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Massive Black Holes in the early Universe

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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 AGN population at $z \gtrsim 6$ with available and planned X–ray 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 ($6 \lesssim z \lesssim 10$). We find that this population of AGN should contribute substantially ($\sim$ 25%) to the unresolved fraction of the cosmic X–ray background in the 0.5–8 keV range. Finally, we show that super–Eddington accretion, suggested by the observed QSOs at $z \simeq 6$, must be a very rare event, confined to black holes living in the highest density peaks.

Key words. Cosmology: theory – black holes – Galaxies: evolution – Quasars: general

1. Introduction

The formation of black hole (BH) seeds and their evolution have been the subject of several theoretical investigations. The mass growth of the most massive BHs at high redshift must proceed very efficiently to explain the luminosity function of luminous quasars at $z \approx 6$ in the Sloan Digital Sky Survey (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 BH seed can be associated with the dead of the first generation of stars and that accretion is triggered by major mergers. They 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 $\epsilon_{\rm max} = 0.12$ (corresponding to an upper limit to the BH spin parameter of 0.8). If, instead, high-redshift massive BHs (MBHs) can accrete at super-critical rate during an early phase, 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 $\epsilon_{\rm max}$ or a model with supercritical accretion cannot be ruled out based on these results only.

In this paper (see Salvaterra, Haardt & Volonteri 2007 for all details) we study by means of a detailed model of MBH assembly, the detectability of very high redshift AGN by available and future X–ray missions and their contribution to the unresolved X–ray background in the 0.5–8 keV band.

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2. High redshift Massive Black Hole 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 halos 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 $\nu - \sigma$ peaks collapsing at $z = 20-25$ (Madau & Rees 2001) as end-product of the very first generation of stars. As our fiducial model we take $\nu = 4$ at $z = 24$, which ensures that galaxies today hosted in halos with mass larger than 10^{11} $M_\odot$ are seeded with a MBH. The assumed threshold allows efficient formation of MBHs in the range of halo masses effectively probed by dynamical studies of MBH hosts in the local universe.

As a reference, we adopt here a conservative model assuming Eddington-limited accretion which is able to reproduce the bright end of the optical LF, as traced by observations in the SDSS (e.g. Fan et al 2001). We then discuss in Section 5 a simple model which considers super-Eddington accretion rates for high-redshift MBHs and one in which more massive seeds form late, as in Koushiappas et al. (2004), and evolve through Eddington–limited accretion.

3. Basic equations

The number of sources observed per unit solid angle at redshift z_0 in the flux range F_{ν_0} and $F_{\nu_0} + dF_{\nu_0}$ at frequency ν_0 is

$$\frac{dN}{d\Omega dF_{\nu_0}}(F_{\nu_0}, z_0) = \int_{z_0}^{\infty} \left(\frac{dV_c}{dz d\Omega}\right) n_c(z, F_{\nu_0})\, dz, \quad (1)$$

where $dV_c/dzd\Omega$ is the comoving volume element per unit redshift per unit solid angle, and $n_c(z, F_{\nu_0})$ 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

$$F_{\nu_0} = \frac{1}{4\pi\, d_L(z)^2} \tilde{L}_\nu(M_{\rm BH})\, {\rm e}^{-\tau_{\rm eff}(\nu_0, z_0, z)}, \quad (2)$$

where $\tilde{L}_\nu(M_{\rm BH})$ 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 eq. (2), $\nu = \nu_0(1+z)/(1+z_0)$, $d_L(z)$ is the luminosity distance, and $\tau_{\rm eff}$ is the effective optical depth of the intergalactic medium (IGM) at ν_0 between redshifts z_0 and z. In the X–ray, the spectrum can be described by a power–law with photon index $\Gamma = 1.9$ ($f_\nu \propto \nu^{-\Gamma}$), and an exponential cutoff at $E_c = 500$ 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 $\Gamma = 0.2$. We further assume a type I/type II ratio of 1/4, independently of redshift and luminosity.

The radiation background $J_{\nu_0}(z_0)$ observed at redshift z_0 at frequency ν_0, is

$$J_{\nu_0}(z_0) = \frac{(1+z_0)^3}{4\pi} \int_{z_0}^{\infty} \epsilon_\nu(z) {\rm e}^{-\tau_{\rm eff}(\nu_0, z_0, z)} \frac{dl}{dz} dz, \quad (3)$$

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

$$\begin{aligned} \epsilon_\nu(t) &= \int dM_{\rm BH} \int_0^t L_\nu(t - t', M_{\rm BH}) \frac{dn_c}{dt' dM_{\rm BH}} dt' \\ &\simeq \int dM_{\rm BH}\ \tau \tilde{L}_\nu(M_{\rm BH}) \frac{dn_c}{dt dM_{\rm BH}}. \quad (4) \end{aligned}$$

The second approximated equality holds once we consider the source light curve averaged over the typical source lifetime τ, and assuming the source formation rate per unit mass as constant over such timescale.

4. X-ray number counts and X–ray background

Direct observations of high redshift AGN is among the main goals of the next generation of X–ray telescopes (e.g. *XEUS*[1]). The

[1] www.rssd.esa.int/index.php?project=XEUS

XEUS mission is expected to have sufficient sensitivity to measure the X–ray spectra of sources as faint as $\sim 10^{-17}$ erg s^{-1} cm^{-2} in the 0.5–2 keV energy range, while the photometric limiting sensitivity is expected to be $\sim 10^{-18}$ erg s^{-1} 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 *XEUS*, we predict almost 5×10^3 (300) AGN in the soft (hard) X–ray band, within a 1 deg^2 f.o.v.. At the photometric flux limits, we expect $\sim 10^5$ ($\sim 10^4$) sources deg^{-2} in the soft (hard) X–ray band.

XEUS will be directly probing the lower end of the mass function of accreting MBHs at $z > 6$ (i.e $M_{\rm BH} \sim 10^{5-6}$ $M_\odot$ or luminosity $L_X > 10^{42}$ erg s^{-1} in the rest-frame 2–10 keV energy band), investigating the early stages of MBH build–up.

We compute then the contribution to the residual unresolved XRB in the soft and hard (0.5–2 keV and 2–8 keV, respectively) energy band from the population of AGN predicted by our model to exist at $z \gtrsim 6$. The integrate contribution to the soft XRB from AGN at $z \gtrsim 6$ is found to be $\sim 0.4 \times 10^{-12}$ erg s^{-1} cm^{-2} deg^{-2}, corresponding to $\sim$ 5% of the total XRB, and to $\sim$ 23% of the unaccounted fraction as measured by Hickox & Marchevitch (2006). Sources with masses $< 5 \times 10^5$ $M_\odot$ shinning at $z > 9$ give the largest contribution to the XRB. In the 2–8 keV band, the XRB from unresolved, $z \gtrsim 6$ AGN is $\sim 0.87 \times 10^{-12}$ erg s^{-1} cm^{-2} deg^{-2}, corresponding to $\sim$ 5% of the total observed hard XRB, and to $\simeq$ 25% of the unresolved fraction. MBHs with masses $< 10^6$ $M_\odot$ give the main contribution also in the hard band, indicating that the unresolved fraction of the XRB can be used to constrain the faint–end of the X-ray luminosity function of AGN at very high redshift.

We find that AGN at $z > 6$ contribute significantly to the unaccounted XRB, although their contribution is still well below the available constraints. We note here that other faint unresolved X-ray sources at $z < 6$ may contribute to the X-ray background, including galaxies, starbursts (e.g., Bauer et al. 2004), and a population of faint AGN (e.g., Volonteri, Salvaterra & Haardt 2006; see also Table 1).

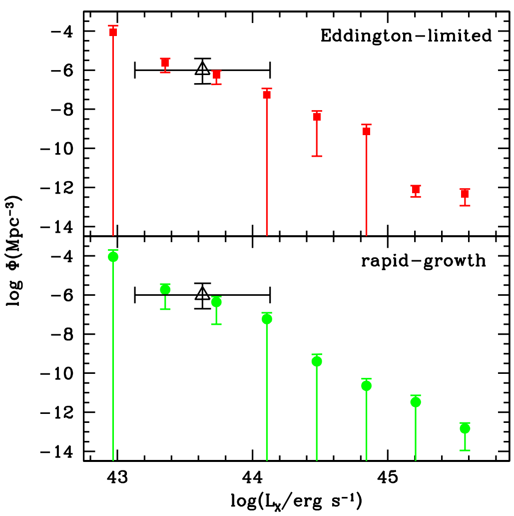

Fig. 1. Predicted luminosity function of quasar in the rest–frame hard X–ray band [2–10 keV] at $z = 6$. The open triangle shows the estimated number density of quasars in the *Chandra* Deep Field North (Barger et al. 2003). Top panel shows the result for the Eddington–limited model, whereas the bottom panel shows the result for the rapid–growth model.

5. 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 super–critical rate during the early phases of their evolution. In Fig. 1 we plot the LF in the rest–frame hard X–ray band [2-10 keV] at $z = 6$ for the two models (top panel: Eddington–limited model; bottom panel: rapid–growth model). Since both models reproduce the observed optical LF at $z = 6$ (Volonteri & Rees 2005, Begelman et al. 2006), the X–ray LFs are also quite similar. Both models are in good agreement with the estimated number density of $z \sim 5.7$ AGN as obtained by Barger et al. (2003) in the *Chandra* Deep Field North (open triangles

Table 1. Contribution to the unresolved XRB from different sources in units of 10^{-12} erg s^{-1} cm^{-2} deg^{-2}.

Sources	XRB 0.5–2 keV	2–8 keV	Reference
Faint AGN ($z < 4$)	0.7	3.5	Volonteri et al. 2006
galaxies	0.4^2	0.2^3	Bauer et al. 2004
AGNs at $z > 6$			
Eddington limited	0.4	0.9	Salvaterra et al. 2007
Rapid growth	1.2	2.3	Salvaterra et al. 2007
Massive seeds	1.5	3.2	Salvaterra et al. 2007
Observed unresolved XRB			
	1.77±0.31	3.4±1.7	HM06

in Fig. 1). Although the two models share similar results at $z = 6$, the LF at higher redshift shows significant differences: for example, the number density of $5 \times 10^{42} < L_X < 3 \times 10^{43}$ erg s^{-1} quasars at $z = 10$ is almost an order of magnitude larger if super–critical accretion is allowed.

It is unlikely that sufficient $z > 6$ AGN will be identified by the Chandra deep field observations to discriminate between these two models. However, we can provide indirect constraints by considering the contribution that each make to the unresolved X-ray background. For the super–critical accretion model, we find that the contribution to the unresolved XRB increases by a factor ~ 3 with respect to the Eddington–limited one. As a net result, once that the contribution to the unresolved XRB of sources at $z < 4$ is considered, rapid–growth model saturates the observed unaccounted background. Similar results are obtained for model in which massive seeds form late, as in Koushiappas et al. (2004). See Table 1 for a summary of the results.

6. Summary and conclusions

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 $z \gtrsim 6$ with currently available and planned X–ray missions. Future X–ray missions, such as *XEUS* will have the technical capabilities to detect accreting MBHs at $z \gtrsim 6$ down to a mass limit as low as $10^5 - 10^6\ M_\odot$. In particular, *XEUS* might detect as many as $\sim 10^5$ sources/deg^2 at their photometric sensitivity limits in the 0.5–2 keV band.

We have shown that our predicted population of high redshift AGN would account for a significant fraction of the unresolved XRB (0.5–8 keV). Almost 5% of the measured XRB (or ~ 25% of the unresolved one) should come from sources at $z \gtrsim 6$. These constraints become much more severe for a model in which super–critical accretion is allowed in the early stages of the MBH growth (Volonteri & Rees 2005). Since faint sources at $z < 4$ are expected to contribute substantially to the unaccounted XRB (Bauer et al. 2004; Volonteri et al. 2006), our result suggests that the occurrence and effectivity of super-critical accretion should be investigated in much more detail.

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