Unresolved X-ray background: clues on galactic nuclear activity at \( z > 6 \)

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ABSTRACT

We study, by means of dedicated simulations of massive black hole build-up, the possibility to constraint the existence and nature of the active galactic nucleus (AGN) population at \( z \gtrsim 6 \) with available and planned X-ray and near-infrared space telescopes. We find that X-ray deep field observations can set important constraints to the faint-end of the AGN luminosity function at very high redshift. Planned X-ray telescopes should be able to detect AGN hosting black holes with masses down to \( \gtrsim 10^5 \) M\(_{\odot}\) (i.e. X-ray luminosities in excess of \( 10^{42} \) erg s\(^{-1}\)), and can constrain the evolution of the population of massive black hole at early times \( \left( 6 \lesssim z \lesssim 10 \right) \). We find that this population of AGN should contribute substantially (\( \sim 25 \) per cent) to the unresolved fraction of the cosmic X-ray background in the 0.5–10 keV range, and that a significant fraction (\( \sim 3–4 \) per cent) of the total background intensity would remain unaccounted even after future X-ray observations. As byproduct, we compute the expected ultraviolet background from AGN at \( z \gtrsim 6 \), and we discuss the possible role of AGN in the reionization of the Universe at these early epochs, showing that AGN alone can provide enough ionizing photons only in the (improbable) case of an almost completely homogeneous intergalactic medium. Finally, we show that super-Eddington accretion, suggested by the observed quasi-stellar objects at \( z \approx 6 \), must be a very rare event, confined to black holes living in the highest density peaks.

Key words: galaxies: evolution – quasars: general – cosmology: theory.

1 INTRODUCTION

The formation of black hole (BH) seeds and their evolution have been the subject of several theoretical investigations. The ‘flow chart’ presented by Rees (1978) still stands as a guideline for the possible paths leading to formation of BH seeds in the centre of galactic structures. One possibility is the direct formation of a massive BH (MBH) from a collapsing gas cloud (Haehnelt & Rees 1993; Loeb & Rasio 1994; Eisenstein & Loeb 1995; Bromm & Loeb 2003; Koushiappas, Bullock & Dekel 2004; Begelman, Volonteri & Rees 2006). The gas can condense to form a central massive object. The masses of the seeds predicted by different models vary, but typically are in the range \( M_{\text{BH}} \sim 10^5–10^7 \) M\(_{\odot}\). Alternatively, the seeds of BHs can be associated with the remnants of the first generation of stars, formed out of zero metallicity gas. The first stars are believed to form at \( z \sim 20 \) in haloes which represent high-\( \sigma \) peaks of the primordial density field. The absence of metals might lead to a very top-heavy initial stellar mass function, and in particular to the production of very massive stars with masses \( > 100 \) M\(_{\odot}\) (Carr, Bond & Arnett 1984). If very massive stars form above 260 M\(_{\odot}\), they would rapidly collapse to BHs with little mass loss (Fryer, Woosley & Heger 2001), i.e. leaving behind seed BHs with masses \( M_{\text{BH}} \sim 10^2–10^3 \) M\(_{\odot}\) (Madau & Rees 2001). The subsequent growth of BHs from these initial seeds has been investigated in the hierarchical framework, typically associating episodes of accretion to galaxy mergers (Haiman 2004; Yoo & Miralda-Escude 2004; Shapiro 2005; Volonteri & Rees 2005, 2006; Lapi et al. 2006).

Only a few observational constraints are currently available. Many are limited to the brightest sources, probing only the very bright end of the luminosity function (LF) of quasars at \( z \sim 6 \) and therefore only the upper end of the MBH mass function (Fan et al. 2001). The observation of very luminous quasars, powered by billion solar masses BHs, at \( z \approx 6 \) in the Sloan Digital Sky Survey (SDSS) (Fan et al. 2001), implies that a substantial population of smaller accreting BHs must exist at earlier times. Deeper but limited constraints have been provided for more typical active galactic nucleus (AGN), with \( \sim 2 \) orders of magnitude smaller MBHs, using deep X-ray observations (e.g. Alexander et al. 2001; Barger et al. 2003b; Koekemoer et al. 2004; Mainieri et al. 2005). However, these constraints lack the detail and depth required to understand and determine the global evolution of BH seeds and of the average MBH.
population at very high redshifts. Accreting BHs are observed as X-ray emitters up to \( z \lesssim 6 \) (Barger et al. 2003b; Steffen et al. 2006), and there are no reasons to believe that higher redshift AGN would be any different. The detection of very high redshift AGN is one of the goals of future space missions. In particular, X-ray telescopes, such as the planned X-ray Evolving Universe Spectrometer (XEUS) and Constellation-X, are expected to detect these sources even at \( z \gtrsim 6 \). Moreover, X-ray observatories can identify even heavily obscured AGN activity, due to the penetrating nature of hard X-rays.

Additional, albeit less direct, limits on the early MBH population can already be placed by the requirement that the cumulative emission from the predicted high-redshift sources does not saturate the observed unresolved X-ray background (XRB) (Dijkstra, Haiman & Loeb 2004; Salvaterra, Haardt & Ferrara 2005). We show that future space borne missions will be able to constrain different proposed models for the accretion history of MBHs at early times. We focus here on a specific model for MBH formation, which traces MBH seeds to the first generation of metal-free stars. We then compare how different accretion histories reflect on to the detectability of X-ray sources.

The mass growth of the most MBHs at high redshift must proceed very efficiently to explain the LF of luminous quasars at \( z = 6 \) in the SDSS (e.g. Fan et al. 2001). Volonteri & Rees (2005) explore the conditions which allow a sufficient growth of MBHs by \( z = 6 \) under the assumption that accretion is triggered by major mergers. At such high redshift, an investigation of the MBH population must take into account the dynamical evolution of MBHs. BH mergers, in fact, can give a net negative contribution to the early BH growth, due to gravitational effects which can kick BHs out of their host haloes (gravitational recoil, due to the non-zero net linear momentum carried away by gravitational waves). Adopting recent estimates for the recoil velocity (Baker et al. 2006), Volonteri & Rees (2005) find that if accretion is always limited by the Eddington rate via a thin disc, the maximum radiative efficiency allowed to reproduce the LF at \( z = 6 \) is \( \epsilon_{\text{max}} = 0.12 \) (corresponding to an upper limit to the MBH spin parameter of 0.8). If, instead, high-redshift MBHs can accrete at supercritical rate during an early phase (Volonteri & Rees 2005; Begelman et al. 2006), then reproducing the observed MBH mass values is not an issue. The constraints from the LF at \( z = 6 \) are still very weak, so either a model with a low \( \epsilon_{\text{max}} \) or a model with supercritical accretion cannot be ruled out based on these results only.

In a previous paper, we have investigated how current observations can constrain the late accretion history of MBHs, at \( z < 4 \) (Volonteri, Salvaterra & Haardt 2006). In this paper, we study by means of a detailed model of MBH assembly, the detectability of very high redshift AGN both at X-ray and near-infrared (near-IR) wavelengths by future missions. We discuss the contribution of these objects to the unresolved XRB (in particular, in the 0.5–2 keV band).

Finally, we discuss the role of an early population of AGN in the reionization of the Universe and their contribution to the ultraviolet (UV) background at high redshift. The paper is organized as follows. In Section 2, we describe briefly the merger tree model for the formation and evolution of MBH in the early Universe. Section 3 presents the basic equations we need in the number counts and background calculation, and in Section 4 we discuss the adopted spectrum of AGN. In Section 5, we present our results and discuss the role of future space mission in the observations of high-redshift AGN. In Section 6, we compare our results to those of a model in which the early evolution of MBH seeds is characterized by a phase of supercritical accretion. Finally, in Section 7, we briefly summarize our results.

Throughout the paper, we use the AB magnitude system\(^1\) and the standard Lambda cold dark matter (ΛCDM) cosmology (Spergel et al. 2003).

## 2 HIGH-REDSHIFT MBH EVOLUTION

The main features of a plausible scenario for the hierarchical assembly, growth and dynamics of MBHs in a ΛCDM cosmology have been discussed in Volonteri, Haardt & Madau (2003). Dark matter haloes and their associated galaxies undergo many mergers as mass is assembled from high redshift to the present. The halo merger history is tracked backwards in time with a Monte Carlo algorithm based on the extended Press–Schechter formalism. ‘Seed’ holes are assumed to form with intermediate masses in the rare high-redshift MBHs. They are expected to detect these sources even at high redshift. The paper is organized as follows.

### 3 BASIC EQUATIONS

The number of sources observed per unit solid angle at redshift \( z_0 \) in the flux range \( F_{\nu_0} \) to \( F_{\nu_0} + dF_{\nu_0} \) at frequency \( \nu_0 \) is

\[
\frac{dN}{d\Omega dF_{\nu_0}}(F_{\nu_0}, z_0) = \int_{\nu_0}^{\nu_0 + \Delta \nu} \frac{dV}{d\Omega} \frac{d\nu}{dF_{\nu_0}} n_{\nu}(z; F_{\nu_0}) \nu_0 d\nu_0,
\]

where \( dV = d\nu d\Omega \) is the comoving volume element per unit redshift per unit solid angle and \( n_{\nu}(z; F_{\nu_0}) \) is the comoving density of sources at redshift \( z \) with observed flux in the range \([F_{\nu_0}, F_{\nu_0} + dF_{\nu_0}]\). The specific flux of a source observed at \( z_0 \) is given by

\[
F_{\nu_0} = \frac{1}{4\pi d_L(z)^2} L_s(M_{\text{BH}}) \epsilon \nu_0^{\alpha} e^{-\tau_{\text{eff}}(\nu_0,z)},
\]

where \( L_s(M_{\text{BH}}) \) is the specific luminosity of the source (in units of erg s\(^{-1}\) Hz\(^{-1}\)) averaged over the source lifetime, which is assumed to be only a function of the mass of the central BH. In the above equation (2), \( \nu = \nu_0(1 + z)/(1 + z_0) \), \( d_L(z) \) is the luminosity distance and \( \tau_{\text{eff}} \) is the effective optical depth of the intergalactic medium (IGM) at \( \nu_0 \) between redshifts \( z_0 \) and \( z \). Shortward of the observed Lyman \( \alpha \), the emergent spectrum is strongly modified by IGM absorption

\(^1\) AB magnitudes are defined as \( AB = -2.5 \log(F_{\nu_0}) - 48.6 \) where \( F_{\nu_0} \) is the spectral energy density within a given passband in units of erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\).
obtained convolving the type I spectrum with a lognormal distribution (SED), $\tilde{\nu}$.

The physical characterization of the source is encoded in its spectral energy distribution (SED), $\tilde{\nu}$. Assuming the source formation rate per unit mass as constant over $E_{\text{t}}$, the spectral cut-off at $E_{\text{t}}$ is considered in this paper. IGM absorption in the observed 0.5–10 keV band (corresponding, for sources at $z > 6$ as those considered here, to rest-frame energy $>3.5$ keV) can be safely neglected.

The radiation background $J_{\nu}(z_0)$ observed at redshift $z_0$ at frequency $\nu_0$ is

$$J_{\nu}(z_0) = \frac{(1 + z_0)^3}{4\pi} \int_{z_0}^{\infty} \epsilon_c(z) e^{-\tau_{\text{red}}(n, m, z)} \frac{d\nu}{dz},$$

(3)

where $\epsilon_c(z)$ is the comoving specific emissivity and $d\nu/dz$ is the proper line element. The source term $\epsilon_c$ is given by

$$\epsilon_c(t) = \int dM_{\text{BH}} \int_0^t L_\nu(t, t', M_{\text{BH}}) \frac{dn_{\nu}}{dt'} \frac{dz}{dM_{\text{BH}}} dt'.$$

(4)

The second approximated equality holds once we consider the source light curve averaged over the typical source lifetime $\tau$, and assuming the source formation rate per unit mass as constant over such time-scale.

4 AGN SPECTRUM

The physical characterization of the source is encoded in its spectral energy distribution (SED), $\tilde{\nu}$. The UV part of the SED of unabsorbed AGN [$\log (N_{\text{HI}}/\text{cm}^{-2}) < 22$, referred to as type I] as a multicolour disc blackbody (Shakura & Sunyaev 1973). Assuming Eddington-limited accretion, the maximum disc temperature is $kT_{\text{max}} \approx 1$ keV ($M_{\text{BH}}/M_\odot)^{-1/4}$. The characteristic multicolour disc spectrum is broadly peaked at $E_{\text{peak}} \approx 3 kT_{\text{max}}$, and follows a power law with $L_\nu \propto \nu^{1/3}$ for energies $h\nu \lesssim E_{\text{peak}}$, and exponentially rolls off for $E \gtrsim E_{\text{peak}}$. In the X-ray, the spectrum can be described by a power law with photon index $\Gamma = 1.9$ ($\gamma_{\text{OX}} \propto \nu^{-\gamma}$), and an exponential cut-off at $E_\gamma = 500$ keV (Marconi et al. 2004). The averaged X-ray SED of absorbed AGN (type II) is described by the same type I spectrum for $E > 30$ keV, and, in the range 0.5–30 keV, by a power law (continuously matched) with photon index $\Gamma = 0.2$, obtained convolving the type I spectrum with a logarithmic distribution of absorption column density centred at $\log (N_{\text{HI}}/\text{cm}^{-2}) = 24$ (Sazonov, Ostriker & Sunyaev 2004). UV emission from type II AGN is assumed to be negligible. We further assume a type I type II ratio of 1/4, independently of redshift and luminosity, since detailed modelling of intrinsic absorption at $z > 6$ is not currently available.

Note that the observed X-rays correspond, for sources at $z \gtrsim 6$, to rest-frame energies between 3.5 and 70 keV, where the emission properties of types I and II AGN are thought to be similar (the rare Compton thick sources are not considered here).

The X-ray emission of type I AGN is normalized to the optical, adopting an optical-to-X-rays energy index $\alpha_{\text{OX}} = 0.126$ log$(L_{2500}) + 0.017 - 2.311$ (see equation 5 of Steffen et al. 2006), where $L_{2500}$ is the monochromatic luminosity at $\lambda = 2500$ Å (rest frame). By definition, the X-ray luminosity at the rest-frame energy of 2 keV, $L_2$, is $L_2 = L_{2500}(2/12500)^{-\alpha_{\text{OX}}}$. The scaling of $\alpha_{\text{OX}}$ with redshift and luminosity has been obtained by Steffen et al. (2006) combining data from the SDSS, COMBO-17 and Chandra surveys. The final sample consists of 333 AGN extending out to $z \sim 6$ spanning five decades in UV luminosity and four decades in X-ray luminosity. Since only a mild dependence on redshift is found, we extrapolate this result also to $z > 6$. We further assume Eddington-limited accretion (see Section 2).

5 RESULTS

5.1 X-ray number counts

We compute the soft (0.5–2 keV) and hard (2–10 keV) X-ray number counts from MBHs shining at $z \gtrsim 6$ predicted by our model of MBH assembly and evolution. Results are shown in Fig. 1, and are compared to available observational data (Moretti et al. 2003). The bow-tie indicates results from the fluctuation analysis of the Chandra Deep Field (Miyaji & Griffiths 2002). Different lines refer to different ranges in BH masses. At the flux limit of current surveys, $\log (S) > -16.6$ $(\pm 15.8)$ erg s$^{-1}$ cm$^{-2}$ in the soft (hard) band (Alexander et al. 2003), the contribution to the $\log N/\log S$ from sources at $z \gtrsim 6$ is $\approx 8$ per cent in the soft X-rays, $\lesssim 1$ per cent in the hard band. In the 0.5–8 keV band, we expect $\sim 3$ sources at $z \gtrsim 6$ in the Chandra Deep Field-North with fluxes exceeding $3 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, to be compared to an upper limit of seven sources with extreme X-ray/optical flux ratios (EO: Koekemoer et al. 2004), that are candidate high-redshift AGN.

The optical identification of these objects is problematic, owing to absorption (both internal and by the IGM) and to their very low optical flux. Barger et al. (2003a,b) searched for optical counterparts (at 5σ confidence) with z-band magnitude $z_{2500} < 25.2$ of AGN of the Chandra Deep Field-North exposure. Apart from a source at $z = 5.19$ with $z_{2500} = 23.9$, no other $z > 5$ candidate was identified. This is consistent with our results, where the majority of the very high redshift sources detected in the deepest Chandra observations should have a z-band magnitude fainter than 27. Barger et al. (2003b) used the lack of optical identifications to derive limits on the number of objects at $z > 5$. They found that in a field of view (FOV) corresponding to 6-arcmin radius circle, only $\sim 6$ sources with fluxes exceeding $2 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ in the 0.4–6 keV band should lie at $z \gtrsim 5$. Our model is consistent with this limit, predicting that only $\sim 1$ sources at $z \gtrsim 6$ should be found in the same FOV.

At fainter fluxes, a significant fraction of the sources identified in the fluctuation analysis of the deepest Chandra data might be AGN.
According to Moretti et al. (2003), the intensity of the total XRB is \(5.2 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2}\) at the flux limit of the fluctuation analysis (\(\sim8000\) sources deg\(^{-2}\) at the flux limit \(\log S = -17.2\) for the soft band, and \(\sim300\) sources deg\(^{-2}\) at the flux limit \(\log S = -16\) for the hard band). Direct observations of such sources are among the main goals of the next generation of X-ray telescopes (e.g. \textit{XEUS}\(^2\) and \textit{Constellation-X}\(^3\)). The \textit{XEUS} mission is expected to have sufficient sensitivity to measure the X-ray spectra of sources as faint as \(\sim10^{-17} \text{erg s}^{-1} \text{cm}^{-2}\) in the 0.5–2 keV energy range, while the photometric limiting sensitivity is expected to be \(\sim10^{-18} \text{erg s}^{-1} \text{cm}^{-2}\). In the hard-X band, the limiting sensitivity, both spectroscopic and photometric, will be larger by almost an order of magnitude. At the spectroscopic flux limit of \textit{XEUS}, we predict almost \(5 \times 10^3\) (300) AGN in the soft (hard) X-ray band, within a 1 deg\(^2\) FOV. At such flux limits, \(\sim3 \times 10^3\) (\(\sim85\)) sources deg\(^{-2}\) are type I objects, indicating that, because of obscuration, deep surveys in the soft (hard) X-ray band will miss nearly 90 per cent (20 per cent) of type II AGN. At the photometric flux limits, we expect \(\sim10^{-13} \text{erg s}^{-1} \text{cm}^{-2}\) in the soft (hard) X-ray band. In this case, the type II missing fraction is 70 per cent (7 per cent).

\textit{XEUS} will be directly probing the lower end of the mass function of accreting MBHs at \(z \geq 6\), \(M_{\text{BH}} \sim 10^{5–6} \text{M}_\odot\) (i.e. for luminosity \(L_x > 10^{42} \text{erg s}^{-1}\) in the rest-frame 2–10 keV energy band). The main contribution to the number counts is still expected from sources at \(z \leq 10\), but almost 10 deg\(^{-2}\) sources, i.e. 1 per cent of the sources, are expected to be detected at \(z \gtrsim 10\). We note here that, assuming an half-energy width of the point spread function of 2 arcsec, \textit{XEUS} will be confusion limited at a sensitivity of \(\sim4 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2}\), saturating the \(N/\log S\) at a level of \(\sim2 \times 10^6\) deg\(^{-2}\) (Arnaud et al. 2000). For bright sources, redshift determination should be possible from the detection of X-ray emission lines (e.g. 6.4 keV K\(\alpha\)). For fainter sources, however, redshift determination in the X-rays might be very challenging, and a combination of deep X-ray observations and ultra-deep optical/near-IR spectroscopy is probably required (see Section 5.3).

In conclusion, we find that the next generation of X-ray missions will be able to investigate the early stages of MBH build-up and to provide fundamental information on the faint-end of the LF of AGN even at very high redshift.

### 5.2 X-ray background

According to Moretti et al. (2003), the intensity of the total XRB is \(7.53 \pm 0.35 \times 10^{-12}\) and \(2.02 \pm 0.11 \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2}\) deg\(^{-2}\) in the 0.5–2 and 2–10 keV energy bands, respectively. A large fraction, \(\sim94\) per cent, of the XRB in the 0.5–2 keV band has been attributed to sources with fluxes exceeding \(2.4 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\), while \(\sim89\) per cent of XRB in the 2–10 keV band is resolved into sources whose flux is \(\gtrsim2.1 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}\) (Moretti et al. 2003). More recently, Hickox & Markevitch (2006) estimate the unaccounted fraction of the XRB due to extragalactic unresolved sources as \(1.77 \pm 0.31 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\) deg\(^{-2}\) in the soft X-ray energy band (0.5–2 keV) and \(3.4 \pm 1.7 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\) deg\(^{-2}\) in the hard X-ray energy band (2–8 keV).

We compute the contribution to the residual unresolved XRB in the soft and hard (0.5–2 and 2–8 keV) energy bands from the population of AGN predicted by our model to exist at \(z \geq 6\).

6. Note that almost all these sources are below the source detection limit used by Moretti et al. (2003). Results are shown in Fig. 2, where the cumulative contribution to the XRB of sources at redshift \(z \geq 6\) contribute significantly to the unaccounted XRB, although their contribution is still well below the available constraints. Other faint unresolved X-ray sources at \(z < 6\) may contribute to the XRB, including galaxies, starbursts (e.g. Bauer et al. 2004) and a population of faint AGN (e.g. Volonteri et al. 2006; see Table 1).

It is interesting to note that at least \(\sim3–4\) per cent of the observed XRB (0.5–10 keV) will remain unaccounted even after \textit{XEUS} observations will become available, as due to sources at \(z > 6\) below the flux detection limit. Only even more sensitive X-ray observatories such as the proposed \textit{Generation-X}\(^4\) will assess these extremely faint sources.

#### 5.3 JWST number counts

Deep field observations in the near-IR might be able, in principle, to detect AGN at very high redshifts. The \(i\)-band ACS data in the

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\(^2\)http://www.rssd.esa.int/index.php?project=XEUS

\(^3\)http://constellation.gsfc.nasa.gov

\(^4\)http://generation-x.gsfc.nasa.gov
Table 1. Contribution to the unresolved XRB from different sources in units of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$.

<table>
<thead>
<tr>
<th>Sources</th>
<th>XRB 0.5–2 keV</th>
<th>XRB 2–8 keV</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faint AGN (z &lt; 4)</td>
<td>0.7</td>
<td>3.5</td>
<td>Volonteri et al. (2006)$^a$</td>
</tr>
<tr>
<td>Galaxies</td>
<td>0.4$^b$</td>
<td>0.2$^c$</td>
<td>Bauer et al. (2004)</td>
</tr>
<tr>
<td>Eddington limited</td>
<td>0.4</td>
<td>0.9</td>
<td>This paper</td>
</tr>
<tr>
<td>Rapid growth</td>
<td>1.2</td>
<td>2.3</td>
<td>This paper</td>
</tr>
<tr>
<td>Massive seeds</td>
<td>1.5</td>
<td>3.2</td>
<td>This paper</td>
</tr>
<tr>
<td>Observed unresolved XRB</td>
<td>1.77 ± 0.31</td>
<td>3.4 ± 1.7</td>
<td>Hickox &amp; Markevitch (2006)</td>
</tr>
</tbody>
</table>

$^a$Model IIIb.
$^b$Based on extrapolation down to log $F_\nu = -18$ in CGS units.
$^c$Based on extrapolation down to log $F_\nu = -17$ in CGS units.

5.4 UV background and reionization

We have also computed (see equations 3 and 4) the background intensity at the Lyman limit (912 Å) as a function of $z$ using the opacity of Fardal, Giroux & Shull (1998; model A1). Results are shown in Fig. 4. As a reference, we show the UV background (blue solid line) as computed with an updated version of the code CUBA (Haardt & Madau 1996), extrapolating the observed AGN LF and IGM opacity. We find a good agreement between the two different approaches. In the bottom panel of Fig. 4, we show the corresponding H$\alpha$ ionization rates. The UV background is dominated by the most massive, i.e. $>10^8 M_\odot$, MBHs up to $z \approx 7$. At higher redshifts, these objects are rarer, and the background is mostly due to MBHs.
in the mass range $10^5$–$10^6$ M$_\odot$. At $z > 10$, the background intensity falls rapidly.

Finally, we may ask whether high-redshift AGN can contribute significantly to the reionization of the Universe. In order to answer this question, we compute the redshift evolution of the filling factor of H II regions as (Barkana & Loeb 2001),

$$Q_{\text{HII}}(z) = \int_0^\infty dz' \left[ \frac{dr}{dz} \frac{dn_r}{dn_{\gamma}} F(z', z) \right],$$

where $n_r = X_H n_0^H$ and $n_{\gamma}^H$ are the present-day number densities of hydrogen and baryons ($X_H = 0.76$ is the hydrogen mass fraction) and $dn_r/dt$ is the production rate of ionizing photons. The function $F(z', z)$ takes into account the effect of recombinations. Assuming a time-independent volume-averaged clumping factor $C$, common to all H II regions, we can write

$$F(z', z) = \frac{2}{3} \frac{\alpha_B n_0^B}{\sqrt{\Omega_M H_0}} C [f(z') - f(z)],$$

and

$$f(z) = \sqrt{\frac{(1 + z)^3 + \frac{1 - \Omega_M}{\Omega_M}}},$$

where $\alpha_B = 2.6 \times 10^{-13}$ cm$^3$ s$^{-1}$ is the hydrogen recombination rate.

The evolution of $Q_{\text{HII}}$ as a function of redshift is shown in Fig. 5 for $C = 1$ (dotted line), $C = 10$ (solid line) and $C = 30$ (dashed line). Complete reionization is reached when $Q_{\text{HII}} = 1$.

6 COMPARISON WITH RAPID-GROWTH MODEL

In this section, we discuss possible differences between the Eddington-limited model and a model allowing MBHs to accrete at supercritical rate during the early phases of their evolution. In Fig. 6, we plot the LF in the rest-frame hard X-ray band (2–10 keV) at $z = 6$. The open triangle shows the estimated number density of quasars in the Chandra Deep Field-North (Barger et al. 2003b). Top panel shows the result for the Eddington-limited model, whereas the bottom panel shows the result for the rapid-growth model.

\[ \text{Figure 4.} \text{ Top panel: UV background at the Lyman limit (912 Å) as a function of redshift in units of } 10^{-21} \text{ erg cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}. \text{ As the reference value we show with the blue solid line, the UV background as computed with the code CUBA (Haardt & Madau 2006, in preparation) extrapolating the observed AGN LF. Bottom panel: the corresponding H I ionization rate in units of } 10^{-11} \text{ s}^{-1}. \text{ Lines are the same as those of Fig. 1.} \]

\[ \text{Figure 5.} \text{ Redshift evolution of the filling factor of H II regions, } Q_{\text{HII}}, \text{ for different values of the clumping factor: } C = 1 \text{ (dotted line), } C = 10 \text{ (solid line) and } C = 30 \text{ (dashed line). Complete reionization is reached when } Q_{\text{HII}} = 1. \]

\[ \text{Figure 6.} \text{ Predicted LF of quasar in the rest-frame hard X-ray band (2–10 keV) at } z = 6. \text{ The open triangle shows the estimated number density of quasars in the Chandra Deep Field-North (Barger et al. 2003b). Top panel shows the result for the Eddington-limited model, whereas the bottom panel shows the result for the rapid-growth model.} \]
Although the two models share similar results at \( z = 6 \), the LF at higher redshift shows significant differences. For example, the number density of bright quasars at \( z = 10 \) (i.e. with luminosity in the rest-frame hard X-ray band in the range \( 5 \times 10^{43} < \dot{L}_X < 3 \times 10^{45} \) erg s\(^{-1}\), corresponding to MBHs with \( 10^9 < M_{\text{BH}} < 10^9 M_\odot \) is \( \sim 10^{-3} \) Mpc\(^{-3}\) for the supercritical accretion model, whereas in the Eddington-limited model this density decreases by almost an order of magnitude. This result is confirmed by Fig. 7, where the solid line shows the redshift distribution of sources with fluxes above \( 10^{-17} \) erg s\(^{-1}\) cm\(^{-2}\) (the planned spectroscopic flux limit of future X-ray missions, solid line), and above \( 10^{-16} \) erg s\(^{-1}\) cm\(^{-2}\) (easily achieved by Chandra deep field observations, dashed line). Dotted lines are the ones with near-IR fluxes above the planned JWST sensitivity. Top panel shows the result for the Eddington-limited model, whereas bottom panel shows the one for the rapid-growth model (see Section 6).

Figure 7. Redshift distribution of sources with fluxes in the observed soft X-ray band (0.5–2 keV) above \( 10^{-17} \) erg s\(^{-1}\) cm\(^{-2}\) (i.e. the planned spectroscopic flux limit of future X-ray missions, solid line), and above \( 10^{-16} \) erg s\(^{-1}\) cm\(^{-2}\) (easily achieved by Chandra deep field observations, dashed line). Dotted lines are the ones with near-IR fluxes above the planned JWST sensitivity. Top panel shows the result for the Eddington-limited model, whereas bottom panel shows the one for the rapid-growth model (see Section 6).

7 SUMMARY AND CONCLUSIONS

In this paper, we have assessed, using Monte Carlo simulations of DM halo merger history coupled with semi-analytical recipes for the assembly of MBHs within galaxy spheroids (Volonteri et al. 2003), the possibility of constraining the AGN population at \( z \geq 6 \) with currently available and planned space borne missions. In particular, we have considered ultra-deep X-ray and near-IR surveys. We claim that, among the unresolved sources in Chandra deep fields, a fraction of \( 3 \sim \% \) of the unabsorbed AGN population lies in the 0.5–2 keV band. XRBSaturation could be a problem for such models, as a substantial contribution to the XRB from low redshift, i.e. \( z < 4 \), unresolved faint sources (Volonteri et al. 2006) and/or galaxies (Bauer et al. 2004) cannot be excluded.
However, we find that in the rapid-growth model, the predicted XRB is three times higher than in the Eddington-limited accretion model, saturating the unresolved fraction of the XRB in both the 0.5–2 and 2–8 keV energy bands. Since faint sources at $z < 4$ are expected to contribute substantially to the unaccounted XRB (Bauer et al. 2004; Volonteri et al. 2006), this result suggests that the occurrence and effectiveness of supercritical accretion should be investigated in much more detail. In particular, super-Eddington accretion could be much less efficient in a few $\sigma$ peaks haloes, due to the gas evacuation from the ionizing radiation emitted by the MBH seed Pop III star progenitor (Johnson & Bromm 2006). Super-Eddington accretion consequently is biased towards the highest density peaks, which experience the largest number of mergers with haloes containing pristine gas to replenish the gas reservoir. Models in which seeds are much more massive than Pop III star remnants, as in Koushiappas et al. (2004), saturate the unresolved fraction of the XRB in both the 0.5–2 and 2–8 keV energy bands as well. We note here that different models for MBH seed formation, although predicting rather large BH masses, can have a lower formation efficiency, which can ease the constraints given by the XRB (see Eisenstein & Loeb 1995; Begelman et al. 2006). Our constraints on theoretical models are conservative, as we adopted the largest value of the unresolved XRB available in the literature.

Finally, we have computed the evolution of the UV background produced by the modelled population of high-redshift AGN. Later than $z \approx 7$, the ionizing intensity is dominated by relatively MBHs, $M \gtrsim 10^6 M_\odot$, while lighter BHs contribute mostly at earlier epochs. The UV background from AGN rapidly declines at $z \gtrsim 10$. We compute the contribution of these sources to the reionization of the Universe, showing that AGN alone can provide enough ionizing photons only in the (improbable) case of an almost completely homogenous IGM. Nevertheless, for a more clumpy medium, the AGN contribution to the ionizing background is never negligible.

We note that high-redshift AGN cannot contribute significantly to the near-IR background.

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