Cosmic backgrounds from miniquasars

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ABSTRACT
A large population of intermediate-mass black holes (IMBHs) might be produced at early cosmic times as a leftover of the evolution of the very massive first stars. Accretion on to IMBHs provides a source of (re)ionizing radiation. We show that the baryon mass fraction locked into IMBHs and their growth is strongly constrained by the observed residual soft X-ray background (SXRB) intensity. Thus, unless they are extremely X-ray quiet, miniquasars must be quite rare and/or have a short shining phase. As a byproduct, we find that miniquasars cannot be the only source of reionization and that their alleged contribution to the near-infrared bands is completely negligible.

Key words: black hole physics – galaxies: formation – intergalactic medium – cosmology: theory – diffuse radiation.

1 INTRODUCTION
Recent numerical (Bromm, Coppi & Larson 1999, 2002; Abel, Bryan & Norman 2000, 2002) and semi-analytical (Omukai & Nishi 1998; Omukai 2002; Nakamura & Umemura 2001, 2002; Schneider et al. 2002, 2003; Omukai & Palla 2003) studies consistently predict that the first, so-called Population III (PopIII), stars had characteristic masses of 100 – 600 M⊙, i.e. roughly 10 times more massive than those observed today. As mass loss at zero metallicity can be neglected (Kudritzki 2002), the final fate of PopIII stars is essentially set by their initial mass. In the narrow range of progenitor masses, 140 M⊙ ⩽ M* ⩽ 260 M⊙, PopIII stars explode as pair in-"
accreting BHs. For example, for fixed $\Delta M_{\mathrm{acc}}$, a shorter $\tau_{\nu}$ would imply a smaller final BH mass (and a larger number of those BHs), with a resulting hotter disc component (see next Section 3).

Note that, because $I_{\nu}$ can be written as a fraction $f_{E}\nu$ of the Eddington luminosity (see the next section), $J(v_{0}, z_{0})$ is independent of this parameter. We compute the source formation rate using the Press–Schechter formalism (Press & Schechter 1974) adopting the minimum dark matter halo mass, $M_{\text{min}}(z)$, computed by Fuller & Couchman (2000).

Throughout the paper, we adopt the ‘concordance’ model values for the cosmological parameters: $h = 0.7$, $\Omega_{m} = 0.3$, $\Omega_{\Lambda} = 0.7$, $\Omega_{h} = 0.044$, $\sigma_{8} = 0.9$, and $\Gamma = 0.21$, where $h$ is the dimensionless Hubble constant, $H_{0} = 100\,h\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.

### 3 MINIQUASAR SPECTRUM

The physical characterization of the sources is encoded in the SED $I_{\nu}$, and in the typical lifetime $\tau$. The ultraviolet (UV)/X-ray SED of an accreting BH, is, observationally, approximatively described in terms of two main continuum components (see, e.g. Tanaka & Lewin 1995). The low-energy component is thought to originate from the putative accretion disc, and, at least in stellar-sized BHs (the so-called galactic black hole candidates, or GBHCs), it is spectroscopically well described by a ‘multicolor disc blackbody’ (Mitsuda et al. 1984). The accreting gas is assumed to be optically thick, and the gravitational power locally released as blackbody radiation. Different radii radiate at different temperatures, with the hottest Planckian emitted at $\sim 5\,R_{S}$, where $R_{S} = 2GM/c^{2}$. Assuming Eddington-limited accretion, this model yields to $t_{\mathrm{Edd}} \approx 1\,\text{keV}(M_{\text{BH}}/M_{\odot})^{-1/4}$ (Shakura & Sunyaev 1973). The characteristic multicolour disc (MCD) spectrum is broadly peaked at $E_{\text{peak}} \approx 3kT_{\mathrm{max}}$, follows a power law with $I_{\nu, \mathrm{MCD}} \propto \nu^{1/3}$ for energies $h\nu < E_{\text{peak}}$ and exponentially rolls off for $E > E_{\text{peak}}$.

The second observed component is a simple power law (PL), $I_{\nu, \mathrm{PL}} \propto \nu^{-\alpha}$ with $\alpha \geq 1$. The precise origin of this power-law emission is controversial (several different models exist to date), and is likely to originate from synchrotron and/or inverse Compton (IC) emission by a mixture of thermal and non-thermal electrons, located in an active corona and/or in a relativistic jet (for a recent review see, e.g. Zdziarski & Gierlinski 2004). Both the low and the high energy ends of the power law are not firmly known. Hard-states of GBHCs (the so-called galactic black hole candidates, or GBHCs), it is dominated with respect to the MCD in terms of emitted ionizing photons.

We account for the population spread of the PL/MCD flux ratio by introducing an empirical parameter:

$$\Phi = \frac{L_{\mathrm{PL}}}{L_{\mathrm{MCD}}} = \frac{\int I_{\nu, \mathrm{PL}}d\nu}{\int I_{\nu, \mathrm{MCD}}d\nu}.$$  \hfill (3)

It may worth noticing that, for a fixed BH mass, the value of $\Phi$ determines the luminosity of the X-ray part of the emitted spectrum. We also parametrize the bolometric luminosity (i.e. MCD + PL) of an IMBH of mass $M_{\text{BH}}$ as a fraction $f_{E}$ of the Eddington luminosity, $L_{E} \approx 1.3 \times 10^{38}(M_{\text{BH}}/M_{\odot})\,\text{erg}\,\text{s}^{-1}$.

### 4 THE SOFT X-RAY BACKGROUND

Moretti et al. (2003) determined the intensity of the total SXRB in the energy range 0.5–2 keV to be $(7.53 \pm 0.35) \times 10^{-12}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{deg}^{-2}$ when combining 10 different measurements reported in the literature. Including further deep pencil beam surveys together with wide field shallow surveys, they find that $(94^{+5}_{-5})$ per cent of the SXRB is made up of discrete X-ray sources (the majority being point sources) at low redshift, $z < 4$ (Barger et al. 2002; Barger et al. 2003). By reanalyzing the Moretti et al. uncertainty budget, Dijkstra et al. (2004) provided a mean and a maximum intensities of the unaccounted SXRB flux, $0.35 \times 10^{-11}$ and $1.23 \times 10^{-12}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{deg}^{-2}$, respectively.

A population of IMBHs forming at high redshift can contribute to the SXRB. We compute here the expected background intensity in the energy band 0.5–2 keV according to equations (1)–(2) for a population of miniquasars whose formation continues down to a given redshift, $z_{\text{end}}$, as a final evolutionary product of massive PopIII stars. Given the hard energy band and low IGM metallicities we are concerned with, we neglect any absorption term in the radiative transfer equation (equation 1).

In the 0.5–2 keV energy range, the background intensity is dominated by the power-law component of the miniquasar spectrum, unless $\Phi \ll 1$. We consider here the two extreme values of $\Phi = 1$, $10^{-3}$. In order to set upper limits on the propriety of this first population of accreting IMBHs, we give the result for the maximum unaccounted SXRB flux derived by Dijkstra et al. (2004).

Unless miniquasars are extremely X-ray quiet (and therefore $\Phi \ll 1$), we find that the SXRB sets strong constraints on the density of miniquasars, which are summarized in the top panel of Fig. 1 as a function of their lifetime. The curves refer to different turn-off redshifts $z_{\text{end}} = 6, 12, 18$ and 24, respectively. Apart from the differences in the value of $z_{\text{end}}$, which introduces an uncertainty of a factor of $\approx 2$ on the estimates, we see that for $\Phi = 1$, the mass fraction of IMBH cannot exceed $10^{-4}\,\Omega_{h}$ (that of the same order of the density of the SMBH today, Merritt & Ferrarese 2001), even for an extremely short lifetime $\tau_{\nu} \approx 10^{6}\,\text{yr}$. This constraint increases to $\Omega_{\Delta \text{IMBH}} < 0.1\,\Omega_{h}$ in the case in which IMBHs are extremely inefficient X-ray emitters ($\Phi = 10^{-3}$), i.e. a large fraction of the baryon density might be locked into BHs without exceeding the SXRB constraint (bottom panel of Fig. 1). As we have assumed the maximal SXRB residual intensity, the above values must be understood as strong upper limits. In addition, other sources, such as high-redshift quasars (Dijkstra et al. 2004), may contribute to the unresolved SXRB, leading to even more stringent limits. We conclude that early miniquasars were quite rare.
sources forming down to redshift $z_{\text{end}} = 6$ (solid line), $z_{\text{end}} = 12$ (dotted), $z_{\text{end}} = 18$ (dashed), and $z_{\text{end}} = 24$ (long-dashed). The top (bottom) panel refers to the case $\Phi = L_{\text{PL}}/L_{\text{MCD}} = 1$ ($\Phi = 10^{-5}$). We adopt here $\epsilon = 0.1$.

and/or their shining phase lasted only for a very short period of time.

We can rewrite these limits in terms of the maximal mass growth of BHs allowed by the unaccounted SXRB. In Fig. 2 we show the final IMBH density and the growth factor, defined as the ratio between final and initial IMBH density, for sources forming at $z = 24$ (different lines refer to different values of accretion radiative efficiency $\epsilon$) as a function of the initial mass density of IMBH, $\Omega_{\text{IMBH,0}}$. For sources forming down to $z_{\text{end}} = 12$ ($z_{\text{end}} = 6$) the limits are tighter by a factor of 1.8 (2.6).

We find that for $\epsilon = 0.1$ a strong upper limit to the final mass density $7 \times 10^{-6} \Omega_b$ for a wide range of initial densities, i.e. for $\Omega_{\text{IMBH}}/\Omega_b \lesssim 10^{-6} \Omega_b$. Since low-redshift ($z \lesssim 6$) accreting BHs are taken into account in the resolved fraction of the SXRB, we can derive an upper limit $\rho_{\text{IMBH}} < 3.8 \times 10^4 M_\odot \text{Mpc}^{-3}$ for $z \gtrsim 6$, which is $\approx 10$ per cent of the present-day SMBH mass density (Yu & Tremaine 2002). This value is not at odds with current models of SMBH assembly in a hierarchical structure formation scenario (Volonteri et al. 2003; Madau et al. 2004). For example, Volonteri et al. (2003) find that the mass density locked into BHs is of the order of $10^4 M_\odot \text{Mpc}^{-3}$ at $z \sim 6$. This mass growth corresponds to a SXRB contribution of $\sim 0.29 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, which is a non-negligible fraction of the maximal unresolved intensity, and it is comparable to the mean value of this quantity. Moreover, we find also a contribution in the hard X-ray band (2–10 keV, so-called HXRB) of the order of $0.33 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, corresponding to $\approx 1.7$ per cent of the observed HXRB. Thus, within hierarchical clustering models, a significant fraction of the unaccounted SXRB (and HXRB) should come from the growth of IMBHs in the early Universe. For example, using the Madau et al. (2004) model we find that the SXRB (HXRB) is $\approx 0.20$ ($0.23$) $\times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ already at $z = 14$ for $3.5 \sigma$ peak seeds, assuming an accreted mass corresponding to $10^{-3}$ of the halo mass.

Stronger constraints on the maximal growth of IMBHs in the early Universe can be set by the next generation of X-ray satellites (e.g. Constellation-X, XEUS) that will be able to resolve sources 10 times fainter than the present facilities. Extrapolating the log $N$/log $S$ to this flux limit will allow one to resolve the SXRB entirely (Moretti et al. 2003). If this were the case, strong limits on the growth history of BHs in the early Universe, or conversely, on the spectral energy distribution at high energies of these sources, can be derived.

**5 LIMITS ON REIONIZATION**

The limits on the radiative proprieties of miniquasars derived from the SXRB constraint allow us to give a simple estimate of the role of these sources in the reionization of the Universe.

The number of ionizing photon per hydrogen atom can be written as

$$n_{\text{ion}}/n_H = \frac{\epsilon m_H c^2}{X} \left( \frac{\Omega_{\text{IMBH}}}{\Omega_b} \right)_{\text{in}}$$

where $(\Omega_{\text{IMBH}}/\Omega_b)_{\text{in}} = (e^{\epsilon_\text{ion}} - 1)(\Omega_{\text{IMBH}}/\Omega_b)_{\text{in}}$, $f_{\text{UV}}$ is the fraction of the bolometric power emitted as hydrogen-ionizing photons with mean energy $(h\nu)$, $m_H$ is the hydrogen mass, and $X \simeq 0.76$ is the mass fraction in hydrogen. In Fig. 3 the limits on this quantity derived from the maximum unaccounted SXRB assuming $\epsilon = 0.1$ are shown. Different lines refer to different lifetime of the miniquasar phase, $\tau_{\text{II}}$. The labels report the number of e-folding times, $\tau_{\text{II}}/\tau_S$.

Sources forming at very high redshift and accreting for 10 e-folding times will be able to produce just 3 photons per hydrogen atom, but shorter lifetimes give lower $n_{\text{ion}}/n_H$, indicating that miniquasars can not easily reionize the Universe if recombination is taken into account. At lower redshift the situation is even worse. Miniquasars forming down to redshift $z = 9$ cannot produce more than one ionizing photon per hydrogen atom without saturating the SXRB. Moreover, these values are to be taken as strong upper limits, as we considered the maximum residual SXRB intensity. Using the mean unaccounted SXRB intensity will lead to a reduction of a factor $\sim 1/3$ in $n_{\text{ion}}/n_H$.

In conclusion, miniquasars unlikely account for the reionization of the Universe even at high redshift, unless they are extremely X-ray quiet. In order to have $n_{\text{ion}}/n_H \sim 10$ without exceeding the
maximum unresolved SXRB we must require $\Phi < 0.15 \ (0.07)$, for sources forming down to redshift $z = 24 \ (z = 9)$ and shining for $\tau_{\text{sh}} \sim 4 \ \tau_s$.

6 THE NEAR INFRARED BACKGROUND

Recent measures of the near-infrared background (NIRB; see Hauser & Dwek 2001 for a review) show an excess with respect of the observed light from galaxies in deep field surveys (Madau & Pozzetti 2000; Totani et al. 2001). The discrepancy is maximal in the J band, corresponding to $1.7 - 4.8 \times 10^{-5} \ \text{erg s}^{-1} \ \text{cm}^{-2} \ \text{sr}^{-1}$. The large uncertainty on this value is given by the different adopted subtraction of zodiacal light (i.e. sunlight scattered by the interplanetary dust) contribution.\footnote{The lower limit is obtained for the zodiacal light model of Wright (1998), whereas the upper limit is for the Kelsall et al. (1998) one.}

Estimates based on theoretical models suggest that this excess can be well produced by redshifted light from the first very massive ($M \geq 100 \ M_\odot$) PopIII stars (Santos, Bromm & Kavnonkowski 2002; Salvaterra & Ferrara 2003) if these form efficiently down to $z_{\text{end}} = 9$. The same stars can also account for the observed small-scale angular fluctuations detected in the same bands (Magliocchetti, Salvaterra & Ferrara 2003). In order to avoid over-enrichment of the IGM with metals at high redshift, most of these massive stars must end up into IMBHs. Cooray & Yoshida (2004) have speculated that if these IMBHs accrete matter and shine as miniquasars, they might give an important contribution to the NIRB.

We have revisited this conclusion in the light of the results of the Section 4. Using the limits implied by the SXRB, we find that the contribution to the NIRB of these sources is completely negligible. In fact, for $z_{\text{end}} = 9$, the NIRB contribution from miniquasars in the J band allowed by the SXRB constrain is $\lesssim 10^{-9} \ \text{erg s}^{-1} \ \text{cm}^{-2} \ \text{sr}^{-1}$, hence well below the observed value.

An appreciable contribution in the NIR bands is possible only in the unlikely case in which miniquasars are extremely X-ray quiet.\footnote{Similar conclusions were reached independently in a similar analysis by Madau & Silk (2005).}

In this case, $\Phi \ll 1$ and the limits set by the SXRB are very weak. For sources forming down to $z_{\text{end}} = 9$ the NIRB excess data can be fitted without saturating the unaccounted SXRB. Assuming $\epsilon = 0.15$, BHs could have increased their mass density for almost 6 e-folding times, or by about a factor of 400. In this case, an initial BH mass density of $10^{-5} \ \Omega_b$ is sufficient to reproduce the NIRB data. On the other hand, these BH have to accrete all the time down to $z = 9$ resulting in a final mass density of $\Omega_{\text{IMBH}} \sim 0.07 \ \Omega_b$.

7 DISCUSSION

We have studied the contribution of the first generation of miniquasar to cosmic backgrounds. In particular, we have shown that the observed residual SXRB intensity (Moretti et al. 2003; Dijkstra et al. 2004) can be used to set strong constraints on the abundance and radiative efficiency of these sources. Unless these objects are extremely X-ray quiet, the SXRB is easily overproduced, requiring miniquasars to be quite rare and/or have a short shining phase. Should accreting IMBHs saturate the SXRB, they would contribute also 6–7 per cent of the HXRB.

As a consequence of our analysis, it is unlikely that miniquasars can reionize the Universe, as they are limited to producing only $\lesssim 3$ photons per hydrogen atom, even at high redshift. This conclusion is similar to that of Dijkstra et al. (2004), though our limits are tighter owing to a more physically motivated description of the miniquasar spectrum. Moreover, our approach allow us to follow the evolution of the mass density of accreting IMBHs with time, so that we can derive important constraints on the mass growth of these objects in the early Universe. We derived a strong upper limit to (active and inactive) IMBHs mass density at $z \geq 6$, which is $\rho_{\text{BH}} \lesssim 3.8 \times 10^4 \ M_\odot \ \text{Mpc}^{-3}$. Although this value is not at odds with current model of SMBH assembly in the hierarchical scenario of structure formation, stronger constraints on the SXRB unaccounted fraction by future X-ray facilities (i.e. Constellation-X, XEUS) could question our ideas of the formation of quasars. In fact, given the prediction of these models we expect that a not negligible fraction of the SXRB will not be resolved, being the signature of the growth of IMBHs in the early Universe.

As a further byproduct, we have shown that their contribution in the near-infrared bands is completely negligible. In the proposed models of the NIRB (Santos et al. 2002; Salvaterra & Ferrara 2003; Magliocchetti et al. 2003) the NIRB excess is due to redshifted light of PopIII stars with masses larger than $100 \ M_\odot$. In order to avoid over-enrichment of the IGM at high redshift, most of these stars must end up in IMBHs, locking $\approx 10$ per cent of the baryons into compact objects already at $z = 9$. Though not excluded by any of the current experiments (including gravitational lensing data, Wambsganss 2002), this requirement is somewhat extreme, as pointed out by Madau & Silk (2005). On the other hand, we have shown that miniquasars powered by accretion on to IMBH cannot contribute appreciably to the NIRB, as they easily exceed the SXRB constraints. In fact, the IMBHs left over by the first stars must be characterized by a very short shining phase ($< 10^7 \ \text{yr}$, assuming $\Phi \approx 1$) and/or very low accretion efficiency in order not to overproduce the SXRB. As a consequence, IMBHs cannot grow appreciably in mass. Only in the unrealistic case, $\Phi \ll 1$, might the contribution to the unaccounted NIRB from miniquasars dominate that of the progenitors.
In this case, we found that \( \sim 7 \) per cent of the baryons must be locked into IMBHs at \( z = 9 \).

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