X-rays from the Dawn of the Modern Universe. Chandra and XMM-Newton Observations of $z > 4$ Quasars

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Abstract. Quasars at $z > 4$ provide direct information on the first massive structures to form in the Universe. Recent ground-based optical surveys (e.g., the Sloan Digital Sky Survey) have discovered large numbers of high-redshift quasars, increasing the number of known quasars at $z > 4$ to $\approx 500$. Most of these quasars are suitable for follow-up X-ray studies. Here we review X-ray studies of the highest redshift quasars, focusing on recent advances enabled largely by the capabilities of Chandra and XMM-Newton. Overall, analyses indicate that the X-ray emission and broad-band properties of high-redshift and local quasars are reasonably similar, once luminosity effects are taken into account. Thus, despite the strong changes in large-scale environment and quasar number density that have occurred from $z \approx 0–6$, individual quasar X-ray emission regions appear to evolve relatively little.

1. Introduction

Our knowledge of the X-ray properties of quasars at $z > 4$ has advanced rapidly over the past few years. In particular, the Sloan Digital Sky Survey (SDSS; e.g., York et al. 2000) has generated large and well-defined samples of $z > 4$ quasars (e.g., Anderson et al. 2001); most of these quasars are suitable for X-ray studies. The X-ray observational strategy has comprised archival studies of high-redshift quasars with ROSAT (Kaspi, Brandt, & Schneider 2000; Vignali et al. 2001, hereafter V01), snapshot $(\approx 4–10 \text{ ks})$ observations with Chandra to define basic quasar X-ray properties such as fluxes and luminosities (e.g., V01; Brandt et al. 2002, 2003; Bechtold et al. 2003; Vignali et al. 2003a,b, hereafter V03a, V03b) and longer observations with XMM-Newton to derive either tight constraints on the X-ray emission (e.g., Brandt et al. 2001) or spectral parameters by direct X-ray fitting (Ferrero & Brinkmann 2003; Grupe et al. 2004). Chandra snapshot observations have also allowed joint spectral fitting of subsamples of quasars drawn from two main samples at $z > 4$: the optically luminous Palomar Digital Sky Survey (e.g., Djorgovski et al. 1998) and the SDSS. The X-ray spectral results provide no evidence of strong spectral evolution
in radio-quiet quasar (RQQ) X-ray emission from local samples up to \( z \approx 5 \); the spectrum at high redshift is well parameterized by a power law in the \( \approx 2–40 \) keV rest-frame band with \( \Gamma = 1.8–2 \) (V03a; V03b). Furthermore, no evidence for widespread intrinsic X-ray absorption has been found, although it seems likely that a few individual objects may be X-ray absorbed (e.g., V01; V03b). These overall results have been supported recently by direct X-ray spectroscopy of QSO 0000–263 at \( z = 4.10 \) with XMM-Newton (Ferrero & Brinkmann 2003).

The color selection of the SDSS has been proven to be effective in finding high-redshift optically luminous quasars up to \( z \approx 5.7 \) (see Fan et al. 2003 for SDSS quasars at higher redshifts). On the other hand, moderately deep Chandra observations and the ultra-deep (2 Ms) survey of the Chandra Deep Field-North (CDF-N; Alexander et al. 2003) can detect Active Galactic Nuclei (AGN) at \( z > 4 \) that are typically \( \gtrsim 10–30 \) times less luminous than the SDSS quasars (e.g., Barger et al. 2002; Silverman et al. 2002; Vignali et al. 2002, hereafter V02; Castander et al. 2003). These AGN are much more numerous and therefore more representative of the AGN population at high redshift than the rare SDSS quasars; however, their X-ray emission does not appear to contribute significantly to reionization at \( z \approx 6 \) (Barger et al. 2003). A detailed X-ray spectral analysis of the \( z > 4 \) AGN in the CDF-N is presented in V02.

Below we present some new X-ray spectral results obtained by joint spectral fitting of all the RQQs at \( z > 4 \) thus far detected by Chandra. A spectral analysis performed on a smaller but more X-ray luminous sample of \( z > 4 \) radio-loud quasars is presented by Bassett et al. (in preparation).

2. Joint X-ray Spectral Results

To define the overall X-ray properties of \( z > 4 \) RQQs, we selected all of the RQQs detected by Chandra with \( > 2 \) counts in the observed 0.5–8 keV band. The sample comprises 46 quasars with a median redshift of 4.43; the number of source counts is \( \approx 750 \). Note that these quasars represent a large fraction \( (\approx 70\%) \) of the optically selected RQQs at \( z > 4 \) with X-ray detections at present.\(^1\) Although it is possible that individual objects are characterized by “peculiar” X-ray properties, our approach obtains average spectral parameters for the quasar population at \( z > 4 \) using a much larger sample than those presented in V03a and V03b. In the X-ray spectral analysis, the Cash statistic (Cash 1979) has been adopted. Our preliminary analysis shows that a power law fits the X-ray data reasonably well; the photon index in the rest-frame \( \approx 2–40 \) keV band is \( \Gamma = 1.9 \pm 0.1 \) (see Fig. 1). This is consistent with previous results obtained for RQQ samples at high redshift observed with Chandra (V03a; V03b) and XMM-Newton (Ferrero & Brinkmann 2003; Grupe et al. 2004), as well as with quasar X-ray spectral results at low and intermediate redshift (e.g., George et al. 2000; Page et al. 2003). Our analyses indicate that the X-ray spectral properties of \( z > 4 \) RQQs and local RQQs are similar; the only significant differences have been found in their broad-band properties using the

\(^1\)See http://www.astro.psu.edu/users/niel/papers/highz-xray-detected.dat for a regularly updated listing of X-ray detections and sensitive upper limits at \( z > 4 \).
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46 RQQs [z=4.0−6.3]
~750 source counts

Figure 1. Combined spectrum of $z > 4$ RQQs detected by Chandra with $> 2$ counts in the observed 0.5–8 keV band. The spectrum shown here (only for presentation purposes) is fitted with a power-law model and Galactic absorption (see the text for details).

SDSS Early Data Release quasar catalog (Schneider et al. 2002) and are likely due to luminosity effects (Vignali, Brandt, & Schneider 2003; see also Brandt, Schneider, & Vignali, these proceedings). Thus, despite the strong changes in large-scale environment and quasar number density that have occurred from $z \approx 0–6$, individual quasar X-ray emission regions appear to evolve relatively little. From the joint X-ray spectral fitting we also find no significant evidence for absorption above the Galactic value; the upper limit in the source rest frame is $N_H < \sim 9 \times 10^{20}$ cm$^{-2}$ (see Vignali et al., in preparation, for detailed discussion).

3. The Future

The correlation found between quasar AB magnitude at a rest-frame wavelength of 1450 Å and the observed 0.5–2 keV flux (e.g., V03b) is a powerful tool to select samples of $z > 4$ quasars suitable for follow-up X-ray observations. The combination of snapshot observations with Chandra and longer exposures with XMM-Newton should continue to be highly effective in allowing the study of the overall X-ray properties of quasars at high redshift. In the coming years, as the SDSS is completed and several thousand Chandra and XMM-Newton archival observations become available to the scientific community, our knowledge of the broad-band properties of quasars at the highest redshifts will significantly increase. However, detailed X-ray spectroscopic analyses of large samples of $z > 4$ quasars must await the more distant future and X-ray missions such as Constellation-X, XEUS, and Generation-X.
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