THE X-RAY SPECTRUM OF THE \( z = 6.30 \) QSO SDSS J1030+0524

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ABSTRACT

We present a deep XMM-Newton observation of the \( z = 6.30 \) QSO SDSS J1030+0524, the second most distant quasar currently known. The data contain sufficient counts for spectral analysis, demonstrating the ability of XMM-Newton to measure X-ray spectral shapes of \( z \sim 6 \) QSOs with integration times \( \geq 100 \) ks. The X-ray spectrum is well fitted by a power law with index \( \Gamma = 2.12 \pm 0.11 \), an optical–X-ray spectral slope of \( \alpha_{ox} = -1.80 \), and no absorption excess to the Galactic value, although our data are also consistent with a power-law index in the range \( 2.02 < \Gamma < 2.5 \) and excess absorption in the range \( 0 < N_H (\text{cm}^{-2}) < 8 \times 10^{22} \). There is also a possible detection (\( \sim 2 \sigma \)) of FeK\( \alpha \) emission. The X-ray properties of this QSO are, overall, similar to those of lower redshift radio-quiet QSOs. This is consistent with the statement that the X-ray properties of radio-quiet QSOs show no evolution over \( 0 < z < 6.3 \). Combined with previous results, this QSO appears indistinguishable in any way from lower redshift QSOs, indicating that QSOs comparable to those seen locally existed less than 1 Gyr after the big bang.

Subject headings: cosmology: observations — galaxies: formation — galaxies: high-redshift — quasars: individual (SDSS J1030+0524) — X-rays: galaxies

1. INTRODUCTION

One of the most important goals in modern cosmology is to understand the formation of galaxies and large-scale structures. According to the currently prevalent theory for structure formation, biased hierarchical buildup within the \( \Lambda \)CDM framework (hereafter referred to as \( \Lambda \)CDM), the growth of large galaxies results from mergers between smaller systems, with more massive galaxies hosted within more massive dark matter halos, themselves the rarest, most biased overdensities in the underlying mass distribution. Observations of QSOs and other massive systems are thus an excellent way of testing structure formation models. This is particularly apposite for QSOs at very high redshifts, where the added constraint of the youth of the cosmos allows for the most stringent tests. The discovery (Fan et al. 2001, 2003) from the Sloan Digital Sky Survey of QSOs at \( z > 6 \), when the universe was (under any currently favored cosmology) less than 1 Gyr old, presents the opportunity to perform such tests. The first step is to determine the nature of the central engines in these QSOs, as \( \Lambda \)CDM models generally extrapolate the host halo mass from the central black hole mass (Haehnelt et al. 1998). This is readily achieved using X-ray observations, which directly probe the central engines of QSOs, largely free of obscuration bias. Deep X-ray observations of \( z > 6 \) QSOs, to measure their X-ray spectral shapes and luminosities, can therefore be used to examine the properties of their central black holes and to compare to the X-ray properties of lower redshift QSOs to search for drivers behind the strong evolution of the QSO luminosity function (Boyle et al. 2000).

One such QSO is SDSS J1030+0524 at \( 10^\circ30'27.1'', +05^\circ24'55.0'' (J2000.0) \), with a redshift of \( z = 6.30 \) (Richards et al. 2004). Deep imaging observations show that this QSO is not significantly lensed (Richards et al. 2004) or beamed (Haiman & Cen 2002) and that the rest-frame optical continuum shape and luminosity are probably similar to those of lower redshift QSOs (Fan et al. 2001). The rest-frame UV spectrum shows an almost complete Gunn-Peterson trough, indicating that this QSO lies within the epoch of reionization (Becker et al. 2001). Further observations found evidence for supersolar metallicities (Pentericci et al. 2002; Freudling et al. 2003) and indirect evidence for a formed host galaxy (Barkana & Loeb 2003). Although not detected in the submillimeter (Priddey et al. 2003), the radio (Petric et al. 2003), or the ROSAT all-sky survey, this QSO is detected in Chandra snapshot observations (Brandt et al. 2002). In this Letter, we present deep XMM-Newton observations of SDSS J1030+0524. We assume \( \Omega = 1 \), \( \Lambda = 0.7 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. OBSERVATIONS AND ANALYSIS

SDSS J1030+0524 was observed continuously by XMM-Newton for 105 ks in 2003 May. The source was placed on-axis and observed by all the onboard instruments, although we only consider data from the European Photon Imaging Counter (EPIC) metal oxide semiconductor (MOS) and pn cameras here. The data were reduced using the XMM Science Analysis System version 6.0 package. The event lists were filtered to include only single and double events (patterns 0–4 for the pn and 0–12 for the MOS) with quality flag 0 and to remove time periods during which the background was excessively high owing to proton flares. Light curves were extracted using the whole MOS and pn fields of view to check that all the flaring background periods had been removed. The resulting effective exposure time was \( \sim 75 \) ks. The source spectrum was extracted using a circular aperture of radius 45” centered on the source, and the
background spectrum was extracted from a contiguous region free from sources and with the same instrumental background as our target. Additional light curves were extracted from the same region as the source spectra to search for short-term variability from the QSO. Spectral analysis was performed using the XSPEC version 11.3 package (Arnaud 1996), using spectra binned to have at least 20 counts per bin.

3. RESULTS

Before undertaking detailed analysis, we checked for consistency between the three EPIC detectors by fitting the MOS and pn spectra with single–power-law models. The derived photon indices and normalizations agreed to within 0.25 and pn spectra with single–power-law models. The derived consistency between the three EPIC detectors by fitting the MOS binned to have at least 20 counts per bin.

The X-ray spectrum of SDSS J1030+0524 is presented in Figure 1. The final spectrum contained ~560 counts in total, where 340 were detected by the pn camera and 220 by the two MOS cameras. A summary of the results from spectral fitting is given in Table 1. For all fits, we assumed a Galactic hydrogen column of $3.2 \times 10^{20}$ cm$^{-2}$ (Stark et al. 1992). We first considered a single–power-law model. This gave a reasonable fit to the combined spectrum with a photon index of $\Gamma = 2.12 \pm 0.11$. We speculate that the excess flux between 0.9 and 1.0 keV may arise from a complex of iron emission features (6.4–7.0 keV rest frame); however, the flux in this bin is only 2.1 $\sigma$ above the power-law fit; we cannot therefore confirm or refute this without higher quality data. We also derived the value of $\alpha_{\text{ox}}$, the slope of a nominal power law between 2500 Å and 2 keV. Using both the 2500 Å flux and the method to compute $\alpha_{\text{ox}}$ described by Brandt et al. (2002), together with our X-ray data, yields $\alpha_{\text{ox}} = -1.80$. No short-term variability in the X-ray emission was detected in any band, although given the low count rates in both EPIC detectors this is not unexpected.

Previous studies (Reeves & Turner 2000, although see also Vignali et al. 2003b) have found possible evidence for increasing absorption with increasing redshift in QSO X-ray spectra, rising from $\sim 10^{20}$ cm$^{-2}$ at $z \sim 0.1$ to $\sim 10^{22}$ cm$^{-2}$ at $z \sim 2$. It is plausible therefore that the X-ray emission from SDSS J1030+0524 is attenuated by absorption local to the QSO. A modest amount of excess absorption might be expected on the grounds that the Ly$\alpha$ emission shows some H i absorption (Barkana & Loeb 2003), although if the absorption is due to shocked material accreting onto the host galaxy halo it may not have sufficient heavy-element content to produce appreciable X-ray absorption. We consider three power-law plus absorption scenarios: a model where both $\Gamma$ and $N_H$, a model where the power-law slope is fixed at $\Gamma = 2$, and a model where the hydrogen column is fixed at $N_H = 10^{22}$ cm$^{-2}$. In the case where $N_H$ is fixed, the derived photon index, at $\Gamma = 2.27 \pm 0.2$, lies within 1 $\sigma$ of the photon index derived assuming zero intrinsic absorption. In the two cases where $N_H$ is allowed to vary, the best-fit values of $N_H$, although statistically consistent with zero, have errors too large to allow an accurate hydrogen column to be quoted. We can, however, explore the range of acceptable values. A confidence plot of $\Gamma$ versus hydrogen column for the fit in which both $\Gamma$ and $N_H$ are allowed to vary is shown in Figure 2. Based solely on this plot, we would quote 1 $\sigma$ ranges of 2.02 $\leq \Gamma \leq$ 2.6 and $0 < N_H(\text{cm}^{-2}) < 9 \times 10^{22}$. A hydrogen column above $\sim 8 \times 10^{22}$ cm$^{-2}$, however, requires $\Gamma > 2.5$; this is significantly higher than for any other observed QSO (see, e.g., Reeves & Turner 2000), although such steep slopes are seen in Seyfert galaxies (Walter & Fink 1993). We therefore quote the “best-

![Image](image1.png)

**Fig. 1.**—EPIC pn spectrum of SDSS J1030+0524 plus a single–power-law fit and fit residuals with absorption fixed at the Galactic value. The MOS spectra have not been plotted for clarity.

![Image](image2.png)

**Fig. 2.**—Confidence plot of $\Gamma$ vs. $N_H$ (units are $10^{22}$ cm$^{-2}$) from the fit where both parameters are allowed to vary. Contours are 1 $\sigma$, 2 $\sigma$, and 3 $\sigma$.

| Model                        | $\chi^2$/dof | $\Gamma$ | $N_H$ (10$^{22}$ cm$^{-2}$) | $f_{5.3-12}$ | $f_{5.3-2}$ | $f_{5-10}$ | $L_{5-10}$ |
|------------------------------|--------------|----------|-----------------------------|-------------|-------------|------------|------------|
| Power law                    | 1.50/24      | 2.12     | $\pm 0.11$                 | 13.70       | 6.28        | 6.73       | 0.17       | 2.87       |
| Power law plus absorption    | 1.51/23      | 2.27     | $\pm 0.19$                 | 12.98       | 6.49        | 5.96       | 0.04       | 2.75       |
| $\Gamma = 2$ power law plus absorption | 1.57/24 | 2.00 | $\pm 0.04$ | 2.78 $\pm 2.97$ | 6.19 | 7.92 | 0.14 | 2.68 |
| Power law plus fixed absorption | 1.48/24   | 2.18     | $\pm 0.11$                 | 13.38       | 6.36        | 6.40       | 0.10       | 2.82       |

*Notes:* All fits include a Galactic column of $3.2 \times 10^{20}$ cm$^{-2}$. Quantities in bold are fixed during fitting. Fluxes are quoted in the observed frame and are in units of $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$. Luminosities are quoted in the rest frame and are in units of $10^{45}$ ergs s$^{-1}$.

**TABLE 1**

Results from Fitting the X-Ray Spectrum of SDSS J1030+0524
The advent of XMM-Newton and Chandra have revolutionized X-ray studies of high-redshift QSOs. Currently, detailed X-ray spectral information is available for a large sample of QSOs in the redshift range $0 < z < 5$ (Laor et al. 1997; Reeves & Turner 2000; Reeves et al. 2001; Ferrero & Brinkmann 2003; Vignali et al. 2003b; Grube et al. 2004). We first compare results from these studies to the X-ray properties of SDSS J1030+0524. Our best-fit spectral index, at $\Gamma = 2.12 \pm 0.11$, lies near the middle of the range of values of $\Gamma$ found for lower redshift RQQs studied with ASCA (Reeves & Turner 2000) and is comparable to the values of $\Gamma$ derived for $z \sim 4$ RQQs from XMM-Newton observations (Ferrero & Brinkmann 2003; Grube et al. 2004). The derived rest-frame luminosity (which has a total 1 $\sigma$ uncertainty of $\sim$15%) is approximately 1.5 times and 3 times higher than those derived from Chandra observations by Mathur et al. (2002) and Brandt et al. (2002), respectively (who assume $\Gamma = 2.0$). We attribute this difference to the lower signal-to-noise ratio of the Chandra data rather than the difference in values of $\Gamma$, although variability is also a possibility and one that our data do not allow us to test for. Our 2–10 keV luminosity is, however, comparable to lower redshift RQQs (Reeves & Turner 2000) and marks SDSS J1030+0524 as being no more than averagely luminous in the X-ray. Our value for the optical–X-ray spectral slope, $\alpha_{\text{ox}} = -1.80$, is well within the observed range for lower redshift RQQs and is statistically identical to the mean value of $\alpha_{\text{ox}}$ for $z \sim 4$ RQQs (Vignali et al. 2003a). Overall, therefore, the X-ray luminosity and spectral shape of SDSS J1030+0524 appear to be indistinguishable from those of RQQs at $0 < z < 5$ (see, e.g., Fig. 8 of Vignali et al. 2003b). Although statistics based on one object are obviously not trustworthy, this result is consistent with the statement that the X-ray properties of optically selected RQQs show no evolution up to $z = 6.3$. The only exceptions would be if (1) this QSO has a very steep intrinsic X-ray spectrum attenuated by heavy absorption—but such systems are rare among the RQQ population—and (2) the marginal excess flux in the 0.9–1.0 keV energy range really is FeKα emission—but this is very rare in QSOs generally. Iron K emission from QSOs and Seyfert galaxies is thought to arise either from a cold reflected component from the accretion disk (for line widths $\sim 50$ eV) or from hot gas in a halo (for line widths $\gtrsim 100$ eV; in this case, we might also expect to see significant thermal X-ray emission). The detection of iron K lines in SDSS J1030+0524 would therefore be especially interesting, but given the quality of our data we do not consider this further.

We can combine this result with previous studies of SDSS J1030+0524 to establish whether its global properties differ from lower redshift RQQs. As described previously, this QSO does not appear to be significantly magnified by lensing (Richards et al. 2004). Together with its measured X-ray luminosity and the spectral shape, this constitutes compelling evidence that the mass estimate of $\sim 2 \times 10^{10} M_\odot$ for the central black hole derived from the 1450 Å magnitude (Fan et al. 2001) is accurate. Considered together with previous observations (see § 1 for a review), SDSS J1030+0524 appears to be indistinguishable in any way from the lower redshift RQQ population. The very existence of such a system only 860 Myr (under our cosmology) after the big bang poses a significant challenge for structure formation theories, and it is this theme we explore in the remainder of this discussion.

To explain the existence of SDSS J1030+0524 requires the formation of an $\sim 10^9 M_\odot$ black hole and probably also an $\sim 10^{10} M_\odot$ dark matter halo (e.g., Haehnelt et al. 1998) and $\sim 10^{11} M_\odot$ of stars (Maccarone et al. 1998), all within 860 Myr. The formation of a suitably massive halo is readily achieved within the ΛCDM framework (Mo & White 2002), and simulations predict that the mass profiles in the inner 10 $h^{-1}$ kpc of the most massive halos evolve very little at $z \lesssim 6$ (Fukugita & Makino 2001; Gao et al. 2004). These simulations, however, only consider the hydrodynamical evolution of the dark matter distribution and do not consider the astrophysical processes of star and black hole formation. The formation of the stars and central black hole must therefore be considered separately. There is evidence, both from observations of old elliptical galaxies at $z = 1.5$ (Peacock et al. 1998) and from the observed upper bound on the line-of-sight velocity dispersions of stars in elliptical galaxies (Loeb & Peebles 2003), that ΛCDM must be capable of forming the stars in a giant elliptical galaxy in
less than 1 Gyr. This requires (for example) a “burst” of 1000 $M_\odot$ yr$^{-1}$ star formation lasting ~100 Myr. Such high instantaneous star formation rates are inferred to exist in the $1 < z < 4$ submillimeter survey sources (e.g., Borys et al. 2003) and in $z \gtrsim 4$ QSOs (Isaak et al. 2002), and 100 Myr is a reasonable upper age limit for starbursts based on observations of local starbursts (Farrah et al. 2003). To form the host galaxy of SDSS J1030+0524 therefore appears feasible, although this inference is based on observations of lower redshift systems, and we note that the upper limit on the submillimeter flux from SDSS J1030+0524 (Priddey et al. 2003) implies an upper limit on the instantaneous star formation rate of 300 $M_\odot$ yr$^{-1}$. The formation of the central black hole is, however, more difficult to explain. If we assume Eddington-limited exponential growth, then a 10$^9 M_\odot$ black hole can grow from a 100 $M_\odot$ “seed” black hole in ~725 Myr; however, the likelihood that the accretion rate is “fine-tuned” to the Eddington limit for many e-foldings appears small, especially considering the role of feedback from the formation of stars in the host galaxy (Burkert & Silk 2001). It seems therefore that, unless the accretion rate exceeded the Eddington limit for some period of time, or the QSO luminosity currently exceeds the Eddington limit, accretion onto an initially stellar mass black hole is unlikely to produce the central black hole in SDSS J1030+0524 within the required timescale and that a significant fraction of the black hole mass must be built via some other mechanism. We briefly mention two of a variety of possibilities (Rees 1984; Haiman & Quataert 2004) here. The first is that a more massive seed black hole could form as result of collision runaway in dense young star clusters (Portegies Zwart et al. 2004; Gurkan et al. 2004), which can produce “intermediate”-mass black holes of several thousand solar masses on rapid timescales. Another possibility is that mergers between ~100 $M_\odot$ black holes created in supernovae of high-mass Population III stars contribute to the buildup of more massive black holes. Numerical simulations (Abel et al. 2002) suggest that one ~100 $M_\odot$ star could form rapidly in each ~10$^9 M_\odot$ ΛCDM “minihalo.” Population III stars are not expected to lose much mass in the final stages of stellar evolution and may thus be expected to form black holes of ~100 $M_\odot$ in less than 1 Myr. A fraction of these black holes are predicted to be driven to the inner regions of larger galaxies by ongoing mergers (Madau & Rees 2001). The space density and the further fate of these black holes is uncertain, but it is at least plausible that mergers between these black holes first form intermediate mass black holes, which then contribute to the buildup of the ~10$^9 M_\odot$ black holes in $z > 6$ QSOs by a mixture of further merging and accretion (Volonteri et al. 2003).

In summary, there is observational and theoretical evidence that the host halo, stellar mass, and central black hole required to make a fully formed QSO can form in less than a gigayear. The existence, however, of an RQQ at $z = 6.3$ that appears indistinguishable from other RQQs at lower redshifts is still surprising, and the most pressing, and as yet unanswered, question is whether the formation of the halo, stars, and central black hole in an object such as SDSS J1030+0524 can be accomplished together in less than a gigayear in the ΛCDM framework.

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