

Stellar feedback from high-mass X-ray binaries in cosmological hydrodynamical simulations

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ABSTRACT

We explored the role of X-ray binaries composed by a black hole and a massive stellar companion [black hole X-ray binaries (BHXBs)] as sources of kinetic feedback by using hydrodynamical cosmological simulations. Following previous results, our BHXB model selects metal-poor stars ($Z = [0, 10^{-4}]$) as possible progenitors. The model that better reproduces observations assumes that an ~ 20 per cent fraction of low-metallicity black holes are in binary systems which produces BHXBs. These sources are estimated to deposit $\sim 10^{52}$ erg of kinetic energy per event. With these parameters and in the simulated volume, we find that the energy injected by BHXBs represents ~ 30 per cent of the total energy released by Type II supernova and BHXB events at redshift $z \sim 7$ and then decreases rapidly as baryons get chemically enriched. Haloes with virial masses smaller than $\sim 10^{10} M_{\odot}$ (or $T_{\text{vir}} \lesssim 10^5$ K) are the most directly affected ones by BHXB feedback. These haloes host galaxies with stellar masses in the range 10^7 – $10^8 M_{\odot}$. Our results show that BHXB feedback is able to keep the interstellar medium warm, without removing a significant gas fraction, in agreement with previous analytical calculations. Consequently, the stellar-to-dark matter mass ratio is better reproduced at high redshift. Our model also predicts a stronger evolution of the number of galaxies as a function of the stellar mass with redshift when BHXB feedback is considered. These findings support previous claims that the BHXBs could be an effective source of feedback in early stages of galaxy evolution.

Key words: galaxies: abundances – galaxies: evolution – galaxies: high-redshift – X-rays: binaries.

1 INTRODUCTION

The regulation of star formation (SF) activity in galaxies of different masses is still an open problem in cosmological simulations. Different feedback mechanisms have been proposed to regulate the transformation of gas into stars. Among them, supernova (SN) feedback is considered to play a critical role in the regulation of SF, with a larger impact for galaxies with circular velocities lower than $\sim 100 \text{ km s}^{-1}$ (Dekel & Silk 1986). The SN feedback modelling in hydrodynamical codes has certainly helped to reach better agreement of the properties of the simulated galaxies with observations (e.g. Scannapieco et al. 2006; Springel, Frenk & White 2006; Governato et al. 2007). However, these studies also show that SN feedback might not be efficient enough to regulate the SF activity in low-mass systems, principally at high redshift. This problem manifests itself, for example, in the apparent inconsistency between the

stellar-to-virial mass relation obtained from abundance matching techniques and that of hydrodynamical simulations in the low-mass end (e.g. Sawala et al. 2011; Behroozi, Wechsler & Conroy 2013; Moster, Naab & White 2013). Different feedback mechanisms such as cosmic rays, radiative feedback or photoionization, among others, have been explored with the aim of improving the regulation of the SF in numerical models (e.g. Wadepuhl & Springel 2011; Stinson et al. 2012; Ceverino et al. 2014; Hopkins et al. 2014). However, much work is still needed to both understand the physical processes which regulate SF as a function of redshift and to improve their modelling in numerical simulations.

High-mass X-ray binaries (HMXBs) are accretion-powered stellar systems composed of a black hole (BH) or a neutron star and a companion massive star, which emit X rays at typical luminosities of $10^{38} \text{ erg s}^{-1}$ (see Fabbiano 2006, for a review) and hence provide a radiative feedback on the interstellar medium. In some cases, they also produce collimated outflows (jets) with similar kinetic luminosities. These jets act as another feedback mechanism, heating the surrounding medium. The interest on HMXBs has increased in the

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last years because theoretical and observational works suggest that the production, and possibly the luminosity of these sources, could increase with decreasing metallicity of the stellar progenitor (e.g. Dray 2006; Linden et al. 2010; Kaaret, Schmitt & Gorski 2011; Brorby, Kaaret & Prestwich 2014). Under this hypothesis, HMXBs could play an important role in the formation and evolution of galaxies at early epochs of the Universe.

Given their radiative feedback, HMXBs have been proposed as effective sources of reionization of the intergalactic medium (IGM) and of heating of the gas component in the small haloes in the very early Universe (e.g. Power et al. 2009). A recent report from Fragos et al. (2013b) uses the results of combining semi-analytical models of galaxy formation with a population synthesis code (Fragos et al. 2013a), to compare the X-ray luminosity density produced by HMXBs and active galactic nuclei as a function of redshift, claiming that the first prevails at $z \gtrsim 6-8$. Different works have also studied the role of these binaries in the heating of the IGM and the shaping of the 21 cm signal from first galaxies (Power et al. 2013; Fialkov, Barkana & Visbal 2014; Kaaret 2014; Pacucci et al. 2014). HMXBs have also been investigated as a source of reionization. Mirabel et al. (2011) suggest that the rate of ionizing photons emitted by HMXBs with BHs might be greater than that of their progenitor stars, and that these sources could heat the IGM up to 10^4 K, keeping it ionized. Using zoomed hydrodynamical simulations of minihaloes, Jeon et al. (2014) have analysed the feedback from Population III (hereafter Pop III) HMXBs. Their results suggest that X-ray photons from these sources may suppress small-scale structures and reduce the recombination rate in the IGM, providing a net positive feedback on reionization. Kneivitt et al. (2014) investigated the effect of HMXBs on the high-redshift IGM using a one-dimensional radiative transfer code. Contrary to previous works, they found that HMXBs do not produce neither any significant additional ionization nor heating of the IGM, except for the distant IGM in the case of continuous SF. As can be seen from the above discussion, the issue of the effects of the radiative feedback from HMXBs is far from being settled.

Recently, Justham & Schawinski (2012) studied HMXBs as a potential source of feedback through the kinetic energy of their jets. Those HMXBs comprising black holes (hereafter BHs) are among the most powerful X-rays and jet emitters. The potential of BHs as an efficient feedback mechanism at high redshift is supported by observational results from Fender, Maccarone & van Kesteren (2005) which suggest that the contribution of kinetic energy from BH jets could be significant compared with the energy injected by SN, in some cases. Ramsey et al. (2006) studied the interstellar environment of seven HMXBs, showing that to understand the ionization and kinematics of the supershells around these sources, it is necessary that HMXBs contribute with a significant amount of kinetic energy. Several works indicate that the energy deposited by BHs in the form of kinetic energy could be as high as their bolometric X-ray luminosities (Gallo et al. 2005; Pakull, Soria & Motch 2010; Feng & Soria 2011; Soria et al. 2014). Based on these pieces of observational evidence, Justham & Schawinski (2012) conclude that the early injection of energy by these sources could heat up the ambient gas without expelling it from the galaxy, preventing the early transformation of gas into stars, and changing the properties of the ISM where SN events will take place. As we mentioned before, the main impact of this process is expected to occur at high redshift, where low-metallicity sources prevail.

In this paper, we implement for the first time a BH feedback model within cosmological hydrodynamical simulation, in a self-consistent way. Our simulations include a chemical evolution model

(Scannapieco et al. 2005) and a physically motivated SN feedback (Scannapieco et al. 2006); therefore, the enrichment of baryons can be followed as galaxies are assembled. Hence, our simulations allow us to describe the metallicity dependence of the sources along the Hubble time. This gives us a further insight into this problem, by providing the self-consistent evolution of the gas cooling, the transformation of gas into stars and the stellar evolution, with the subsequent chemical enrichment of the baryons. We will consider very low metallicity stars as BH progenitors, since they are expected to be most energetic and abundant. We explore the effect of BH feedback on the cosmic SF history and on the properties of galaxies within haloes of different masses. Our results are in agreement to those reported by Justham & Schawinski (2012) where a semi-analytical model is developed to study the effects of BH feedback.

This paper is summarized as follows. In Section 2, we describe the numerical simulations and the implementation of BH feedback. In Section 3, we explore the effects of this feedback on the cosmic SF history, while in Section 4 we study its effect on simulated galaxies. Finally, we present our main conclusions in Section 5.

2 NUMERICAL METHODOLOGY

In this section, we describe the main characteristics of the cosmological code, the simulations and the model developed to incorporate the BHs self-consistently in the numerical code.

2.1 The cosmological code

We use an extended version of the TreePM/smoothed particle hydrodynamics (SPH) code P-GADGET-3 (Springel 2005), which includes a multiphase model for the gas component, metal-dependent cooling and SN feedback as described by Scannapieco et al. (2005, 2006).

The multiphase scheme allows the coexistence of low- and high-density gas clouds, diminishing the problems of oversmoothing of standard SPH. The main difference is that neighbouring particles are selected not only by a distance criterion, but also by considering their relative entropy. The decisions are made on a particle–particle basis, which implies no mass-dependent parameters to be fixed (see Scannapieco et al. 2006, for details). The multiphase model works coherently with the SN feedback model, which includes Type II and Type Ia SN events (hereafter SNII and SNIa, respectively). When SN events are produced, metals and energy are distributed within the hot and cold gaseous phases surrounding the star particle representing a single stellar population. The cold phase of the star particle is defined by gas particles with $T < 2T_*$ and $\rho > 0.1\rho_*$, while the rest of the gas determines the hot phase ($\rho_* = 7 \times 10^{-26} \text{ g cm}^{-3}$ and $T_* = 4 \times 10^4 \text{ K}$; see Scannapieco et al. 2006 for a detailed discussion on these parameters). The fraction of energy distributed into the cold phase is defined by the parameter ϵ_c . An exploration of this parameter and its effects is given by Scannapieco et al. (2006, 2008). Here, we adopt $\epsilon_c = 0.5$ as has been done in previous works which used this SN feedback model (Scannapieco et al. 2009; De Rossi et al. 2013; Pedrosa, Tissera & De Rossi 2014). Note that these cold and hot gaseous phases are defined for the stellar populations where SN events are estimated to be produced, and for the only purpose of distributing metals and energy. They have no direct relation with the SPH integration itself. Hot gas particles thermalize immediately the SN energy they receive, whereas cold gas particles build up an energy reservoir. The feedback energy is stored in these reservoirs until gas particles have enough energy to change their entropy in

order to match that of their surrounding hot neighbour media. When this occurs, the reservoir energy is pumped into the internal energy. This SN scheme is able to produce powerful, mass-loaded galactic winds as has been shown in previous works (e.g. Scannapieco et al. 2008, 2009).

Stars more massive than $8 M_{\odot}$ are considered as SNII progenitors. We estimate the number of SNII by adopting the initial mass function (IMF) of Chabrier (2003). For SNIa, we use the simple model of Mosconi et al. (2001) where the SNIa rate is estimated by adopting an observationally motivated ratio (~ 0.0015). The lifetimes of SNIa progenitors are randomly selected within the range [0.1–1] Gyr. This model, albeit simple, allows a good representation of the chemical patterns of the stellar populations (Jimenez, Tissera & Matteucci 2014). The initial chemical composition of the gas component is assumed to be primordial ($X_{\text{H}} = 0.76$, $X_{\text{He}} = 0.24$). The chemical model follows the enrichment by 12 isotopes: ^1H , ^2He , ^{12}C , ^{16}O , ^{24}Mg , ^{28}Si , ^{56}Fe , ^{14}N , ^{20}Ne , ^{32}S , ^{40}Ca and ^{62}Zn . For SNIa we adopt the nucleosynthesis model of Iwamoto et al. (1999) and for SNII that of Woosley & Weaver (1995). Chemical elements are distributed in a similar fashion as the energy, although 80 per cent of the new elements are dumped into the cold phase (i.e. 20 per cent goes into the hot phase). The cooling functions are metal dependent (Sutherland & Dopita 1993).

2.1.1 Numerical experiments

The simulated volumes represent 14 Mpc comoving-side boxes, and are consistent with the cosmology Λ cold dark matter with $\Omega_{\Lambda} = 0.7$, $\Omega_{\text{m}} = 0.3$, $\Omega_{\text{b}} = 0.04$, $\sigma_8 = 0.9$ and $H_0 = 100 h \text{Mpc}^{-1} \text{km s}^{-1}$ with $h = 0.7$. Although this is not the current favourite set of cosmological parameters, we use it because it allows us to compare these simulations with previous ones. The variation of the cosmological parameters will not affect the conclusions of this work, which is related to the effects of feedback on the properties of the ISM and the regulation of SF within individual galaxies. For this purpose, we compare runs of the same initial conditions but with different feedback mechanisms.

Initially, the simulations contain 230^3 dark matter particles and 230^3 gas particles (we will refer to these simulations as S230). The dark matter and initial gas particle masses are $\sim 9.1 \times 10^6 M_{\odot}$ and $\sim 1.3 \times 10^6 M_{\odot}$. The adopted gravitational softening length is $1.24 h^{-1} \text{kpc}$. S230 runs were followed down to $z = 0$, but we focus the analysis on $z > 4$.

Higher numerical resolution runs of 2×320^3 particles were also performed to investigate the dependence on mass resolution (we will refer to these simulations as S320). The dark matter and initial gas mass in this case are $\sim 3.1 \times 10^6 M_{\odot}$ and $\sim 4.9 \times 10^5 M_{\odot}$, and the gravitational softening length is $0.5 h^{-1} \text{kpc}$. These simulations were run down to $z \sim 7$ due to their high computational cost. We adopted the same SF and feedback parameters used in S230. As a consequence, the SF activity starts at higher redshift since smaller systems are better resolved. As a result, the impact of BHs occurs also at higher redshift in S320 than in S230. Nevertheless, this behaviour does not affect our analysis since we are always comparing runs with and without BH feedback with the same resolution to draw conclusions.

We have run the same initial condition with SN feedback (S230-SN and S320-SN) and with SN+BHX feedback (S230-BHX and S320-BHX) in order to assess the effects clearly. Although in this work, we only discuss the most successful implementation, we have

run the same initial conditions varying the parameters of the BH feedback models, as explained in the following section.

2.2 The stellar feedback model for BH-HMXBs

We are interested in studying the effects of the kinetic feedback of BHs originated from very low metallicity progenitors. As these metal-poor progenitors are expected to form principally in the early Universe, their contribution should be relevant for the regulation of the SF in the early stages of galaxy evolution. As mentioned in the introduction, we considered previous results from Power et al. (2009) and Justham & Schawinski (2012) to develop our model, which is fully implemented within our SPH code.

We will consider BH populations rather than individual sources due to the numerical resolution of our simulations. We assume that massive stars with metallicities in the range $Z_{\text{EMP}} = [0, 10^{-4}]$ will give origin to *extremely metal poor* progenitors of BHs (see below for more details). This metallicity range is taken as indicative, since there is no clear theoretical or observational value to be used. Nevertheless, theoretical works predict larger formation rates for $Z < 0.01 Z_{\odot}$ (e.g. Linden et al. 2010). The upper limit represents the characteristic value of the oldest Population II stars (Belczynski, Sadowski & Rasio 2004). We would like to stress that although the upper metallicity limit was selected with this criterion, sensitive variations should not affect strongly our results. Note also that we are not modelling Pop III stars. We assume our sources to be very low metallicity stars but not representative of the first stars. Pop III sources are beyond the scope of this paper and would demand the treatment of other physical mechanisms which are not included in our code (e.g. Chen et al. 2014). Our model includes the $Z = 0$ stellar populations since there are not efficient mixing processes within the SPH kernel. Their treatment should increase the metallicity floor quickly from $Z = 0$.

In order to estimate the number of BHs produced in each young stellar population, we adopt the model of Georgy et al. (2009) for the evolution of massive stars. This model includes stellar rotation and a dependence of the type of compact remnant on the metallicity of the progenitor. The fraction of massive stars that end their life as BHs increases with decreasing metallicity. Therefore, for each young stellar population, we estimate the number of BHs produced by adopting the IMF of Chabrier (2003). We consider stellar masses in the range of 30–120 M_{\odot} and metallicities consistent with the defined Z_{EMP} interval. We assume that ~ 20 per cent of low-metallicity BHs will end up in binary systems, producing a BH ($f_{\text{BHX}}^{\text{EMP}} = 0.20$). This value is roughly comparable to the 30 per cent reported by Power et al. (2009), after correcting for by the different IMF adopted.

As we mentioned before, in BHs the BH accretes mass from its companion star releasing a significant amount of energy in the form of radiation and outflows. Observational evidence from shock-ionized bubbles in the environment of these sources (~ 50 – 300pc) suggests that their mechanical output energy would be around $\sim 10^{52} \text{erg}$ (Soria et al. 2014). On the other hand, many authors have reported that the kinetic power from accreting BHs could be as high as their Eddington luminosity limit (Pakull & Mirioni 2003; Pakull et al. 2010). For example, for Cygnus X-1, Gallo et al. (2005) have found that its jet transforms its total power into kinetic energy, and that the latter could be greater than its bolometric X-ray luminosity. Similar results have been found by Soria et al. (2010) for the microquasar S26 in NGC 7793, and by Soria et al. (2014) for an accreting BH in M83.

Motivated by these observations, we assume that the energy deposited by low-metallicity BHxs in the form of kinetic energy is $E_{\text{BHx}} = 10^{52}$ erg (Feng & Soria 2011; Mirabel et al. 2011). Assuming that a similar amount of energy is radiated in the X-ray band during ~ 3 Myr, the mean X-ray luminosity per source is $L_{\text{X, source}} \sim 10^{38}$ erg s $^{-1}$, which is typical of HMXBs. We also tested larger and smaller energy values. Energies of the order of $E_{\text{BHx}} = 10^{53}$ erg sweep the gas in haloes too efficiently while lower values ($E_{\text{BHx}} \sim 10^{51}$ erg) produce no significant impact on the regulation of the SF activity.

Hence, for each young stellar population with metallicity in the range $Z_{\text{EMP}} = [0, 10^{-4}]$, we estimate the number of BHxs as $N_{\text{BHx}} = f_{\text{BHx}}^{\text{EMP}} \times N_{\text{BH}}(Z)$, where $N_{\text{BH}}(Z)$ is the number of BHs produced according to Georgy et al. (2009) and $f_{\text{BHx}}^{\text{EMP}} = 0.20$, as we discussed before. Each of these N_{BHx} sources releases $E_{\text{BHx}} = 10^{52}$ erg into the ISM. We assume that this energy will be efficiently thermalized by the surrounding gas clouds where the events took place. This hypothesis is supported by pieces of observational evidence that show that these events are expected to affect the region surrounding the stellar progenitors (~ 300 pc; e.g. Pakull et al. 2010). As a consequence, the released energy is dumped into the internal energy of the nearby cold gas phase, contributing to build up their energy reservoir.

3 THE COSMIC SF RATE DENSITY

The SN and BHx feedback mechanisms modify the thermodynamical properties of the ISM, thus affecting the transformation of gas into stars, which is the main effect we analyse in this paper. In order to have a global picture of their impact, we estimate the cosmic star formation rate density (cSFR) for both simulations, S230-SN and S230-BHX. As shown in Fig. 1, the confrontation of the cSFR with observational results compiled by Behroozi et al. (2013) suggests that the treatment of BHx feedback worked in the expected way, yielding an improved description of the observations. The factor $f_{\text{BHx}}^{\text{EMP}} \sim 0.20$ was actually chosen to be able to represent this obser-

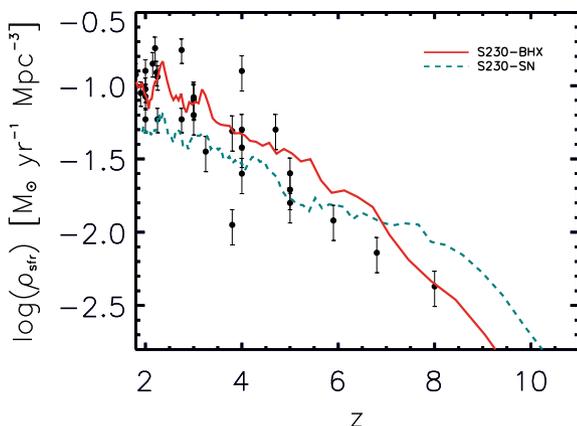


Figure 1. The cSFR estimated from simulations with SN feedback (S230-SN, blue dashed line) and with both SN and BHx feedbacks (S230-BHX, red solid line). For comparison, the observations compiled by Behroozi et al. (2013) are also included (black filled circles). The two runs share the same cosmology, and the SF and SN feedback parameters. The cSFR is diminished by BHx feedback at early epochs ($z \gtrsim 7$) through cold gas heating, and boosted at lower redshift as more gas is available to feed the SF activity.

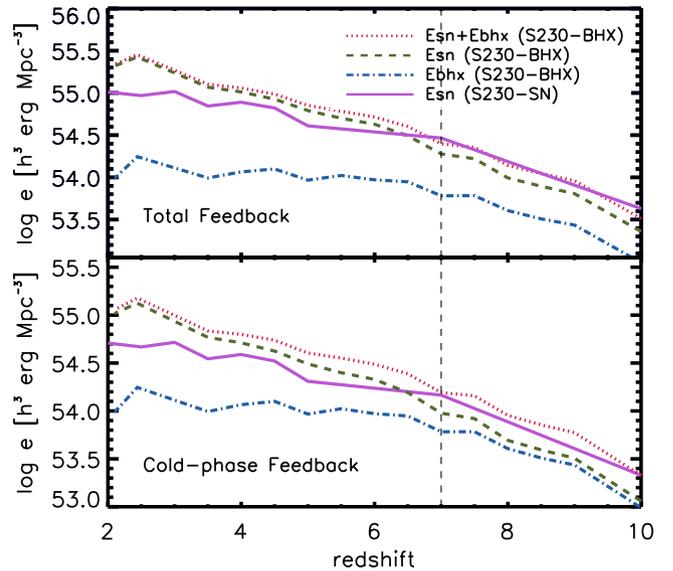


Figure 2. Upper panel: Comoving energy density released by different feedback mechanisms as a function of redshift: SNIi in S230-SN (magenta solid line), SNIi in S230-BHX (green dashed line) and BHxs in S230-BHX (blue dot-dashed line). The total comoving energy density released by all agents in S230-BHX (BHxs+SNe) is also plotted (red dotted line). BHxs release a significant amount of energy, of ~ 30 per cent of the SNIi+BHX feedback at $z \gtrsim 7$, but its fractional contribution decays for lower redshifts, down to ~ 10 per cent at $z \sim 4$. Lower panel: same as above, but taking into account only the energy injected into the cold gas phase of the ISM. The contribution of BHxs is larger in this case because they dump all their energy into the cold phase.

vatinal relation.¹ The fact that it agrees roughly with that derived by Power et al. (2009) is encouraging.

In order to understand the combined effects of the two feedback mechanisms, in Fig. 2 (upper panel), we show the comoving energy density (e) released by SNIi and BHxs, as a function of redshift, for both S230-SN and S230-BHX. We only considered SNIi contributions since they also originate from massive stars. SNIa events will also contribute but with a larger time-scale and lower rate.

Both the SNIi and the BHx energy contributions grow with redshift, due to the increasing cosmic SF activity. However, BHx energy feedback grows at a slower rate than SNIi one, due to the metallicity dependence of the progenitors. As the metallicity of the ISM increases, the number of BHx events diminishes, making SNe the dominating feedback mechanism. As can be seen from Fig. 2, BHx feedback is significant for $z > 7$. As an example, at $z \gtrsim 7$ it represents ~ 30 per cent of the total energy (SNIi+BHX) released into the ISM. For lower redshift, the contribution of BHx feedback progressively decays, reaching less than ~ 10 per cent of the total at $z \sim 4$ (~ 5 per cent at $z \sim 2$). The total e released by SNIi and BHx together is comparable to that of S230-SN for $z \gtrsim 7$, while for lower redshift, that of S230-BHX is greater due to the SFR enhancement

¹ For the adopted $E_{\text{BHx}} = 10^{52}$ erg, we tested $f_{\text{BHx}}^{\text{EMP}}$ between ~ 1 and ~ 20 per cent, finding $f_{\text{BHx}}^{\text{EMP}} \sim 0.20$ reproduced the observed trend (Fig. 1). However, this factor might vary if the E_{BHx} is changed accordingly so that the total amount of released energy per population remains within the same values. Otherwise, the effects on the ISM are found to be too weak or too strong.

triggered in this simulation, as can be seen in Fig. 1.² We will come back to this point later on.

The SNII and BHX energy release should affect the regulation of the SF in different ways, depending on the energy available to heat up the cold gas clumps where stars are born. Fig. 2 (lower panel) displays the energy released by SNII and BHXs to the cold gas phase, as a function of redshift. For S230-BHX, the amount of energy dumped by BHXs at high redshift is similar to that of SNII. The total amount of feedback into the cold gas is then larger in S230-BHX than in S230-SN, producing an early heating of the gas that diminishes the SF activity. In fact, this can be appreciated from the cSFR, shown in Fig. 1 for both simulations. As expected, in S230-BHX the BHX feedback diminishes the SF activity for $z \gtrsim 7$ with respect to that of S230-SN, because it provides a larger amount of energy used directly in cold gas heating. The lower SF rate in S230-BHX also explains the lower SNII feedback in this simulation (Fig. 2). We note that the SF activity in S230-BHX increases for $z < 7$ faster than in S230-SN, reaching values comparable to observations (Behroozi et al. 2013). Hence, the impact of BHXs on the regulation of the SF is boosted to lower redshift by making gas available to SF at late times.

4 THE EFFECTS OF BHX FEEDBACK ON SIMULATED GALAXIES

In order to assess the effects of BHX feedback on the regulation of the SF in galaxies of different masses, we first constructed galaxy catalogues from S230-SN and S230-BHX. We use the friends-of-friends technique to select the virialized structures, and the SUBFIND algorithm (Springel et al. 2001) to identify the substructures within the virial radii. We only consider simulated galaxies resolved with more than 500 particles. In order to test the robustness of our results against numerical resolution, we run a higher numerical resolution initial condition increasing the mass resolution by a factor of 8. We acknowledge the fact that our simulated volume is small to provide a complete description of the galaxy populations. However, by comparing the same initial condition run with different feedback agents, we are able to underpin the effects of these agents within the mass range of $\sim 10^9$ – $10^{11} M_{\odot}$. Hence, the analysis should be taken on individual galaxy basis, and as a first step towards understanding the impact of BHXs as a possible feedback mechanism.

We carry out an analysis of the simulated galaxies from $z \sim 9$ to $z \sim 4$. For each available snapshot of the simulations, simulated galaxies are defined at the optical radius which corresponds to that enclosing 83 per cent of the baryonic mass of the selected system. The dark matter halo masses are calculated at the virial radius.

² The impact of BHX feedback on the global SF activity when the numerical resolution is increased is similar, although as explained before, S320 runs formed more stars for the same set of SN and SF parameters (see Section 2.1.1). By comparing the energy released by BHX and SNII events in S320-SN and S320-BHX, we found a maximum of ~ 30 per cent contribution from BHX feedback, which decays rapidly with redshift as the ISMs are chemically enriched, in a similar fashion as reported for S230 in Section 3. The specific redshift at which BHX feedback is maximum over SNII feedback is a statement which depends on the box-size. Our simulated box correspond to a small field region, so a larger volume will be required to make a full statement on this aspect.

4.1 The stellar-to-dark mass ratio

First, we study the ratio between the mean stellar mass and their virial halo mass of the simulated galaxies as a function of the latter. The estimated relations for S230-SN and S230-BHX are shown in Fig. 3. For comparison, we also show the results obtained using the abundance matching technique by Behroozi et al. (2013) at redshift $z \sim 7, 5, 4$, and by Moster et al. (2013) at redshift $z \sim 4$. In the case of Moster et al. (2013) data, we extrapolate their stellar-to-halo mass relation to lower halo masses. We note that the simulations tend to resolve smaller virial haloes compared to those shown by Behroozi et al. (2013), except for $z \sim 7$ where there is a better match of the mass range. Therefore, we extrapolate the trends to draw conclusions.

At $z \sim 7$, there is an excess of stars in small haloes in S230-SN compared to those detected in S230-BHX. This excess originates in the very efficient transformation of gas into stars at the early stages of evolution in S230-SN as also reported in previous works (e.g. Sawala et al. 2011; De Rossi et al. 2013). Although our SN feedback model is successful at producing galactic outflows and fountains, which regulate the SF, it is less efficient in the first stages of galaxy formation. When the energy released by BHXs is added to the SN feedback, then a decrease in the SF activity at high redshift is detected. In Fig. 2, we compared the relative importance of both feedback mechanisms as a function of redshift. In Fig. 3, we can appreciate the effects on individual galaxies. In fact, the regulation of the SF by BHX events is more efficient in low-mass haloes, steepening the relation between the stellar-to-halo mass ratio and the halo mass of the galaxies. In haloes less massive than $\sim 10^{10} M_{\odot}$, simulated galaxies in S230-BHX have less stellar mass than those in S230-SN. For larger halo masses instead, the simulated galaxies in S230-BHX reach larger fractions of stars compared to the SN feedback run. This trend is produced because simulated galaxies in these haloes have larger amount of gas to feed the subsequent SF process. This can be explained as a consequence of the impact of BHXs at early times, when the systems were smaller and could be affected by BHX feedback.

We note that although the cSFR of S230-BHX reproduces the observations compiled by Behroozi et al. (2013), there seem to be still more stars per dark matter halo at $z \lesssim 7$. However, the slope of stellar-to-halo mass relation agrees better to the extrapolation of observations for lower masses. This is also valid when compared to Moster et al. (2013) at $z \sim 4$.

4.2 Gas fractions

The impact of the SN and BHX feedback on the stellar mass of galaxies can also be studied by comparing the ratio between the mean gas mass and the virial halo mass. Fig. 4 shows this relation as a function of the halo mass for galaxies in S230-BHX and S230-SN, and for the same redshift range displayed in Fig. 3. The gas mass of the simulated galaxies is estimated as the total mass of gas particles inside their optical radii.

As can be seen from Fig. 4, simulated galaxies in S230-BHX have higher gas masses than those in the simulation without BHX feedback, regardless of their host haloes. At $z \sim 7$, we detect the smaller gas fraction in S230-SN for $M_h > 10^{10} M_{\odot}$. This result seems to be at odds with the trends shown in Fig. 3, under the hypothesis of a close-box model. Indeed, if there were no gas infall or outflow, then the galaxies with the larger stellar mass fraction should have had the smaller gas fraction. However, this is not what we see in Fig. 4. The fact that galaxies in S230-BHX have larger

fraction of gas within their optical radii suggests that their counterparts in S230-SN have lost larger fractions of their gas reservoirs and hence, the subsequent SF is lower. If this were the case, then galactic outflows should have carried out more material to

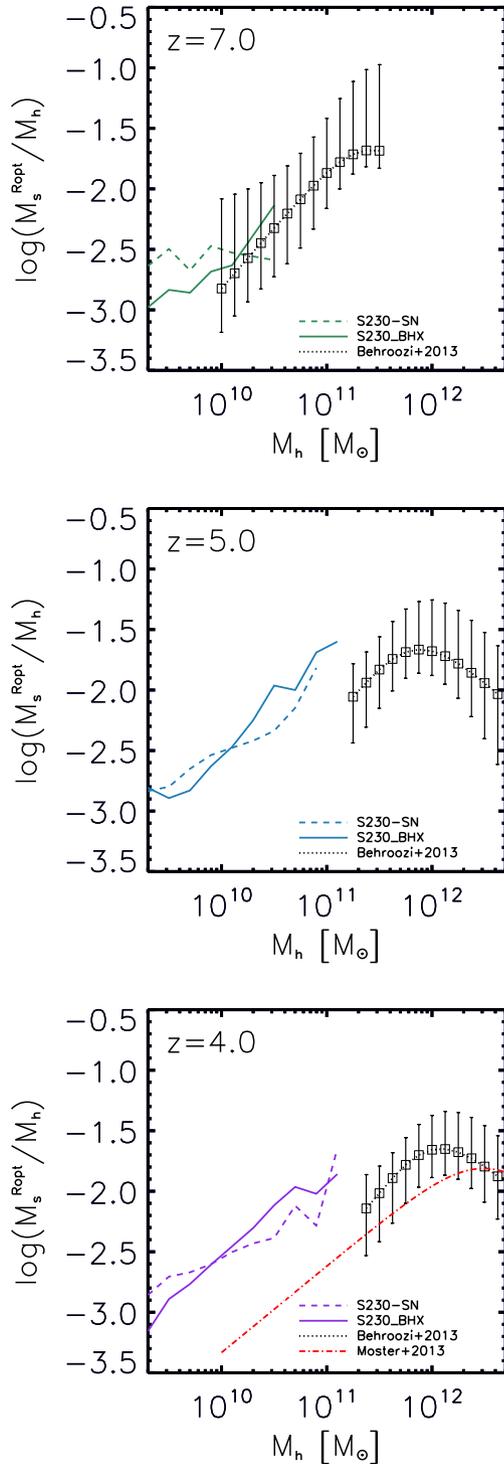


Figure 3. Mean stellar-to-halo mass ratio as a function of halo mass, for redshifts $z \sim 7, 5$ and 4 . We estimate the stellar mass of a galaxy as the total mass of stellar particles inside the optical radius. Dashed lines represent galaxies in S230-SN, while solid lines show those in S230-BHX. The results of abundance matching techniques taken from Behroozi et al. (2013) are plotted in black as open squares plus a dotted line. For $z \sim 4$ we include also the extrapolation of the data of Moster et al. (2013, dash-dotted red line).

the circumgalactic medium (CGM) of these galaxies, increasing its temperature.

In order to analyse this feedback loop between the ISM and the CGM of the simulated galaxies, we estimate the fraction of the total gas mass within the virial radius which remains within the optical radius in both simulations. As can be seen in Fig. 5, in S230-BHX, simulated galaxies in haloes with virial masses in the range $10^{10} M_{\odot} \lesssim M_h \lesssim 10^{11} M_{\odot}$ are able to retain larger amounts of gas than their counterparts in S230-SN. For smaller and larger haloes, both simulations show the same level of remnant gas within the optical radius. In the quoted halo mass range, galaxies in S230-SN have been able to lose a larger fraction of gas, which can be understood considering their higher early SF activity. As a consequence, gas outflows are triggered, expelling larger amount of gas. This produces a decrease of the SF activity afterwards since there is less gas to fuel it. In fact, as shown in Fig. 1, the SF activity of S230-SN at low redshift remains lower than that estimated by Behroozi et al. (2013), whereas it is higher at high redshift. Hence, this suggests that it will not be possible to reach an agreement if only SN feedback is present (see also Stinson et al. 2012). Increasing the SN feedback to decrease the SF at high redshift would make the

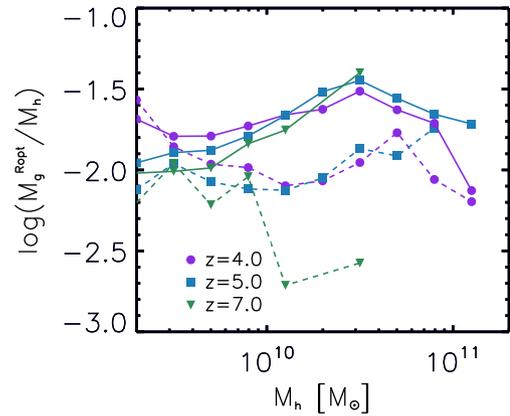


Figure 4. Gas-to-halo mass ratio as a function of halo mass for simulated galaxies in S230-BHX (solid lines) and S230-SN (dashed lines). The relations are shown for three different redshifts: $z = 7$ (green triangles), 5 (blue squares) and 4 (violet circles). Gas mass is estimated as the total mass of gas particles enclosed within the optical radius of a galaxy at a given redshift.

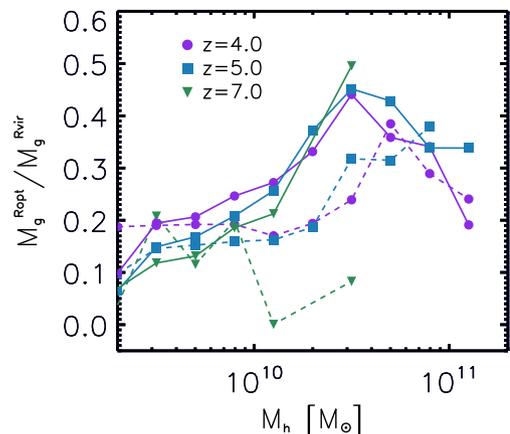


Figure 5. Fraction of the total gas within the virial radius retained within the optical radius, for simulated galaxies in S230-BHX (solid lines) and in S230-SN (dashed lines) at $z = 7$ (green triangles), 5 (blue squares) and 4 (violet circles).

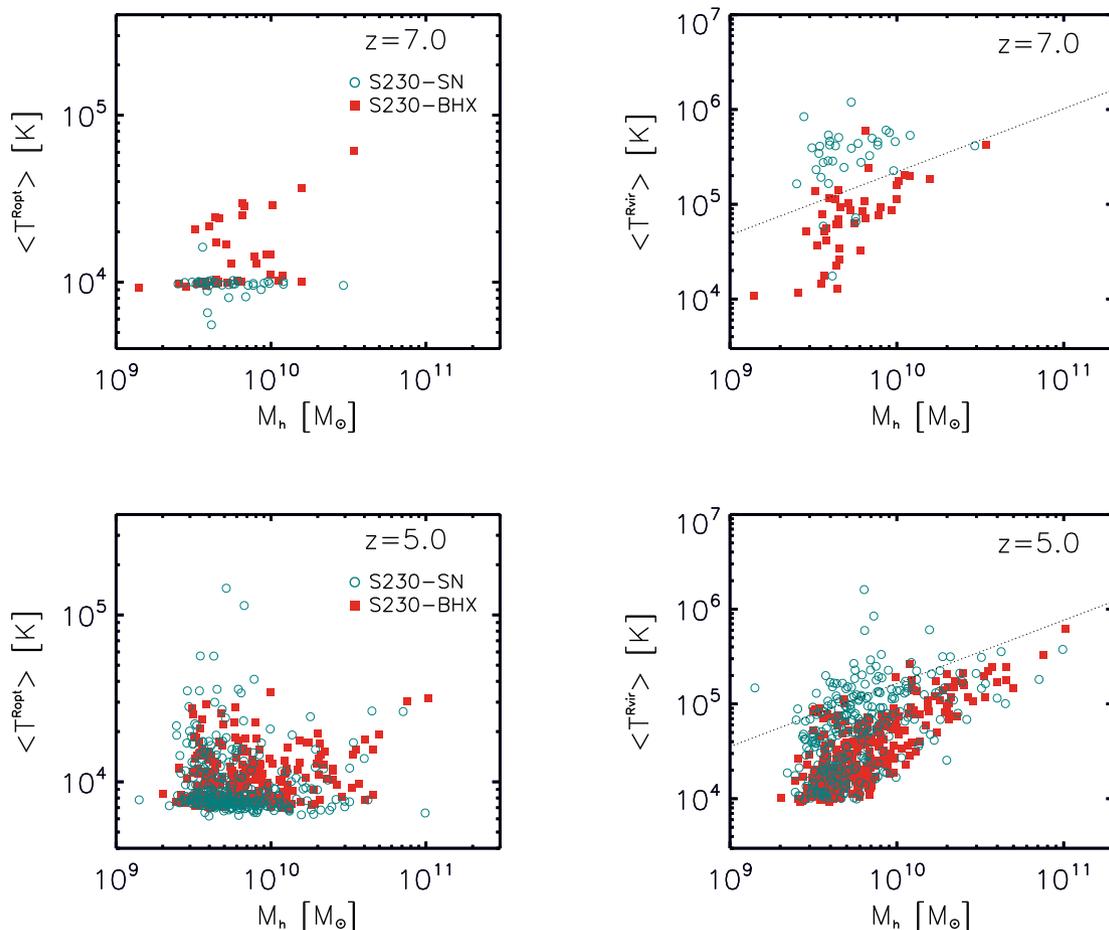


Figure 6. Median temperatures of the gas component within the optical radius (left-hand panels) and within the virial radius (right-hand panels), for galaxies in S230-BHX and S230-SN at $z = 7$ and 5. The dotted lines represent the relation between virial mass and virial temperature. Note that at $z = 7$, simulated galaxies in S230-BHX have hotter ISMs than their counterparts in S230-SN. Conversely, the CGMs of galaxies in S230-SN get hotter sooner, as a consequence of the hot material transported by outflows. These outflows are triggered by the more violent SN feedback, produced by the larger SFR taken place in this run at very high redshift.

discrepancy at lower redshift even larger. It is the action of the BHX feedback that helps to regulate the SF at very high redshifts, which then results in the desired trend at lower ones.

As we can see from Fig. 3, there seems to be a halo mass threshold below which BHXs are efficient at modulating the SF. This is approximately $M_h \sim 10^{10} M_\odot$, which corresponds to circular velocities $V_{\text{vir}} \sim 40 \text{ km s}^{-1}$ or a virial temperature of $T_{\text{vir}} \sim 50\,000 \text{ K}$ (assuming primordial abundances). For galaxies below this threshold, the BHX feedback is strong enough to heat the ISM to $T \sim T_{\text{vir}}$, decreasing the SF activity without expelling a significant fraction of gas mass.

To illustrate this, in Fig. 6 we show the mean temperature of the gas within the optical (left-hand panels) and the virial (right-hand panels) radius, for simulated galaxies in both runs, at $z \sim 7$ and $z \sim 5$. The run with BHXs shows hotter environment within the optical radius, although with temperatures smaller than T_{vir} . Conversely, galaxies in S230-SN have lost gas by SN feedback. In fact, SN feedback has been successful at building a hot CGM even at these high redshifts. The CGMs are colder in the run with S230-BHX, since the total stellar mass formed per halo is not enough to drive powerful winds yet. The BHX feedback has contributed to heat up the gas within the galaxies, decreasing the mass of new-

born stars in haloes with $M_h < 10^{10} M_\odot$. Therefore, as they grow by hierarchical clustering, they will be able to have larger gas reservoirs to continue their SF activity. Later on, as the SN rate increases, the SN feedback contributes to heat up the CGMs of galaxies in S230-BHX.

4.3 The stellar mass of galaxies

To assess how the effects of BHX feedback modify the stellar mass of galaxies, we estimate the cumulative number of galaxies as a function of their stellar mass. As can be seen from Fig. 7, the simulations behave differently. The simulation with BHX feedback shows a notable evolution with redshift, with ~ 80 per cent of the galaxies exhibiting stellar masses smaller than $10^7 M_\odot$ at $z \sim 7$, percentage which decreases to ~ 50 per cent at $z \sim 4$. Conversely, the simulation with only SN feedback does not present a clear evolution in this redshift range. On average, ~ 50 – 60 per cent of the galaxies have stellar masses smaller than $\sim 10^7 M_\odot$. These trends confirm that galaxies in S230-BHX form less stars in small galaxies than those in S230-SN. Hence, BHX thermal feedback affects directly small galaxies but indirectly larger ones. Those mostly affected

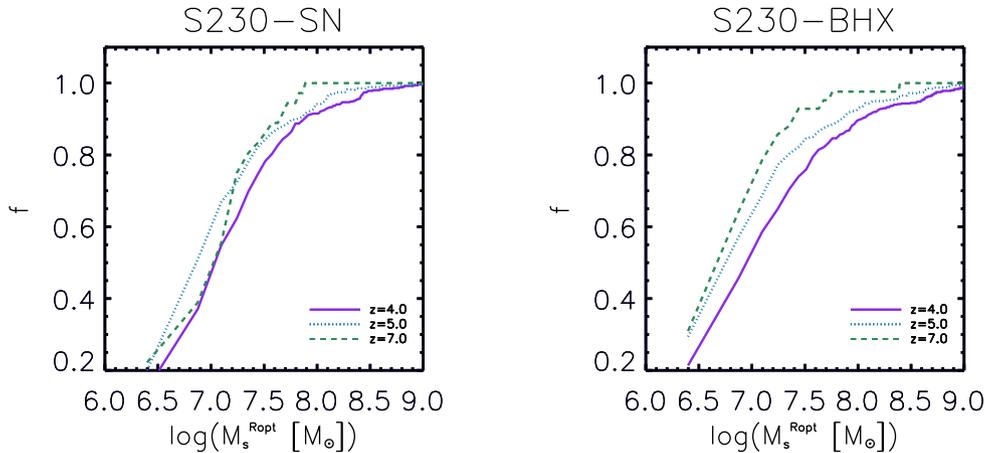


Figure 7. Cumulative distribution of the stellar mass within the optical radius at $z \sim 7$ (green dashed line), $z \sim 5$ (blue dotted line) and $z \sim 4$ (violet solid line). Left: simulation without BHX feedback. Right: simulation with BHX feedback.

have stellar masses between 10^7 and $10^8 M_\odot$ and inhabit haloes with $V_{\text{vir}} \sim 40 \text{ km s}^{-1}$.

4.4 Testing numerical resolution

In order to test the robustness of our trends against numerical resolution, we analyse the simulated galaxies in S320-SN and S320-BHX at $z \sim 7.5$ and $z \sim 8$. Galaxies have been selected and analysed by using the same criteria, although the minimum number of particles was increased to 2000 in order to avoid including very small systems which were not considered in S230-BHX.

In Fig. 8, we show the stellar-to-virial mass relation in a similar fashion as in Fig. 3. The relations for galaxies in S320-BHX and S320-SN cross each other at about $M_h \sim 10^{10} M_\odot$ in agreement with the trends found in the S230 runs. Even more, the cumulative distribution of stellar mass also exhibits a similar trend to those found in S230 (Fig. 7). And as a consequence, this agreement between the low- and high-resolution runs suggests that the results are numerically robust.

4.5 Contribution of X-ray photons

As already discussed, the rate and X-ray luminosity of BHXs are expected to be highly related to the metallicity of the progenitor stars as suggested by observational and theoretical studies. Due to the long mean free path of X-ray photons, BHXs could contribute significantly to the heating and ionization of the IGM at early stages of galaxy evolution (e.g. Mirabel et al. 2011; Power et al. 2013; Jeon et al. 2014; Kneivt et al. 2014). Mirabel et al. (2011) show how the evolution of the temperature of the low-density neutral IGM due to heating by X-rays from BHXs may depend on the value of the parameter f_X . This parameter is defined as the ratio of the total X-ray luminosity L_X of a galaxy in the 2–10 keV band to its SFR, and its value can be estimated from the expression

$$f_X = (3.5 \times 10^{40} \text{ SFR})^{-1} L_X, \quad (1)$$

where L_X is measured in erg s^{-1} and the SFR in $M_\odot \text{ yr}^{-1}$. An increase of f_X would cause the neutral IGM to be heated earlier due to the presence of BHXs. This could limit the cold gas accretion in dwarf galaxies at high redshift.

Although the detailed analysis of X-ray feedback of BHXs into the IGM is out of the scope of this work, we estimate the value

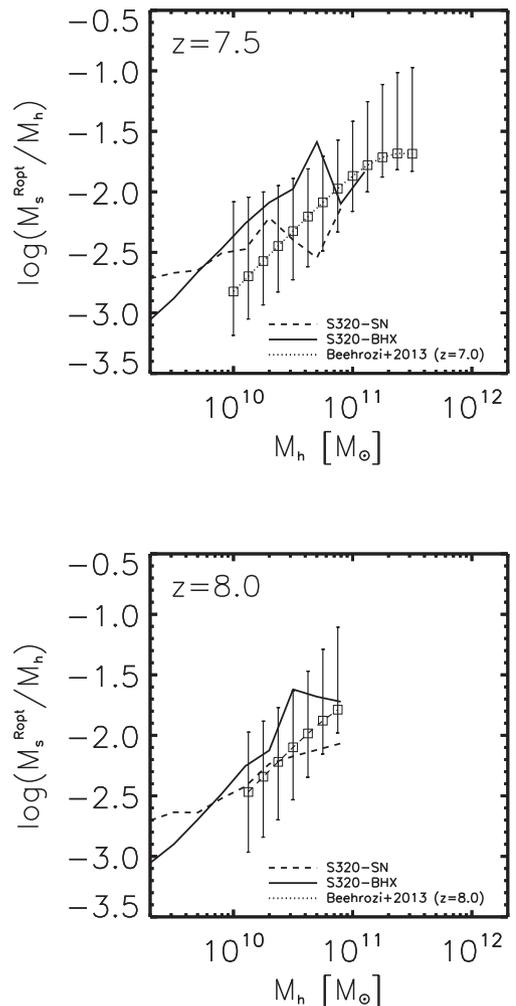


Figure 8. Mean stellar-to-virial mass relation at $z = 7$ and 8 , for simulated galaxies in S320-SN (dashed lines) and S320-BHX (solid lines). The results of abundance matching technique from Behroozi et al. (2013) are included (dotted line plus open squares). The main impact of BHX feedback occurs for $M_h < 10^{10} M_\odot$, in agreement with results found for S230-BHX.

of f_X using our model for extremely metal poor BHs in order to evaluate its compatibility with expectations from other models. The emission of these BHs should dominate the X-ray luminosity of star-forming galaxies mainly at high redshift when most young stellar populations were metal poor. In any case, our predicted f_X represents a lower limit, resulting in a conservative contribution to radiative feedback in the early Universe.

Assuming that BHs radiate a similar amount of energy in X-ray luminosity to that injected in kinematic outflows (i.e. $\epsilon_X = E_{\text{BH}} = 10^{52}$ erg), and a mean emission time of ~ 3 Myr, the mean X-ray luminosity per source is $L_X \sim 10^{38}$ erg s $^{-1}$, as already mentioned in Section 2.2. If the number of BHs produced in a galaxy is N_{BH} , then the mean total X-ray luminosity of a simulated galaxy originated from BHs is $L_X^G = N_{\text{BH}} L_X$, which can be easily computed at each time step of the simulation. To make a proper comparison with Mirabel et al. (2011), we use the galaxy catalogue of S320-BH at $z \sim 9$. These simulated galaxies have SFR and L_X^G in the range $[0.01\text{--}20] M_\odot \text{yr}^{-1}$ and $[10^{39}\text{--}10^{41}] \text{Jerg s}^{-1}$, respectively. Hence, the mean f_X value obtained at $z \sim 9$ is $\langle f_X \rangle = 0.65$.

Note that the total X-ray luminosities of simulated galaxies do not exceed the X-ray luminosity limit of the deepest surveys (4 Ms *Chandra Deep Field-South*, CDF-S; Xue et al. 2011). At $z \sim 9$, the 2–10 keV rest-frame energy band corresponds roughly to the observed soft band 0.2–1 keV. The flux limit of the 4 Ms CDF-S in the soft band is 9.1×10^{-18} erg cm $^{-2}$ s $^{-1}$; therefore, the (k -corrected) luminosity limit at $z \sim 9$ is $L_{X,\text{lim}} \sim 4.6 \times 10^{42}$ erg s $^{-1}$. Hence, our BHs model does not contradict the upper limits imposed by current surveys.

The $\langle f_X \rangle$ value obtained does not take into account the absorption of X-ray photons before reaching the IGM. A rough estimation of the fraction of escaping photons into the IGM could be obtained by adopting a power-law spectral energy distribution for the sources, with an index of 1.7 in the 0.5–10 keV range (Swartz et al. 2004). We calculate this fraction for a typical halo of $M_h = 10^8 M_\odot$, assuming an exponential surface density for the galaxy. We assume that the ratio of the baryonic-to-dark-matter mass is $m_d = 0.17$, the spin parameter is $\lambda \sim 0.03$ and $j_d/m_d = 1$, where j_d is the ratio of the angular momentum of baryons to that of the halo (Mo, Mao & White 1998; Fernandez & Shull 2011). Considering that X-ray photons would ionize both hydrogen and helium in the IGM, we use the cross-sections of Kuhlen & Madau (2005). The estimated escape fraction is then $f_{\text{esc}} \sim 0.53$. Therefore, the effective $\langle f_X \rangle$ would be $\langle f_X \rangle_{\text{eff}} \sim 0.34$ at redshift $z \sim 9$. This value is lower than that proposed by Mirabel et al. (2011) where $f_{\text{esc}} \sim 1.0$ is assumed. Our simple estimation implies that the generated X-ray photons could barely heat the temperature of the IGM above 10^3 K. However, our estimations are too crude to draw more robust conclusions on this aspect. This effect can be studied with radiative transfer models in detail (e.g. Kneivitt et al. 2014).

5 CONCLUSIONS

In this work, we explore the effects of HMXBs composed of an accreting BH, on galaxy evolution (Justham & Schawinski 2012). Following previous results, our model assumes that the rate, X-ray luminosity and outflow energy of BHs increase for low-metallicity progenitors (Dray 2006; Linden et al. 2010). The BH feedback model is grafted into a version of P-GADGET-3 which includes SN feedback and chemical evolution (Scannapieco et al. 2006), so that its effects can be studied as the structure forms and evolves.

The estimated kinetic energy released by BHs is assumed to be efficiently thermalized and hence, is pumped into the cold gaseous

phase in the surrounding region of the sources. This extra source of energy has an impact on the properties of the ISM at early stages of evolution and in low-velocity haloes. Encouragingly, our results agree with those reported by Justham & Schawinski (2012) where a semi-analytical model was used to implement a scheme based on similar hypotheses.

Our results can be summarized as follows.

(i) Following observations which indicate that the kinetic energy deposited by these sources might be comparable to that radiated in the X-ray bands (during ~ 3 Myr), we estimate that each BH event could inject $\sim 10^{52}$ erg in the form of kinetic energy in the ISM. With these hypotheses and in order to reproduce the observed cSFR, our BH model requires that a fraction of ~ 20 per cent of BHs with metallicity in the range $Z_{\text{EMP}} = [0, 10^{-4}]$ should end up as X-ray binary systems. We tested combinations of larger and lower released kinetic energy and BH fractions finding that they produce too strong or too weak effects, resulting in an inadequate regulation of the SF at high redshift.

(ii) Our model predicts BH feedback to affect more strongly galaxies with stellar masses in the range $10^7\text{--}10^8 M_\odot$ which inhabit haloes with virial velocities smaller than $V_{\text{vir}} \sim 40$ km s $^{-1}$. Larger haloes would experience a negligible impact due to their larger potential wells but they could be indirectly affected by the accretion of smaller haloes. These results are shown to be robust against numerical resolution.

(iii) The energy injected by BHs helps to regulate the SF activity in low-mass haloes, decreasing the fraction of stars formed at very high redshift. As a consequence, there is more gas available for SF at later times. Therefore, when BH feedback is included, the cSFR reproduces closely observational results (Behroozi et al. 2013). In this simulated volume, we found that the BH energy represents an ~ 30 per cent of total feedback energy released into the ISM at $z \sim 7$ and a 10 per cent at $z \sim 4$.

(iv) When BH feedback is included, the number of galaxies as a function of stellar masses shows a larger evolution with redshift (for $z > 4$) compared to the run with only SN feedback turned on. The variation of the evolution is driven by the low-mass haloes which are more significantly affected by BH feedback, and hence, its characteristics could be an observational test to probe the action of this feedback.

(v) The stellar-to-virial mass relation for $z \sim 7$ is in better agreement to that predicted from abundance matching (Behroozi et al. 2013; Moster et al. 2013). For lower redshift, there is still an excess of stars, although the slope of the relation is more comparable to the predicted trends.

(vi) Simulated galaxies with BH+SN feedbacks exhibit hot ISM at very high redshift but their mean temperature is smaller than the virial temperature of the haloes. If the BH feedback is switched off, the resulting ISMs are colder and the fraction of new-born stars is higher in low-mass haloes. As a consequence, the number of SNe is enough to blow part of the ISMs, contributing to building up hotter CGMs. In order to prevent this, the SN feedback should be weakened but this would lead to a further increase of the SF, producing a larger stellar fraction.

Hence, our results support previous claims that the BHs could be an important source of feedback in early stages of galaxy evolution by regulating the SF in haloes with $V_{\text{vir}} \leq 40$ km s $^{-1}$. It goes in the same direction as the so-called enhanced feedback although BH feedback would have significant impact only in the very early Universe.

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