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X-RAY EMISSION FROM THE FIRST QUASARS

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ABSTRACT

It is currently unknown whether the Universe was reionized by quasars or stars at $z \gtrsim 5$. We point out that quasars can be best distinguished from stellar systems by their X-ray emission. Based on a simple hierarchical CDM model, we predict the number counts and X-ray fluxes of quasars at high redshifts. The model is consistent with available data on the luminosity function of high-redshift quasars in the optical and soft X-ray bands. The cumulative contribution of faint, undetected quasars in our model is consistent with the unresolved fraction of the X-ray background. We find that the *Chandra X-ray Observatory* might detect $\sim 10^2$ quasars from redshifts $z \gtrsim 5$ per its $17' \times 17'$ field of view at the flux threshold of $\sim 2 \times 10^{-16}$ erg s⁻¹ cm⁻². The redshifts of these faint point-sources could be identified by follow-up infrared observations from the ground or with the *Next Generation Space Telescope*.

Subject headings: cosmology: theory – quasars: general – black hole physics

1. INTRODUCTION

Cold dark matter (CDM) cosmologies predict that the first baryonic objects appeared near the Jeans mass ($\sim 10^6 M_\odot$) at redshifts as high as $z \sim 30$, and larger objects assembled later (Haiman & Loeb 1999b, and references therein). It is natural to identify these objects as the sites where the first stars or quasar black holes formed. Observationally, bright quasars are currently detected out to $z \sim 5$ (Fan et al. 1999), and galaxies out to $z \sim 6.7$ (Chen et al. 1999; Weymann et al. 1998). Although the abundance of optically and radio bright quasars declines at $z \gtrsim 2.5$ (Schmidt et al. 1995; Pei 1995; Shaver et al. 1996), simple models based on the Press–Schechter formalism reproduce this decline and simultaneously predict a population of low-luminosity quasars that are too faint to be detected in current surveys (Haiman & Loeb 1998; Haehnelt et al. 1998). Preliminary evidence for such a population might already be indicated by the X-ray luminosity function (LF) of quasars recently measured by ROSAT (Miyaji et al. 1998a). The X-ray data probes fainter quasars than the optical data does, and has not revealed a decline in the abundance of high-redshift quasars as found in the optical (e.g. Schmidt et al. 1995).

The current census of high-redshift galaxies provides an estimate of the global evolution of the star formation rate (SFR) in the redshift range $0 \leq z \lesssim 5$ (Madau 1999). Nevertheless, there is still considerable uncertainty about the evolution of the SFR at the highest redshifts probed ($z \gtrsim 3$). Recent sub-mm observations from SCUBA indicate the existence of a substantial population of dust-obscured star-forming galaxies that could raise the implied SFR at high redshift (Barger et al. 1999, and references therein). This uncertainty is particularly important, since it leaves open the question of whether the observed population of stars produce sufficient ionizing radiation by $z \sim 5$

to reionize the intergalactic medium (IGM). The indication from the present data is that the SFR either declines or remains roughly constant at $z \gtrsim 3$; however, in order to satisfy the Gunn–Peterson constraint for the ionization of the IGM, the SFR needs to rise at high redshifts above its value at $z \sim 3$ (Madau 1999).

The presence of a substantial population of faint quasars at $z \gtrsim 5$ is therefore consistent with current data, and is suggested by cosmological models for hierarchical structure formation. If future data would indicate a non-increasing cosmic SFR at $z \gtrsim 3$, then quasars would be the likely sources of reionization. Recent theoretical models have focused on the properties of the quasar population in the optical (Haehnelt & Rees 1993; Haiman & Loeb 1998; Haehnelt et al. 1998), and in the infrared (e.g. Sanders 1999; Almaini et al. 1999). These models were shown to be only mildly constrained by the lack of $z \gtrsim 3.5$ quasars in the Hubble Deep Field (HDF; see Haiman, Madau & Loeb 1999).

In this *Letter* we point out that quasars can be best distinguished from star forming galaxies at high redshifts by their X-ray emission. First, we illustrate the agreement between our simplest hierarchical model for quasars and existing ROSAT data on the X-ray LF (Miyaji et al. 1998a) and the soft X-ray background (XRB; Miyaji et al. 1998b). We then show that forthcoming X-ray observations with the *Chandra X-ray Observatory* (CXO; formerly known as AXAF) will be able to probe the abundance of quasars during the reionization of the Universe at $z \gtrsim 5$.

2. MODEL DESCRIPTION AND QUASAR SPECTRA

Our model is based on the Press–Schechter mass function of CDM halos (see Haiman & Loeb 1998 for complete details). We assume that each halo of mass M_{halo} forms a

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central black hole of mass M_{bh} . The black hole mass fraction $r \equiv M_{\text{bh}}/M_{\text{halo}}$ is assumed to obey a log-Gaussian probability distribution

$$p(r) = \exp[-(\log r - \log r_0)^2/2\sigma^2] \quad (1)$$

with $\log r_0 = -3.5$ and $\sigma = 0.5$ (Haiman & Loeb 1999b). These values roughly reflect the distribution of black hole to bulge mass ratios found in a sample of 36 local galaxies (Magorrian et al. 1998) for a baryonic mass fraction of $\sim (\Omega_{\text{b}}/\Omega_0) \approx 0.1$. We further postulate that each black hole emits a time-dependent bolometric luminosity in proportion to its mass, $L_{\text{q}} \equiv M_{\text{bh}} f_{\text{q}} = M_{\text{bh}} L_{\text{Edd}} \exp(-t/t_0)$, where $L_{\text{Edd}} = 1.5 \times 10^{38} M_{\text{bh}}/M_{\odot} \text{ erg s}^{-1}$ is the Eddington luminosity, t is the time elapsed since the formation of the black hole, and $t_0 = 10^6 \text{ yr}$ is the characteristic quasar lifetime. Finally, we assume that the shape of the emitted spectrum follows the mean spectrum of the quasar sample in Elvis et al. (1994) up to a photon energy of 10 keV. We extrapolate the spectrum up to $\sim 50 \text{ keV}$, assuming a spectral slope of $\alpha=0$ (or a photon index of -1).

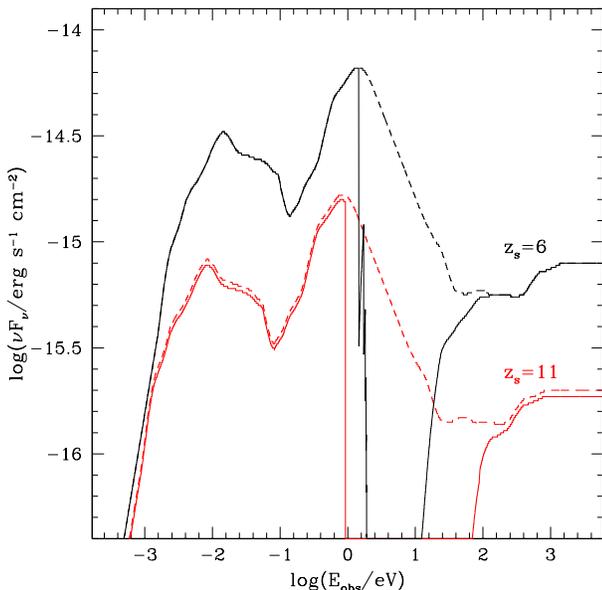


Fig. 1.— The observed spectra of quasars with a central black hole mass of $M_{\text{bh}} = 10^8 M_{\odot}$. The upper curves correspond to a source redshift of $z_{\text{s}} = 6$ and the lower curves to a source redshift of $z_{\text{s}} = 11$. In both cases we assume sudden reionization at $z_{\text{r}} = 10$. The dashed curves show the intrinsic spectral shape, taken from Elvis et al. (1994). We include the opacity of the neutral H and He in the IGM at $z > z_{\text{r}}$ and the opacity due to electron scattering and the (extrapolated) Ly α forest in the IGM at $z < z_{\text{r}}$.

This simple model was demonstrated to accurately reproduce the evolution of the optical luminosity function in the B-band (Pei 1995) at redshifts $z \gtrsim 2.2$ (Haiman & Loeb 1998). Because our model incorporates several simplifying assumptions, we regard it as the minimal toy model which successfully reproduces the existing data. If one of our input assumptions was drastically violated and our model had failed to fit the observed LF, then a modification of its basic ingredients would be needed. In this *Letter*, we focus on the predictions of this minimal model in anticipation of the forthcoming launch of *CXO*; an investigation of a broader range of plausible toy models will be made elsewhere. We adopt the concordance cosmology of

Ostriker & Steinhardt (1995), namely a Λ CDM model with a tilted power spectrum $(\Omega_0, \Omega_{\Lambda}, \Omega_{\text{b}}, h, \sigma_{8h^{-1}}, n) = (0.35, 0.65, 0.04, 0.65, 0.87, 0.96)$.

Figure 1 shows the adopted spectrum of quasars, assuming a black hole mass $M_{\text{bh}} = 10^8 M_{\odot}$, placed at two different redshifts, $z_{\text{s}} = 11$ and $z_{\text{s}} = 6$. In computing the intergalactic absorption, we included the opacity of both hydrogen and helium as well as the effect of electron scattering. We assumed that reionization occurred at $z_{\text{r}} = 10$ and that at higher redshifts the IGM was homogeneous and fully neutral. At lower redshifts, $0 < z < z_{\text{r}}$, we included the hydrogen opacity of the Ly α forest given by Madau (1995), and extrapolated his fitting formulae for the evolution of the number density of absorbers beyond $z = 5$ when necessary. As Figure 1 shows, the minimum black hole mass detectable by the $\sim 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ flux limit of *CXO* (see below) is $M_{\text{bh}} \sim 10^8 M_{\odot}$ at $z = 10$ and $M_{\text{bh}} \sim 2 \times 10^7 M_{\odot}$ at $z = 5$. In our model, the corresponding halo masses are $M_{\text{halo}} \sim 3 \times 10^{11} M_{\odot}$; and $M_{\text{halo}} \sim 6 \times 10^{10} M_{\odot}$; respectively. Although such massive halos are rare, their abundance is detectable in wide-field surveys. Note that an accurate determination of the spectrum below $\sim 0.1 \text{ keV}$ could have provided an estimate of the reionization redshift z_{r} . Unfortunately, this spectral regime suffers from Galactic absorption (O’Flaherty and Jakobsen 1997) and is outside the 0.4–6 keV detection band of *CXO*.

3. THE X-RAY LUMINOSITY FUNCTION

In our model, the X-ray luminosity function at a redshift z [in $\text{Mpc}^{-3} (\text{erg/s})^{-1}$] is given by a sum over halos that formed just before that redshift,

$$\phi(L_X; z) = \int_0^{t(z)} \frac{dt}{f_X f_{\text{q}}(\Delta t)} \left. \frac{d^2 N}{dM_{\text{bh}} dt} \right|_{M_{\text{bh}} = \frac{L_X}{f_X f_{\text{q}}(\Delta t)}} \quad (2)$$

where L_X is the observed X-ray luminosity in the instrument’s detection band (0.5–3 keV for ROSAT and 0.4–6 keV for *CXO*); f_X is the fraction of the quasar’s bolometric luminosity emitted in this band; $d^2 N/dM_{\text{bh}} dt$ is the black halo formation rate, given by a convolution of the Press–Schechter halo mass function with equation (1); and $\Delta t = t(z) - t$ is the time elapsed from a cosmic time t until a redshift z .

Although our model was constructed so as to fit the observed optical LF, Figure 2 demonstrates that it is also in good agreement with the data on the X-ray LF. This implies that the choice of quasar spectrum in our model is reasonable. The solid curve in this figure shows the prediction of equation (2) at $z = 3.5$, near the highest redshift where X-ray data is available. The bottom curve corresponds to a cutoff in circular velocity for the host halos of $v_{\text{circ}} \geq 50 \text{ km s}^{-1}$, which is introduced here in order not to over-predict the number of quasars in the HDF (Haiman, Madau & Loeb 1999). The data points are from recent ROSAT measurements, and the dashed curve in this figure shows a fitting formula from Miyaji et al. (1998). Note that the faintest quasar actually observed has $L_X \lesssim 10^{44} \text{ erg s}^{-1}$, and the fitting formula below this luminosity is highly uncertain. Nevertheless, it is important to remember that our model was calibrated so as to fit

the observed optical luminosity function of quasars; the existence of a population of obscured quasars which are faint in the optical band but bright in X-rays could increase the number counts beyond our model predictions.

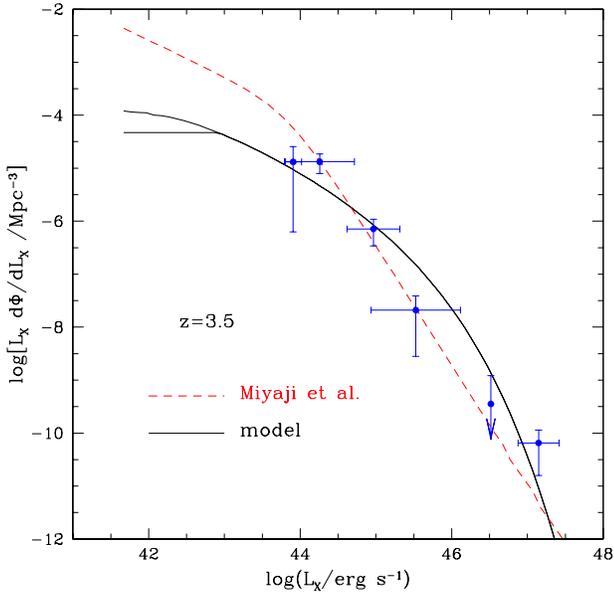


Fig. 2.— The predicted X-ray luminosity function at $z = 3.5$ in our model (solid curves). The lower curve shows the effect of a cutoff in circular velocity for the host halos of $v_{\text{circ}} \geq 50 \text{ km s}^{-1}$. The ROSAT data points are adopted from Miyaji et al. (1998a) and the dashed curve shows their fitting formula (for our background cosmology).

4. THE X-RAY BACKGROUND

Existing estimates of the X-ray background (XRB) provide another useful check on our quasar model. The unresolved background flux at a photon energy E is given by (Peebles 1993)

$$F(E) = c \int_0^\infty dz \frac{dt}{dz} j(E_z, z) \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}, \quad (3)$$

where $E_z = E(1+z)$; and $j(E_z, z)$ is the comoving emissivity at a local photon energy E_z , in units of $\text{keV cm}^{-3} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}$, from quasars shining at a redshift z . This emissivity is a sum over all quasars whose individual observed flux at $z = 0$ is below the ROSAT PSPC detection limit for discrete sources of $2 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Hasinger & Zamorani 1997).

Figure 3 shows the predicted spectrum of the XRB in our model at $z = 0$ (solid lines). In computing the background spectrum, we ignored the HI absorption in the IGM, since it is negligible at energies above 100 eV. We also carried out the integral in equation (3) only for $z > 2$, the redshift range where our model is valid (Haiman & Loeb 1998). The short dashed lines show the predicted fluxes assuming a steeper spectral slope beyond 10 keV ($\alpha = -0.5$, or a photon index of -1.5). The long dashed line shows the 25% unresolved fraction of the soft XRB observed with ROSAT (Miyaji et al. 1998b; Fabian & Barcons 1992). This fraction represents the observational upper limit on the component of the soft XRB that could in principle arise from high-redshift quasars. As the figure

shows, our quasar model predicts an unresolved flux just below this limit in the 0.5–3 keV range. The model also predicts that most ($\gtrsim 90\%$) of this yet unresolved fraction arises from quasars beyond $z = 5$.

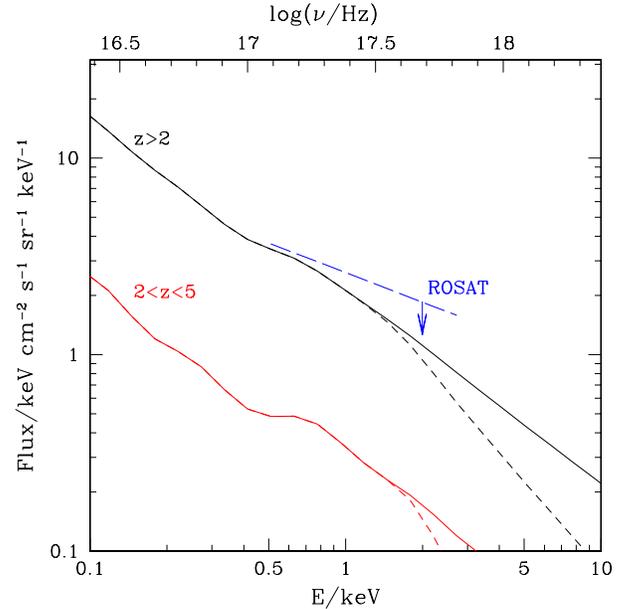


Fig. 3.— Spectrum of the soft X-ray background in our model. We assume that the median X-ray spectrum of each source follows the mean spectrum of Elvis et al. (1994) up to 10 keV, and has a spectral slope of 0.5 (solid lines) or -0.5 (short-dashed lines) at higher photon energies. The lower curves show the spectra resulting from quasars with redshifts between $2 < z < 5$, and the upper curves include contributions from all redshifts $z > 2$. In both cases, we include only quasars whose individual fluxes are below the ROSAT PSPC limit of $2 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ for the detection of a discrete source. The long-dashed line shows the unresolved fraction (assumed to be 25%) of the soft X-ray background spectrum from Miyaji et al. (1998b).

5. PREDICTED NUMBER COUNTS FOR THE CHANDRA X-RAY OBSERVATORY

By summing the luminosity function over redshifts, we obtain the number counts of quasars per solid angle expected to be detectable in a flux interval dF_X around $F_X = L_X / 4\pi d_L^2(z)$, for all sources above a redshift z :

$$\frac{dN}{dF_X d\Omega} = \int_z^\infty dz \left(\frac{dV}{dz d\Omega} \right) \phi(L_X, z) 4\pi d_L^2(z), \quad (4)$$

where $(dV/dz d\Omega)$ is the comoving volume element per unit redshift and solid angle, and $d_L(z)$ is the luminosity distance at a redshift z .

In Figure 4, we show the predicted counts from equation (4) in the 0.4–6 keV energy band of the CCD Imaging Spectrometer (ACIS) of *CXO*. Note that these curves are insensitive to our extrapolation of the template spectrum beyond 10 keV. The figure is normalized to the $17' \times 17'$ field of view of the imaging chips. The solid curves show that of order a hundred quasars with $z > 5$ are expected per field. The abundance of quasars at higher redshifts declines rapidly; however, a few objects per field are still detectable at $z \sim 8$. The dashed lines show the results for a minimum circular velocity of the host halos of $v_{\text{circ}} \geq 100 \text{ km s}^{-1}$, and imply that the model predictions

for the *CXO* satellite are not sensitive to such a change in the host velocity cutoff. This is because the halos shining at the *CXO* detection threshold are relatively massive, $M_{\text{halo}} \sim 10^{11} M_{\odot}$, and possess a circular velocity above the cutoff. In principle, the number of predicted sources would be lower if we had assumed a steeper spectral slope. However, the agreement between the LF predicted by our model at $z \approx 3.5$ and that inferred from ROSAT observations would be upset by such a change, and require a modification of the model that would in turn tend to counter-balance the decrease in the predicted counts.

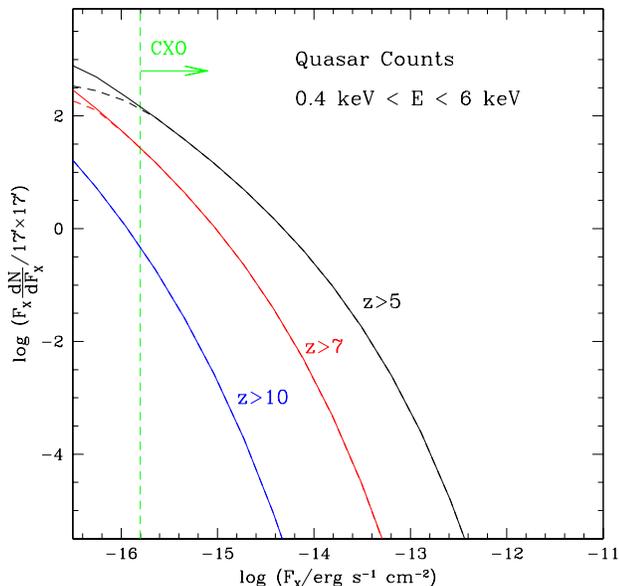


Fig. 4.— The total number of quasars with redshift exceeding $z = 5$, $z = 7$, and $z = 10$ are shown as a function of observed X-ray flux in the *CXO* detection band. The solid curves correspond to a cutoff in circular velocity for the host halos of $v_{\text{circ}} \geq 50 \text{ km s}^{-1}$; the dashed curves to a cutoff of $v_{\text{circ}} \geq 100 \text{ km s}^{-1}$. The vertical dashed line show the *CXO* sensitivity for a 5σ detection of a point source in an integration time of 5×10^5 seconds.

6. DISCUSSION

The existence of quasars at redshifts $z \gtrsim 5$ has important consequences for the reionization history of the Universe. Quasars can be easily distinguished from stellar systems by their X-ray emission. We have demonstrated that state-of-the-art X-ray observations could provide more stringent constraints on quasar models than currently provided by the Hubble Deep Field (Haiman, Madau, & Loeb

1999). In particular, we have found that forthcoming X-ray observations with the *CXO* satellite might detect of order a hundred quasars per field of view in the redshift interval $5 \lesssim z \lesssim 8$. Our numerical estimates are based on the simplest toy model for quasar formation in a hierarchical CDM cosmology, that satisfies all the current observational constraints on the optical and X-ray luminosity functions of quasars. Although a more detailed analysis is needed in order to assess the modeling uncertainties in our predictions, the importance of related observational programs with *CXO* is evident already from the present analysis. Other future instruments, such as the HRC or the ACIS-S cameras on *CXO*, or the EPIC camera on *XMM*, might also be useful in searching for high-redshift quasars.

Follow-up optical and infrared observations are needed in order to identify the redshifts of the faint point-like sources that might be detected by the *CXO* satellite. Quasars emit a broad spectrum which extends into the UV and includes strong emission lines, such as Ly α . For quasars near the *CXO* detection threshold, the fluxes at $\sim 1 \mu\text{m}$ are expected to be relatively high, $\sim 0.5\text{--}0.8 \mu\text{Jy}$. Therefore, infrared spectroscopy of X-ray selected quasars could prove to be a particularly useful approach for unraveling the reionization history of the intergalactic medium at $z \gtrsim 5$ (for the potential lessons to be learned, see Miralda-Escudé 1998; Haiman & Loeb 1999a; Loeb & Rybicki 1999; and Rybicki & Loeb 1999).

At present, the best constraints on hierarchical models of the formation and evolution of quasars originate from the Hubble Deep Field. However, *HST* observations are only sensitive to a limiting magnitude of $V \sim 29$ and cannot probe the earliest quasars. The Next Generation Space Telescope (*NGST*), scheduled for launch in 2008, will achieve nJy sensitivity at wavelengths $1 - 3 \mu\text{m}$, and could directly probe the earliest quasars (Haiman & Loeb 1998). The combination of X-ray data from the *CXO* satellite and infrared spectroscopy from *NGST* could potentially resolve one of the most important open questions about the thermal history of the Universe, namely whether the intergalactic medium was reionized by stars or by accreting black holes.

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