CHANDRA SURVEY OF RADIO-QUIET, HIGH-REDSHIFT QUASARS

JILL BECHTOLD,1 ANETA SIEMIGINOWSKA,2 JOSEPH SHIELDS,3 BOŻENA CZERNY,4 AGNIESZKA JANIUK,4
FRED HAMANN,5 THOMAS L. ALDCROFT,6 MARTIN ELVIS,2 AND ADAM DOBRZYCKI2

Received 2002 February 7; accepted 2002 July 1

ABSTRACT

We observed 17 optically selected, radio-quiet, high-redshift quasars with the Chandra ACIS and detected 16 of them. The quasars have redshifts between 3.70 and 6.28 and include the highest-redshift quasars known. When compared with low-redshift quasars observed with ROSAT, these high-redshift quasars are significantly more X-ray–quiet. We also find that the X-ray spectral index of the high-redshift objects is flatter than the average at lower redshift. These trends confirm the predictions of models in which the accretion flow is described by a cold, optically thick accretion disk surrounded by a hot, optically thin corona, provided the viscosity parameter \( \alpha \geq 0.02 \). The high-redshift quasars have supermassive black holes, with masses of \( \sim 10^{10} M_\odot \), and are accreting material at \( \sim 0.1 \) times the Eddington limit. We detect 10 X-ray photons from the \( z = 6.28 \) quasar SDSS 1030+0524, which might have a Gunn-Peterson trough and be near the redshift of reionization of the intergalactic medium. The X-ray data place an upper limit on the optical depth of the intergalactic medium, \( \tau (\text{IGM}) < 10^6 \), compared to the lower limit from the spectrum of Ly\( \alpha \) and Ly\( \beta \), which implies \( \tau (\text{IGM}) > 20 \).

Subject headings: accretion, accretion disks — intergalactic medium — quasars: general — X-rays: galaxies

1. INTRODUCTION

Rapid growth in the number of quasars discovered with \( z > 4 \) has taken place in the last few years (Warren et al. 1987; Schneider, Schmidt, & Gunn 1989; Kennefick et al. 1995a; Kennefick, Djorgovski, & de Carvalho 1995b; Hook et al. 1996; Storrie-Lombardi et al. 1996; Hook & McMahon 1998; Fan et al. 1999b, 2000, 2001; Becker et al. 2001; Schneider et al. 2002). We are thus now able to probe the quasar phenomenon in a new regime of high luminosity and youth that is important for understanding the structure of quasars and their evolution. At the present time, there are about 130 quasars identified at \( z > 4 \) (NED),6 but X-ray data for these sources remain sparse, especially for the radio-quiet majority (Bechtold et al. 1994a, 1994b; Pickering, Impey, & Foltz 1994; Henry et al. 1994; Mathur & Elvis 1995; Siebert et al. 1996; Fabian et al. 1997; Zickgraf et al. 1997; Siebert & Brinkmann 1998; Schneider et al. 1998; Wu, Bade, & Beckmann 1999; Kaspi, Brandt, & Schneider 2000; Brandt et al. 2001; Vignali et al. 2001). The X-ray continuum in active nuclei is thought to arise in a Comptonized wind or corona associated with the inner accretion disk around a supermassive black hole (Haardt & Maraschi 1993; Czerny & Elvis 1987). Additional components of the X-ray emission are also commonly seen in high signal-to-noise ratio spectra at low redshift, including X-rays associated with beamed synchrotron plasma, Compton reflected emission, line emission in Fe K\( \alpha \), weak absorption from warm, ionized material, and strong absorption from cold material (see George et al. 2000; Reeves & Turner 2000 and references therein). Whether or not there is evolution in the structure of quasars with redshift can, in principle, be learned from X-ray spectroscopy of high-redshift quasars.

We report here a survey with the Chandra X-Ray Observatory of optically selected, radio-quiet, high-redshift quasars. This project is part of our long-term program to characterize the multiwavelength emission from quasars as a function of redshift (Bechtold et al. 1994a, 1994b; Kuhn et al. 2001). The statistical properties of the ensemble population of quasars evolve strongly with redshift; the break point, \( L^* \), of the luminosity function shifts to higher luminosities by a factor of \( \sim 50 \) between \( z = 0 \) and \( z = 2 \) (Boyle et al. 1987). We hope to understand this evolution in terms of a physical model for the evolution of individual objects: does this evolution reflect slow changes in a few rare objects or a short-lived phase that most galaxies go through? Are there differences in the spectral evolution of radio-loud and radio-quiet quasars? Can these be used to understand the origin of the radio emission? The X-ray photons, whose production is closely linked to processes in the central engine, should provide direct clues to the physical conditions in the central few parsecs, where most of the quasar energy is produced, and will therefore help answer these questions. With the recent suggestion that reionization of the intergalactic medium happened at \( z \approx 6 \) (Becker et al. 2001), it is possible that \( z \approx 6 \) is the epoch when the first quasars were born. Thus, the quasars targeted in our survey are among the first objects formed in the universe.

High-redshift quasars are rare and require pointed observations at known objects for study; our expectation is that XMM and Chandra serendipitous surveys will not cover sufficient area on the sky to find many of them. The increase in sensitivity provided by Chandra and XMM, however, makes

---

1 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721; jbechtold@as.arizona.edu.
2 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; asiemiginowska@cfa.harvard.edu, aldercroft@cfa.harvard.edu, elvis@cfa.harvard.edu, adam@cfa.harvard.edu.
3 Department of Physics and Astronomy, Ohio University, Athens, OH 45701; shields@phy.ohiou.edu.
4 Nicolaus Copernicus Astronomical Center, Warsaw, Poland; agnes@camk.edu.pl, bcz@camk.edu.pl.
5 Department of Astronomy, University of Florida, 211 Bryant Space Science Center, Gainesville, FL 32611; hamann@astro.ufl.edu.
6 NASA/IPAC Extragalactic Database, available at http://nedwww.ipac.caltech.edu.
it possible to increase significantly the number of \( z > 4 \) quasars with X-ray data, with only a relatively modest investment of telescope time per object.

We chose targets from samples of high-redshift quasars, based on their optical luminosity. The quasars were found in optical surveys, including the APM multicolor survey (Williger et al. 1994; Storrie-Lombardi et al. 1994, 1996), the Second Palomar Observatory Sky Survey (Smith et al. 1994; Kennefick et al. 1995a, 1995b), and the Sloan Digital Sky Survey (Fan et al. 1999a, 2000; Becker et al. 2001). Subsequent observations with FIRST and the NRAO VLA Sky Survey (NVSS) confirm that all but one are radio-quiet (Stern et al. 2000; Fan et al. 2001; also, see NED). Since these quasars are unusually bright, they have been the subject of other studies, including high-quality optical spectroscopy to study the emission lines (Constantin et al. 2001) and absorption lines (Storrie-Lombardi et al. 2001; Péroux et al. 2001).

We calculated observing times required to detect the quasars in X-rays with 100 photons, if the quasar had the average optical to X-ray flux ratio seen at lower redshift, so that we would be assured of a detection (9–10 photons) if the quasar were more X-ray–weak. In fact, we detected all but one quasar in the sample. Observations of three quasars were taken from the public archive, to extend our sample to \( z = 6.28 \).

2. OBSERVATIONS AND ANALYSIS

Seventeen quasars were observed with the Chandra X-Ray Observatory and Advanced CCD Imaging Spectrometer (ACIS-S; G. P. Garmire et al. 2003, in preparation; Weisskopf & O’Dell 1997). All the observations were taken with the quasar on the ACIS-S3 CCD and reduced with the standard pipeline reduction software and CIAO (version 2.2).\(^7\) Initially, we pointed off-axis to mitigate pileup, in anticipation of high count rates, but later moved the quasar position on axis. Pileup is negligible for all observations in our survey.

The observations are summarized in Table 1. We list the exposure times, observation times, and net counts detected. For every object, except PSS 1435+3057, we detected a significant X-ray source within 1\( ^{\circ} \) of the optical position, so there is no doubt to the identification.

For PSS 1435+3057, we give a 3\( ^{\sigma} \) upper limit to the X-ray photons at the optical position. There is a weak source (11 photons) located 3\( ^{\circ} \)8 from the optical position. This source is beyond the range of aspect errors (Aldcroft 2002),\(^8\) but it might be associated with an extended structure from the quasar (see Schwartz 2002).

In Table 2, we list X-ray flux rates and other X-ray parameters. Although the number of photons detected is small, we were able to derive meaningful spectral fits. We used SHERPA (in CIAO, version 2.2) to fit power-law parameters to the counts, including absorption by the Milky Way column density of neutral hydrogen fixed at the value inferred from 21 cm maps (COLDEN,\(^9\) which is based on Dickey & Lockman 1990). We fitted a function of the standard form

\[
A(E) = f_0 \left( \frac{E}{1 \text{ keV}} \right)^{-\Gamma_X},
\]

where \( \Gamma_X \) is the energy index and \( f_0 \) is the normalization at 1 keV, with units of photons keV\(^{-1} \) cm\(^{-2} \) s\(^{-1} \). We restricted

\[\text{Note.} — \text{Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.}\]

\(^a\) AB magnitude at 1450 A in quasar rest frame, \( B = -2.5 \log f_{\text{opt}} - 48.57 \), where \( f_{\text{opt}} \) is in units of ergs cm\(^{-2} \) s\(^{-1} \) Hz\(^{-1} \).

\(^b\) Galactic H\( ^\text{I} \) column, in units of 10\(^{20} \) atoms cm\(^{-2} \), from COLDEN.

\(^c\) Net number of photons in the observed energy range 0.3–6.5 keV.

\(^d\) SDSS J0836+0054 is radio-loud; see Fan et al. 2001.

\(^7\) For CIAO, see http://asc.harvard.edu/CIAO/index.html.

\(^8\) See http://CXC.harvard.edu/cal/ASPECT/celmon.

\(^9\) For COLDEN, see http://asc.harvard.edu/toolkit/colden.jsp.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Quasar & \( z_{\text{em}} \) & AB\(^a\) & Observation ID & Date & Exposure (s) & R.A. (J2000.0) & Decl. (J2000.0) & \( N_{\text{Gal}} \)\(^b\) & Net Count\(^c\) & References \\
\hline
PSS 0059+0003 & 4.178 & 19.45 & 2179 & 2001 Sep 18 & 2682 & 00 59 22.80 & 00 03 01.0 & 3.20 & 12 & 1, 2 \\
BR12105+0352 & 4.437 & 18.84 & 2180 & 2001 Sep 18 & 3709 & 01 06 19.20 & 00 48 22.0 & 3.10 & 26 & 1, 2, 3 \\
SDSS 0150+0041 & 3.67 & 18.35 & 2181 & 2001 Aug 31 & 3228 & 01 30 48.80 & 00 41 26.0 & 2.79 & 7 & 4 \\
BR12041–0146 & 4.653 & 18.45 & 875 & 2001 Sep 11 & 7365 & 02 44 01.90 & 01 34 03.0 & 3.73 & 17 & 5 \\
PSS 0248+1802 & 4.43 & 18.24 & 876 & 1999 Dec 27 & 1731 & 02 48 54.30 & 18 02 50.0 & 9.72 & 19 & 1, 2 \\
BR12041–1711 & 4.236 & 18.84 & 2182 & 2001 Aug 3 & 3841 & 04 03 56.60 & 17 12 24.0 & 2.34 & 15 & 5 \\
SDSS J0356+0005\(^d\) & 5.82 & 18.8 & 3359 & 2002 Sep 29 & 5687 & 08 36 43.85 & 00 54 53.3 & 4.15 & 24 & 6 \\
SDSS 1030+0524 & 6.28 & 19.7 & 3357 & 2002 Sep 29 & 7955 & 10 30 27.10 & 05 24 55.1 & 3.09 & 10 & 6 \\
BR1033–0327 & 4.599 & 18.84 & 877 & 2000 Jan 26 & 3477 & 10 36 23.70 & 00 43 20.0 & 4.85 & 16 & 7, 8 \\
PSS 1057+4555 & 4.10 & 17.53 & 878 & 2000 Jan 26 & 2808 & 10 57 56.40 & 45 55 52.0 & 1.17 & 34 & 2 \\
SDSS 1204–0020 & 5.10 & 19.05 & 2183 & 2000 Dec 2 & 1570 & 12 04 41.70 & 00 21 49.0 & 2.14 & 26 & 9 \\
SDSS 1306+0356 & 5.99 & 19.96 & 3358 & 2002 Sep 29 & 8156 & 13 06 08.26 & 03 56 26.3 & 2.08 & 19 & 6 \\
PSS 1317+3551 & 4.36 & 19.55 & 879 & 2000 Jun 14 & 2788 & 13 17 43.20 & 35 31 30.0 & 0.99 & 9 & 2 \\
PSS 1435+3057 & 4.35 & 19.12 & 880 & 2000 May 21 & 2811 & 14 35 23.50 & 30 57 23.0 & 1.21 & <9 & 1, 2 \\
PSS 1443+2724 & 4.42 & 19.23 & 881 & 2000 Jun 12 & 2170 & 14 43 31.20 & 30 57 23.0 & 2.33 & 10 & 1, 2 \\
SDSS 1621–0042 & 3.70 & 17.41 & 2184 & 2001 Sep 5 & 1570 & 16 21 16.90 & 00 42 51.1 & 7.29 & 26 & 9 \\
BR1221–1628 & 3.99 & 18.6 & 3518 & 2001 Dec 16 & 3222 & 22 15 27.20 & 16 11 33.0 & 3.64 & 15 & 5 \\
\hline
\end{tabular}
\caption{Summary of Observations}
\end{table}
our fits to the range 0.3–6.5 keV, where the calibration is reliable at the present time and the Chandra background is the lowest. The source extraction region for each quasar was a circle with a 10 pixel (492) radius. There were no background flares during the observations.

The choice of cosmology is important when converting fluxes to luminosities. The absolute B magnitude, \( M_B \), is related to apparent magnitude, \( m_B \), by

\[
M_B = m_B + 5 - 5 \log D,
\]

where

\[
D = \frac{c}{H_0} A,
\]

where \( c \) is the speed of light and \( H_0 \) is the Hubble constant. In general, for a flat universe

\[
A = (1 + z) \left[ \Omega_\Lambda + \Omega_M (1 + z)^3 \right]^{-1/2} dz
\]

(Peacock 1999; his eq. [3.39]). For \( q_0 > 0 \) and \( \Omega_\Lambda = 0 \), we have

\[
A = z \left[ 1 + \frac{z(1 - q_0)}{1 + 2q_0 z^{0.5} + (1 + q_0 z)} \right],
\]

which simplifies to

\[
A = z \left( 1 + \frac{z}{3} \right)
\]

for \( q_0 = 0 \) (see also Carroll, Press, & Turner 1992).

The quasar luminosity function is usually reported assuming \( q_0 = \frac{1}{3} \), \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \), and \( \Lambda = 0 \), while observers often adopt \( q_0 = 0 \), \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), and \( \Lambda = 0 \). The “best” fits to cosmic microwave background data, Type Ia supernova light curves, and large-scale structure models suggest \( \Omega_\Lambda = 0.7, \Omega_M = 0.3 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). We refer to this choice of cosmological parameters as “\( \Lambda \text{CDM} \)” in calculations below. Note that the integral of equation (4) must be evaluated numerically. Below we report luminosities for each of these three cosmologies.

### 3. THE EVOLUTION OF \( \alpha_{ox} \) FOR RADIO-QUIET QUASARS

Following Zamorani et al. (1981), we compute a ratio of X-ray to optical flux, \( \alpha_{ox} \), where

\[
\alpha_{ox} = \frac{- \log (f_X/f_{opt})}{\log (\nu_X/\nu_{opt})}
\]

and \( \log \nu_X = 17.6845 \) for rest-frame 2 keV and \( \log \nu_{opt} = 15.0791 \) for rest-frame 2500 Å.

In Table 2 we give the results. For all objects, the continuum flux at 1450 Å is available from the literature (see Table 1), usually in the form of apparent AB magnitude at 1450 Å in the rest frame of the quasar, \( m_{AB} \), where

\[
m_{AB} = -2.5 \log f_i - 48.57
\]

so that \( f_i \) has units of ergs s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\). We compute \( f_i \) at 2500 Å, which has units of ergs s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\), assuming that the optical continuum has a power-law spectral energy.
distribution with frequency spectral index $\alpha = -0.3$. We compute $f_X$ at 2 keV in the rest frame of the quasar from the measured flux at 1 keV in our observed frame, assuming a power law with energy index $\Gamma_X = 2.2$.

Figure 1 shows $\alpha_{ox}$ versus redshift, $z$, and Figure 2 shows $\alpha_{ox}$ versus absolute $B$ magnitude, $M_B$. For clarity, we plot the errors on $\alpha_{ox}$ only for the quasars with $z > 5$. For the rest, although the number of X-ray photons detected is small and the uncertainties on $f_X$ correspondingly large, the division by $\log(\nu_X/\nu_{opt}) = 2.60$ makes the errors only $\sim 0.2$.

For a low-redshift comparison sample, we use the compilation of $ROSAT$ all-sky survey and pointed observations for radio-quiet quasars (Yuan et al. 1998) and radio-loud quasars and blazars (Brinkmann et al. 1997), supplemented with observations of other high-redshift quasars from the literature (Schneider et al. 1998; Kaspi et al. 2000; Brandt et al. 2001; Vignali et al. 2001). Since Yuan et al. (1998) and Brinkmann et al. (1997) did not list $\alpha_{ox}$, we computed it from the listed unabsorbed X-ray flux density (0.1–2.4 keV), assuming that the spectrum is a power law with energy index $\Gamma_X$, with the best-fit $\Gamma_X$ listed by Yuan et al. (1998). For objects with no $\Gamma_X$ measured, we assume $\Gamma_X = 2.58$ for $z < 0.5$, $\Gamma_X = 2.46$ for $0.5 < z < 1.0$, $\Gamma_X = 2.35$ for $1.0 < z < 2.0$, and $\Gamma_X = 2.2$ for $z > 2.0$ (Yuan et al. 1998). For the optical flux, we used the absolute $B$ magnitude for each object listed in Véron-Cetty & Véron (2000), which includes a $K$-correction. We extrapolated to 2500 Å in the rest frame of the quasar, assuming a power law with $\alpha = -0.3$. The data points plotted in Figures 1 and 2 are available on our Web site.\(^{10}\)

The $z > 4$ radio-quiet quasars are clearly more X-ray–quiet than their low-redshift counterparts, even when their extreme luminosity is taken into account. Previous studies (see, e.g., Avni, Worrall, & Morgan 1995; Brandt et al. 2001; and references therein) found that $\alpha_{ox}$ depends mostly on optical luminosity, although the correlation of luminosity and redshift in the observed samples made it difficult to sort out whether $\alpha_{ox}$ depended mostly on optical luminosity or redshift (see, e.g., Bechtold et al. 1994a, 1994b; Pickering et al. 1994). The $Chandra$ sample also suffers from a strong correlation between redshift and luminosity. In Figure 1 the three $Chandra$ quasars at $z \sim 3$ are strikingly offset from the $ROSAT$ quasars to larger $\alpha_{ox}$, while in Figure 2 they show no offset. This is likely due to the newer surveys from which they are taken, which cover a larger solid angle than those used to select the $ROSAT$ high-$z$ quasars. As a result, they find systematically more luminous quasars.

To quantify the result, we computed the generalized Kendall’s $\tau$, including lower limits on $\alpha_{ox}$ for quasars not detected at high redshift (Avni 1976; Avni et al. 1980; Feigelson & Nelson 1985; Avni & Tananbaum 1982, 1986; Isobe, Feigelson, & Nelson 1986; Akritas & Siebert 1996). We used the IRAF program BHKMETHOD to search for correlations between (1) redshift and $\alpha_{ox}$ and (2) absolute $B$ magnitude and $\alpha_{ox}$.

We find that $\alpha_{ox}$ is anticorrelated with redshift, with Kendall’s $\tau = -0.38$ and $Z$-value $= 8.4$, so that a correlation is present at 8.4 $\sigma$ significance. On the other hand, the probability is 0.05 that $\alpha_{ox}$ is not correlated with absolute $B$ magnitude ($Z$-value $= 1.9$). Thus, we find that $\alpha_{ox}$ depends primarily on redshift and weakly on luminosity.

Does this conclusion depend upon our assumptions for the X-ray spectral index, $\Gamma_X$? In Figure 4, we plot $\Gamma_X$ versus redshift and versus luminosity, for the Yuan et al. (1998) $ROSAT$ sample and our high-redshift sample. The high-redshift quasars are, if anything, flatter (smaller $\Gamma_X$) than

\(^{10}\) Electronic files with the data used in Figs. 1–3 are available at http://lithops.as.arizona.edu/~jill and http://heawww.harvard.edu/QEDT.
Future observations can confirm this intriguing result. In our sample, as discussed above, we see a similar source 3′ 8 from the optical position of PSS 1435+3057.

For the core X-ray fluxes, we measure slightly different values than those reported in the three other papers. We measure 24, 10, and 19 photons for SDSS 0836+0054, SDSS 1306+0356, and SDSS 1030+0524, respectively. Schwartz (2002) measures 21, 6, and 16 photons; Mathur et al. (2002) measure 21, 6, and 18 photons; and Brandt et al. (2002) measure 21, 6, and 17 photons. The difference lies in two factors: the energy range used (we use 0.3–6.5 keV, whereas the others use 0.5–7 or 0.5–8 keV) and the difference in circle radius used for source extraction (we use 4′, whereas they use 1′ 2–2′ 9). We chose the 0.3–6.5 keV range because it has the lowest background and the larger circle extraction to include the point-spread function at all energies. The result is a greater number of net photons for all sources and a more reliable measure of the source properties.

5. MEAN X-RAY SPECTRUM

Figure 3 suggests that the X-ray spectral index flattens at high redshifts. This could be caused by two effects. First, as the redshift increases, the observed X-ray band samples greater and greater energies. Thus, the flattening might be caused by intrinsic flattening of the power law at high energies. Second, the quasars in our survey might have flatter intrinsic spectra at all energies, because of their high luminosities or high redshift.

We applied Kendall’s generalized τ to investigate the dependence of ΓX on redshift and optical luminosity. We did not include objects for which a power-law index had not been measured. We found that ΓX is anticorrelated with redshift (Kendall’s τ = −0.4319, Z-value = 8.46) and positively correlated with luminosity (Kendall’s τ = 0.2330, Z-value = 4.57). The data suggest that ΓX depends strongly on both redshift and luminosity.

4. COMPARISON WITH OTHER STUDIES

After submission of this paper, three papers were submitted to the Astrophysical Journal Letters about the Chandra observations of SDSS 0836+0054, SDSS 1306+0356, and SDSS 1030+0524. These quasars were observed with Director’s Discretionary Time and were placed in the public archive immediately. Brandt et al. (2002) and Mathur, Wilkes, & Ghosh (2002) report fluxes for the three quasars and conclude, contrary to the results reported here, that the optical to X-ray flux ratios of these three highest-redshift quasars are not significantly different from those of low-redshift quasars. The differing conclusion is a result of the different comparison samples used, which in both papers were smaller than the one presented here. Schwartz (2002) not only reported the core fluxes for the three quasars, but also argued that an X-ray source 23′′ from SDSS 1306+0356 with no optical counterpart on the Palomar Sky Survey is in fact associated with the quasar. He postulates that the X-rays are Compton-scattered cosmic microwave background photons from a jet structure, similar to those seen at lower redshift (Tavecchio et al. 2000; Celotti, Ghisellini, & Chiaberge 2001; Siemiginowska et al. 2002).

The result is a greater number of net photons for all sources and a more reliable measure of the source properties.

TABLE 3
X-RAY LUMINOSITIES

| Quasar     | z_em | log L_X(\phi_0 = 0)^{a,b} (ergs s^{-1}) | log L_X(\phi_0 = 1/2)^{c,e} (ergs s^{-1}) | log L_X(\Lambda CDM)^{d} (ergs s^{-1}) |
|------------|------|---------------------------------------|------------------------------------------|---------------------------------------|
| PSS 0059+0003……… | 4.178 | 46.39 | 45.70 | 46.06 |
| BR1 0103+0032……… | 4.437 | 46.07 | 45.35 | 45.71 |
| SDSS 0150+0041……… | 3.67 | 46.11 | 45.48 | 45.83 |
| BR1 0241–0146……… | 4.053 | 45.74 | 45.06 | 45.42 |
| PSS 0248+1802……… | 4.43 | 46.27 | 45.54 | 45.91 |
| BR1 0401–1711……… | 4.236 | 46.04 | 45.34 | 45.70 |
| SDSS 0836+0054……… | 5.82 | 46.48 | 45.62 | 46.00 |
| SDSS 1030+0524……… | 6.28 | 47.10 | 46.19 | 46.58 |
| BR1 1033–0327……… | 4.509 | 45.53 | 44.80 | 45.17 |
| PSS 1057+4555……… | 4.10 | 46.14 | 45.46 | 45.82 |
| SDSS 1204–0021……… | 5.10 | 45.97 | 45.17 | 45.54 |
| SDSS 1306+0356……… | 5.99 | 46.30 | 45.43 | 45.81 |
| PSS 1317+3531……… | 4.36 | 45.26 | 44.55 | 44.91 |
| PSS 1443+2724……… | 4.42 | 46.04 | 45.32 | 45.69 |
| SDSS 1621–0042……… | 3.70 | 46.48 | 45.84 | 46.20 |
| BR1 2212–1626……… | 3.99 | 46.04 | 45.37 | 45.73 |

a X-ray luminosity, in observed 2–10 keV band.
b \phi_0 = 0, H_0 = 70 km s^{-1} Mpc^{-1}, \Lambda = 0.
c \phi_0 = 1/2, H_0 = 70 km s^{-1} Mpc^{-1}, \Lambda = 0.
d \Omega_M = 0.7, \Omega_{\Lambda} = 0.3, H_0 = 70 km s^{-1} Mpc^{-1}.
We note that at the redshifts of the quasars in our sample, the usable Chandra energy range, 0.3–6.5 keV, corresponds to relatively hard X-rays, 1.5–32 keV. Therefore, we expect absorption by intervening damped Lyα systems and other intervening absorbers to be negligible, unless the absorbers are at low redshift. Since we chose the sample objects to avoid known broad absorption line quasars (see Green et al. 2001), intrinsic absorption is also probably negligible. We discuss the special case of SDSS 1030+0524 at $z = 6.28$ below (§ 8).

6. IMPLICATIONS FOR $M_{\text{BH}}$ AND $\dot{m}$

A successful model for explaining the optical/UV continuum of quasars (the big blue bump) involves accretion onto a supermassive black hole through an optically thick, physically thin disk (Shields 1978; Malkan 1983; Bechtold et al. 1987; Czerny & Elvis 1987; Sun & Malkan 1989). The emitted spectrum is then the integral of Planck spectra of different temperatures, resulting in a flat continuum $\propto \nu^{-1/3}$ through the optical/UV. There is a near-exponential falloff blueward of a cutoff energy, $E_{\text{co}}$, since there is a maximum temperature for the accreting material nearest the black hole. For the supermassive black holes in quasars accreting near the Eddington limit, the cutoff is $E_{\text{co}} \approx 10$–100 eV.

The spectral shape and luminosity of the accretion disk can be predicted and depend on five parameters: the black hole mass, $M_{\text{BH}}$; the mass accretion rate, $\dot{m}$; the total angular momentum; the viscosity in the disk, $\alpha$; and the inclination at which we observe the disk. If we make the usual assumptions that the black hole is maximally spinning (Kerr black hole; see Elvis, Risalti, & Zamorani 2002), that we are observing the disk face-on, and that the viscosity $\alpha = 0.1$, then the spectral energy distribution and luminosity depend on two parameters, $M_{\text{BH}}$ and $\dot{m}$.

Malkan (1991) showed that for a Kerr black hole, an analytical expression for the emitted spectrum is

$$L_{\nu} \sim A \left(\frac{\nu}{\nu_{\text{co}}}\right)^{1/2} \exp\left(-\frac{\nu}{\nu_{\text{co}}}\right),$$

where $A$ and $\nu_{\text{co}}$ are the normalization and cutoff frequency. The cutoff energy can then be written as

$$h\nu_{\text{co}} = (6 \text{ eV})m^{1/4}M_{8}^{-1/4} = (20 \text{ eV})L_{46}^{-1/4}M_{8}^{-1/2}$$

(Wandel 2000), where $M_{8}$ is the black hole mass in units of $10^{8} M_{\odot}$.

Observationally, it is also possible to relate $M_{\text{BH}}$ to the width of the broad emission lines, assuming that the BLR gas is in Keplerian motion and calibrating the size (and hence ionization parameter) of the gas by reverberation mapping of low-redshift active galactic nuclei (AGNs; Peterson & Wandel 1999; Wandel, Peterson & Malkan 1999).

Thus, with two observations—the width of Hβ and the continuum luminosity—we can solve for the two free parameters of the model, $M_{\text{BH}}$ and $\dot{m}$ (Wandel & Petrosian 1988; Wandel & Boller 1998; Wandel 1999). In Figures 4 and 5 we plot the result. For comparison, we also plot the results for narrow-line Seyfert 1 galaxies (NLS1's; Crenshaw 1986; Stirpe 1990; Boller, Brandt, & Fink 1996; Brandt, Mathur, & Elvis 1997), the Palomar-Green (PG) quasars (Schmidt & Green 1983; Boroson & Green 1992; Miller et al. 1992), and the Large Bright Quasar Survey (LBQS) quasars (Hewett, Foltz, & Chaffee 1995; Forster et al. 2001). For high-redshift quasars, Hβ is in the near-IR.
and only the most luminous quasars have measurements. We use H/$\beta$ whenever possible (Hill, Thompson, & Elston 1993; Rokaki, Boisson, & Collin-Souffrin 1992; Nishihara et al. 1997; McIntosh et al. 1999). For the rest, we use the FWHM of the C$^4$ emission line and assume the relation given by Corbin (1991),

$$\text{FWHM} \left( \frac{\text{H}/\beta}{\text{C}^4} \right) = 1.35 \text{FWHM} \left( \frac{\text{C}^4}{\text{C}^0} \right) / 1391 \text{ km s}^{-1}. \quad (11)$$

We use C$^4$ for intermediate-redshift quasars from the LBQS (Forster et al. 2001) and observations of $z \sim 4$ quasars from Constantin et al. (2002). To estimate the luminosity, we use the optical luminosities computed from the magnitudes listed in Table 1, or from the Véron-Cetty & Véron (2000) catalog. For all quasars, we apply a bolometric correction of 10.

For the $\Lambda$CDM cosmology (Fig. 5), we see that the NLS1's have relatively low mass black holes, PG quasars are more massive, and the high-redshift quasars have very massive black holes. The typical black hole mass for the $z = 4$–6 quasars is $\sim 10^{10} M_\odot$, with most objects accreting at between 0.01 and 0.8 times the Eddington mass accretion rate.

7. ACCRETION DISK AND X-RAY–EMITTING CORONA

We now use the X-ray measurements to further investigate the nature of the black hole and accretion in quasars. Janiuk & Czerny (2000) have presented calculations of the X-ray spectrum expected from a hot corona associated with an accretion disk. The model predicts the fraction of energy dissipated in the corona as a function of the disk radius. The coronal dissipation is assumed to be proportional to the gas pressure, and the pressure at the base of the corona is determined by the condition for the disk/corona transition. This requirement is consistent with the evaporation/condensation equilibrium condition (Różańska & Czerny 2000) and effectively means that bremsstrahlung and Compton cooling at the base of the corona are comparable. The spectrum from the disk and the corona is computed locally, taking into account the Comptonization in the hot coronal plasma.

The observed model spectrum is integrated over the disk surface. The spectrum is parameterized by the black hole mass, accretion rate, and coronal viscosity, $\alpha$. Here we use a code that includes tabulated amplification factors for Comptonization in the corona derived from Monte Carlo simulations (Janiuk, Czerny, & Życki 2000), instead of the analytical approach used by Janiuk & Czerny (2000). In contrast to the calculations described in § 6, we assume a Schwarzschild, not Kerr, black hole. We calculate model spectra assuming that the disk is face-on. Based on low-luminosity accretion models (advection-dominated accretion flows, or ADAFs; Kurpiewski & Jaroszyński 2000, 1999), we expect that the X-ray spectra will be harder for the maximally rotating black hole. Kerr geometry should be considered in the future models to quantify the effects.

We defer a detailed comparison of the new data with the models to a future paper and here present only the general trends. In Figure 6, we plot representative spectral energy distributions in order to illustrate the dependence on parameters. We plot models with the black hole mass fixed at $10^{10} M_\odot$ and different viscosities and accretion rates. We see that the X-ray spectral index is only a weak function of the parameters, but that the optical/UV luminosity and $\alpha_{\text{ox}}$ are strong functions of the viscosity, $\alpha$, and accretion rate. We use the standard $\alpha$ viscosity prescription (Shakura & Sunyaev 1973), which describes the efficiency of angular momentum transfer in the disk.

Figure 7 shows how $\alpha_{\text{ox}}$ and $\Gamma_X$ depend on parameters. We plot the results for models with black hole mass $10^7$ and $10^{10} M_\odot$ and accretion of 0.01 and 0.8 times the Eddington rate, which bracket the values derived for the luminous...
they have detected a Gunn-Peterson trough. They conclude that the intergalactic medium (IGM) was in the process of reionization at \( z \sim 6 \). They derive a lower limit on the optical depth of neutral hydrogen in the IGM, from analysis of Ly\( \alpha \) and Ly\( \beta \), of \( \tau(\text{IGM}) > 20 \).

With Chandra, we detect 10 photons for SDSS 1030+0524 in the observed 0.3–6.5 keV band, which is 2.2–47.0 keV in the quasar’s rest frame. In fact, all 10 photons have \( E < 2.5 \) keV observed, or \( E < 18 \) keV. The limits on IGM absorption are weak. We used SHERPA to fit the 10 photons with a model that had the Galactic absorption fixed, a power law with fixed \( \Gamma_X = 2.2 \), and absorption at \( z = 6.28 \). The column of the redshifted absorption and normalization of the flux were free parameters. Significant absorption was not detected, and we can place a 3 \( \sigma \) upper limit to the absorbing column of \( 7.6 \times 10^{22} \) atoms cm\(^{-2} \) if the IGM has solar abundance and \( 5.3 \times 10^{24} \) atoms cm\(^{-2} \) if the IGM has hydrogen and helium only, at the solar ratio. In either case, the Chandra data imply that at the Lyman limit, \( \tau(\text{IGM}) < 10^6 \) at redshift \( \sim 6 \).

9. DISCUSSION

We have studied the evolution of quasars from \( z = 6 \) to the present day, putting together what is known about the optical continuum luminosities, broad emission line widths, and X-ray flux and spectrum. The data are consistent with a model in which the optical/UV continuum arises in a cold, thin, optically thick accretion disk and the X-rays are produced at high redshift by a Comptonized corona. At low redshift, extra components are likely making the X-ray spectrum more complex than the simple power-law fits available so far for most objects.

The high-redshift quasars have systematically more massive central black holes than their low-redshift counterparts and are accreting at high rates, several tenths of the Eddington limit. Their observed, relatively weak X-ray fluxes are a natural outcome of the accretion disk coronal models, with no cold absorption necessary to suppress the X-ray emission (cf. Brandt et al. 2001; Mathur 2001).

The Chandra observations require large values of the viscosity parameter, \( \alpha > 0.02 \), for the high-redshift quasars. Numerical simulations show that the turbulent part of the \( \alpha \) parameter is negligible in comparison with the magnetic term arising from magnetorotational instability and that \( \alpha \) should be within \( 0.001–0.1 \) (Balbus & Hawley 1998; Armitage 1998; Armitage, Reynolds, & Chiang 2001). Observational constraints based on AGN variability are limited (Siemiginowska & Czerny 1989), but in general they are in agreement with the theoretical predictions, although for high disk luminosities \( \alpha \) exceeds 0.1 for the PG sample of quasars (R. Starling, A. Siemiginowska, & P. Uttley 2003, in preparation).

We conclude that even at the highest redshifts probed to date, quasars were producing prodigious UV and soft X-ray photons, which no doubt had interesting effects on the IGM and the formation of galaxies at the earliest times.

We thank Harvey Tananbaum, Chandra director, for using his director’s time to observe three of the high-redshift quasars included in this study and for putting the data in the public archive immediately. We thank Harvey Tananbaum, Belinda Wilkes, and Dan Schwartz for reading the first version of this paper carefully and for suggestions that improved it. This research is funded in part by NASA con-

---

**Fig. 7.**—Predicted dependence of \( \alpha_{\text{ox}} \) (top) and X-ray power-law spectral index \( \Gamma_X \) (bottom) on viscosity \( \alpha \) for two-phase accretion disk models of Janiuk & Czerny (2000). Dotted lines are for a supermassive black hole with \( 10^{10} M_\odot \) and dashed lines for a \( 10^7 M_\odot \) black hole. Points are plotted for accretion rates of 0.01, 0.1, 0.3, 0.5, 0.8 times the Eddington limit.

---

**8. DETECTION OF SDSS 1030+0524 AT \( z = 6.28 \)**

SDSS 1030+0524 is the highest-redshift quasar discovered to date. Becker et al. (2001) present the UV spectrum, which shows very strong absorption just blueward of the Ly\( \alpha \) emission line. They convincingly argue that the absorption is far stronger than what is predicted from a simple extrapolation of the Ly\( \alpha \) forest from lower redshift, so that they have detected a Gunn-Peterson trough. They conclude...
tracts NAS8-39073. Support for this work was provided by the National Aeronautics and Space Administration through Chandra Awards GO-12117B, GO-01015A, and GO-12117A issued by the Chandra X-Ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS 8-39073. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Partial support was provided by NSF program AST 96-17060.

REFERENCES

Akitas, M. G., & Siebert, J. 1996, MNRAS, 278, 919
Avni, Y., & Tananbaum, H. 1981, ApJ, 245, 574
Boller, T., Brandt, W. N., & Fink, H. 1996, A&A, 305, 821
Chen, D., & Bingemans, R. 1999, ApJ, 520, L13
Crenshaw, D. M. 1986, ApJS, 62, 821
Dickson, E. S., Weir, N., Fayyad, U., & Roden, J. 1995a, AJ, 110, 78
Dickson, E. S., Weir, N., Fayyad, U., & Roden, J. 1995b, AJ, 110, 78
Dopita, M. A., & Sutherland, P. 1995, ApJ, 446, L105
Fabian, A. C., Brandt, W. N., McMahon, R. G., & Hook, I. M. 2001, MNRAS, 322, L1
Feigelson, E. D., & Nelson, P. I. 1985, ApJ, 293, 192
Forster, K., Green, P. J., Aldcroft, T. L., Vestergaard, M., Foltz, C. B., & Hewett, P. C. 2001, ApJS, 134, 35
Giacconi, R., Trümper, J., & Zamorani, G. 1998, AJ, 115, 1230
Henry, J. P., et al. 1994, AJ, 107, 1270
Hewett, P. C., Foltz, C. B., & Chaffee, F. H. 1995, AJ, 109, 1498
Hill, G. J., Thompson, K. L., & Elvis, M. 1993, ApJ, 414, L1
Hook, I. M., & McMahon, R. G. 1998, MNRAS, 294, L7
Kelling, J. D., & Carvalho, R. R., Jogłowski, S. G., Wilger, M. M., Dickson, E. S., Weir, N., Fossey, U., & Roden, J. 1995a, AJ, 110, 78
Kennefick, J. D., Jogłowski, S. G., & Carvalho, R. R. 1995b, AJ, 110, 2553
Kuhn, O., Elvis, M., Bechtold, J., & Elvis, M. 2001, ApJS, 136, 225
Kurpiewski, A., & Janiuk, A. 1999, A&A, 346, 715
Malkan, M. A. 1991, in IAU Colloq. 129, Structure and Emission Properties of Accretion Disks, ed. C. Bertout, S. Collin-Souffrin, J.-P. Lasota, and J. Trümper (Versailles: Editions Frontieres), 165
Mathur, S. 2001, AJ, 122, 1688
Mathur, S., & Elvis, M. 1995, AJ, 110, 1551
Mayer, M., Wilkes, B. J., & Elvis, M. 2002, ApJ, 570, L5
McIntosh, D. H., Rieke, M. J., Rix, H.-W., Foltz, C. B., & Weymann, R. J. 1999, ApJ, 514, 40
Miller, P., Rawlings, S., Saunders, R., & Eales, S. 1992, MNRAS, 254, 93
Nishihara, E., Yamashita, T., Watanabe, E., Okumura, S., Mouri, A., & Iye, M. 1997, ApJ, 488, L27
Peacock, J. A. 1999, Cosmological Physics (Cambridge: Cambridge Univ. Press).
Pe´roux, C., Storrie-Lombardi, L. J., McMahon, R. G., Irwin, M., & Hook, I. M. 2001, AJ, 121, 1799
Peterson, B. M., & Wandel, A. 1999, ApJ, 521, L95
Pickering, T. E., Impey, C. D., & Foltz, C. B. 1994, AJ, 108, 1504
Reeves, J. N., & Turner, M. J. L. 2000, MNRAS, 316, 234
Rokaki, E., Boisson, C., & Collin-Souffrin, S. 1992, A&A, 253, 57
Różańska, A., & Czerny, B. 2000, MNRAS, 316, 473
Schmidt, M., & Green, R. F. 1983, ApJ, 269, 552
Schneider, D. P., & Schmidt, M. 1985, ApJ, 288, 106
Sun, W.-H., & Malkan, M. A. 1989, ApJ, 346, 68
Wandel, A. 1999, ApJ, 527, 649
Wandel, A., & Boller, T. 1998, A&A, 331, 884
Wandel, A., & Peterson, B. M., & Malkan, M. A. 1999, ApJ, 526, 579
Wandel, A., & Petrov, S. 1998, ApJ, 329, L11
Wannier, G. W., Hewett, P. C., Irwin, M. J., McMahon, R. G., & Bridgeland, M. T. 1987, Nature, 325, 131
Weisskopf, M. C., & O'Dell, S. L. 1997, Proc. SPIE, 3113, 2
Williams, G. W., Baldwin, J. A., Carswell, R. F., Cooke, A. J., Hazard, C., McNamara, B. R., & Eddy, S. 1990, AJ, 109, 2454
Zickgraf, F.-J., Voges, W., Kretzschmar, T., Thiering, I., Appenzeller, I., Mujica, R., & Serrano, A. 1997, A&A, 323, L21