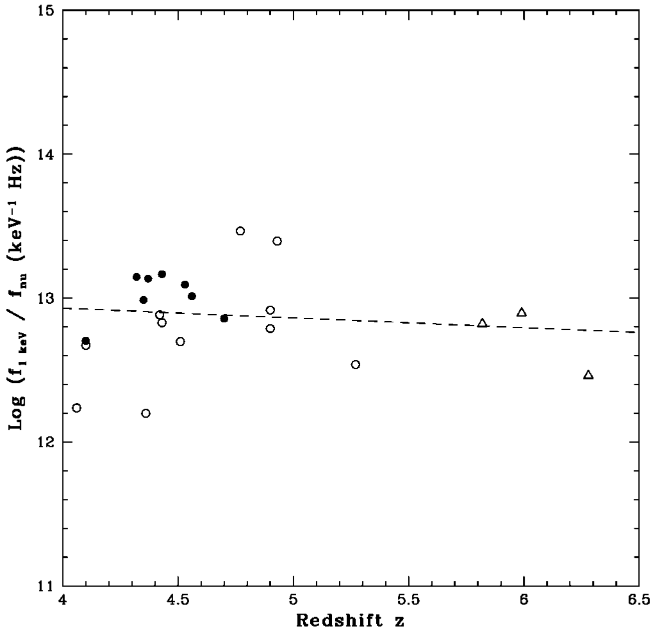

Fig. 3.—Observed X-ray (1 keV) to optical [1450(1 + z) Å] flux ratio plotted as a function of redshift. Symbols are the same as in Fig. 2. Optical f_ν is calculated from published $AB_{1450(1+z)}$ magnitudes following Fukugita et al. (1996). The dashed line corresponds to the locus of $\alpha_{ox} = 1.6$. It is clear that the redshift 6 quasars are not significantly different from their lower redshift cousins.

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[4] We have not included the $z = 5.8$ quasar SDSSp J104433−012502 in the discussion or in the figures, because it is known to be a broad absorption line quasar and has weak X-ray flux as a result of strong absorption.

emission. The HR ratio of SDSSp J083643+005453, $0.8^{+0.2}_{-0.3}$, is consistent with that expected with a power-law slope $\alpha_X = 1$. This object, however, is radio-loud (Paper I), and so its X-ray slope is expected to be flatter around a mean $\alpha_X = 0.5$ (Wilkes & Elvis 1987). For SDSSp J103027+052455, no counts are detected in the hard band, resulting in $\mathrm{HR} = 1^{+0.0}_{-0.6}$. A power law with slope $\alpha_X \gtrsim 2$ would then be required. For SDSSp J130608+035626, on the other hand, a flatter power law with $\alpha_X \sim 0.3$ would be required to reproduce the observed HR of 0.6 ± 0.3. We caution, however, against attaching too much significance to the above results, given the errors associated with the small number of observed counts in each band. Within the errors, the sources are consistent with the normal power-law slope expected for quasars.

Perhaps the most remarkable thing about these highest redshift quasars is that they are so absolutely unremarkable in both optical and X-ray bands, implying no strong evolution out to redshifts of ∼6. The only possible difference could be in the X-ray spectral slope, which could not be determined with the *Chandra* data. Many more counts are needed to determine the spectral shape of these objects. The expected count rates with *XMM-Newton* are 11, 3, and 6 ks^{-1} for the three objects, respectively, for combined EPIC-pn and EPIC-MOS detectors with thin filters. For the brightest two objects, a crude spectrum with about 300 counts can be obtained in a reasonable observing time of 25–50 ks. We have an ongoing program with *XMM-Newton* to do precision spectroscopy of some $z > 4$ quasars. Extending this program to the highest redshifts would be particularly interesting. Clearly, we have to work harder and look deeper to understand quasar evolution.

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