Photoheating and supernova feedback amplify each other’s effect on the cosmic star formation rate

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ABSTRACT

Photoheating associated with reionization and kinetic feedback from core-collapse supernovae have previously been shown to suppress the high-redshift cosmic star formation rate. Here, we investigate the interplay between photoheating and supernova feedback using a set of cosmological, smoothed particle hydrodynamics simulations. We show that photoheating and supernova feedback mutually amplify each other’s ability to suppress the star formation rate. Our results demonstrate the importance of the simultaneous, non-independent inclusion of these two processes in models of galaxy formation to estimate the strength of the total negative feedback they exert. They may therefore be of particular relevance to semi-analytic models in which the effects of photoheating and supernova feedback are implicitly assumed to act independently of each other.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift.

1 INTRODUCTION

The cosmic star formation rate (SFR) is an important observable of our Universe. It is affected by a variety of physical processes, many of which are in turn regulated by the SFR, giving rise to so-called feedback loops (for an overview see, e.g. Ciardi & Ferrara 2005). Photoionization heating due to the absorption of ionising photons from star-forming regions and the injection of kinetic energy from supernova (SN) explosions of massive stars provide two such feedback loops. Their implications for the assembly of the first generation of galaxies have been extensively discussed in studies of the epoch of reionization (for a review of this epoch see, e.g. Loeb & Barkana 2000).

Photoheating associated with reionization increases the mean temperature of the intergalactic medium (IGM) to \(\sim 10^4\) K (e.g. Hui & Gnedin 1997) and reduces the rate at which hotter gas can cool (Efstathiou 1992; Wiersma, Schaye & Smith 2009). The increase in the gas temperature keeps the IGM smooth and prevents the assembly of low-mass galaxies, that is, galaxies with masses corresponding to a virial temperature \(\lesssim 10^4\) K (e.g. Shapiro, Giroux & Babul 1994; Gnedin & Hui 1998). Moreover, the gas in galaxies that have already collapsed is relatively quickly photoevaporated (e.g. Shapiro, Iliev & Raga 2004; Iliev, Shapiro & Raga 2005), strongly decreasing the gas fraction of low-mass haloes (e.g. Thoul & Weinberg 1996; Barkana & Loeb 1999; Dijkstra et al. 2004; Susa & Umemura 2006). Indeed, the cosmic SFR has been predicted to exhibit a distinct drop around the redshift of reionization (Barkana & Loeb 2000). Photoionization heating is therefore said to provide a negative feedback on reionization.\footnote{As pointed out by Pawlik, Schaye & van Scherpenzeel (2009), photoheating also provides a strong positive feedback on reionization because the increase in the gas temperature smooths out density fluctuations, reducing the recombination rate.}

SN explosions of massive stars typically inject a few solar masses of gas with velocity of \(\sim 10^4\) km s\(^{-1}\), corresponding to a kinetic energy of \(\sim 10^{51}\) erg. The ejected material sweeps up and shock heats the surrounding gas, entraining outflows sufficiently powerful to, at least temporarily, substantially reduce the gas fractions for galaxy-scale dark matter haloes (e.g. Yepes et al. 1997; Scannapieco et al. 2006). Since this leads to a suppression of the SFR, SN explosions, like photoheating from reionization, provide a negative feedback on reionization. In addition to the depth of the gravitational potential, the ability of SN feedback to reduce the gas fractions generally depends on the geometry of the gas distribution (e.g. Mac Low & Ferrara 1999).

Studies of the effects of photoheating and SN feedback on the SFR that considered each process in isolation have been augmented by studies that included both photoheating and SN feedback. These studies include simulations of the formation of the first stars (e.g. Greif et al. 2007; Whalen et al. 2008; Wise & Abel 2008) of the evolution of isolated galaxies (e.g. Fujita et al. 2004; Dalla Vecchia & Schaye 2008; Tasker & Bryan 2008), and of galaxies in a cosmological volume (e.g. Tassis et al. 2003). Some of these studies also investigate the interplay between photoheating and SN feedback. For example, Kitayama & Yoshida (2005) demonstrated in a one-dimensional hydrodynamical study that a previous episode...
of photoheating may increase the efficiency of the evacuation of dark matter haloes by (thermal) SN feedback and enable the destruction of galaxies out to much larger masses. In this Letter, we report on another interaction of star formation feedbacks, using three-dimensional galaxy formation simulations.

We employ a set of Smoothed Particle Hydrodynamics (SPH) cosmological simulations that include star formation, and photoionization heating from a uniform ultraviolet (UV) background and/or kinetic feedback from core-collapse SNe. We investigate how photoheating affects the high-redshift ($z \geq 6$) SFR in the presence and absence of SN feedback and, conversely, how SN feedback affects the cosmic SFR in the presence and absence of a photoionising background. We find that the inclusion of SN feedback amplifies the suppression of the cosmic SFR due to the inclusion of photoheating. On the other hand, the inclusion of photoheating amplifies the suppression of the cosmic SFR due to the inclusion of SN feedback.

Photoheating and SN feedback therefore mutually amplify each other in suppressing the SFR. Our results are relevant to current implementations of (semi-)analytic models of galaxy formation (see Baugh 2006 for a review), in which the effects of photoheating and SN feedback are implicitly assumed to act independently of each other. These models may thus underestimate the strength of the combined negative feedback from photoheating and SNe.

We emphasize that none of our simulations has a sufficiently high resolution to achieve convergence in the cosmic SFR. Future simulations will therefore be required to quantify our qualitative statement. We show, however, that the factor by which photoheating and SN feedback amplify each other’s ability to suppress the cosmic SFR becomes larger with increasing resolution, giving credibility to our main conclusion.

This letter is organised as follows. We present our simulation method in Section 2 and we illustrate our main result in Section 3. Finally, we summarize our conclusions and discuss the caveats inherent to the present work in Section 4.

2 SIMULATIONS

Our simulation method is identical to that employed in Pawlik et al. (2009), to which we refer the reader for more details. We use a modified version of the $N$-body/TreePM/SPH code GADGET-2 (Springel 2005) to perform a total of 12 cosmological SPH simulations at different resolutions, using different box sizes. We employ the set of cosmological parameters \( \Omega_m, \Omega_b, \Omega_{\Lambda}, \sigma_8, n_s, h \) given by \([0.258, 0.0441, 0.742, 0.796, 0.963, 0.719]\), in agreement with the Wilkinson Microwave Anisotropy Probe (WMAP) 5-yr observations (Komatsu et al. 2009). The simulations include radiative cooling, star formation and, optionally, photoheating by a uniform UV background and/or kinetic feedback from SNe (see Table 1).

The gas is of primordial composition and is allowed to cool by collisional ionization and excitation, emission of free–free and recombination radiation and Compton cooling off the cosmic microwave background. Molecular hydrogen is kept photoionized at all times by the inclusion of a soft UV background. We employ the star formation recipe of Schaye & Dalla Vecchia (2008), to which we refer the reader for details. According to this recipe, gas forms stars at a pressure-dependent rate that reproduces the observed Kennicutt–Schmidt law (Kennicutt 1998).

Photoionization (heating) is included in the optically thin limit using a uniform Haardt & Madau (2001) UV background from quasars and galaxies for redshifts \(z \leq z_\star = 9\). The value for \(z_\star\) is consistent with the most recent determination of the Thomson optical depth towards reionization from the WMAP (5-yr) experiment (Komatsu et al. 2009). We inject an additional thermal energy of \(2\,\text{eV}\) per proton at \(z = z_\star\). In the absence of shocks, gas particles at the cosmic mean density are therefore kept at a temperature \(T \approx 10^4\,\text{K}\) for \(z < z_\star\) (see fig. 1 of Pawlik et al. 2009).

We model kinetic feedback from star formation using the prescription of Dalla Vecchia & Schaye (2008), according to which core-collapse SNe locally inject kinetic energy and kick gas particles into winds. The feedback is specified by two parameters, the initial wind mass loading in units of the newly formed stellar mass, \(\eta\), and the initial wind velocity \(v_w\). We adopt \(\eta = 2\) and \(v_w = 600\,\text{km}\,\text{s}^{-1}\), consistent with observations of local (e.g. Veilleux, Cecil & Bland-Hawthorn 2005) and redshift \(z \approx 3\) (e.g. Shapley et al. 2003) starburst galaxies. This choice of parameters implies that 40 per cent of the energy available from core-collapse SNe is injected as kinetic energy (assuming a Chabrier initial mass function in the range \(0.1 \leq M/M_\odot \leq 100\) and \(10^{51}\,\text{erg per}\,M > 6\,M_\odot\) star), while the remaining 60 per cent is implicitly assumed to be lost radiatively.

We use a Friends-of-Friends halo finder with linking length \(b = 0.2\) to obtain a list of dark matter haloes contained in each of our simulation outputs. Only haloes containing more than 100 dark matter particles are included in these lists. For each simulation output, we compute the SFR associated with dark matter haloes as follows. First, gas particles are attached to the nearest dark matter particle.

### Table 1. Simulation parameters. From left- to right-hand side, table entries are: simulation label; comoving size of the simulation box, \(L_{\text{box}}\); number of dark matter particles, \(N_{\text{dm}}\); mass of dark matter particles, \(m_{\text{dm}}\). A prefix \(r\) indicates the inclusion of photoheating in the optically thin limit from a uniform UV background (for \(z \leq 9\)) and a suffix \(\text{winds}\) indicates the inclusion of SN feedback (with initial wind velocity \(v_w = 600\,\text{km}\,\text{s}^{-1}\) and mass loading \(\eta = 2\)). A bold font marks our set of reference simulations.

| Simulation            | \(L_{\text{box}}\) (h\(^{-1}\) Mpc) | \(N_{\text{dm}}\) | \(m_{\text{dm}}\) (10\(^{10}\) h\(^{-1}\) M\(_\odot\)) |
|-----------------------|-------------------------------------|---------------------|---------------------------------------------|
| L6N256                | 6.25                                | 256\(^{3}\)         | 8.6                                         |
| r9L6N256              | 6.25                                | 256\(^{3}\)         | 8.6                                         |
| L6N256winds           | 6.25                                | 256\(^{3}\)         | 8.6                                         |
| r9L6N256winds         | 6.25                                | 256\(^{3}\)         | 8.6                                         |
| L3N256                | 3.125                               | 256\(^{3}\)         | 1.1                                         |
| r9L3N256              | 3.125                               | 256\(^{3}\)         | 1.1                                         |
| L3N256winds           | 3.125                               | 256\(^{3}\)         | 1.1                                         |
| r9L3N256winds         | 3.125                               | 256\(^{3}\)         | 1.1                                         |
| L3N128                | 3.125                               | 128\(^{3}\)         | 8.6                                         |
| r9L3N128              | 3.125                               | 128\(^{3}\)         | 8.6                                         |
| L3N128winds           | 3.125                               | 128\(^{3}\)         | 8.6                                         |
| r9L3N128winds         | 3.125                               | 128\(^{3}\)         | 8.6                                         |

3 RESULTS

Our main result is shown in Fig. 1. The top panel shows the evolution of the total SFR, defined as the sum of the SFRs over all haloes, for our set of reference simulations. We use \(\dot{\rho}_{\text{sh}}\), \(\dot{\rho}_{\text{h}}\) and \(\dot{\rho}_{\text{sh, winds}}\) to denote, respectively, the SFR densities in the simulations with both SN feedback and photoheating (red dashed curve, \(r9L6N256\)) and with SN feedback but without photoheating (red solid curve, \(r9L6N256\)) and with SN feedback but without photoheating (blue dashed curve, \(L6N256\))
density in the simulation that included neither photoheating nor wind feedback with $\rho_s$ (blue solid curve, $L6N256$).

Both the inclusion of photoheating and the inclusion of kinetic feedback from SNe lead to a significant suppression of the SFR. The factor $s_h \equiv \rho_s/\rho_{s,h}$ by which the SFR is suppressed due to photoheating is smaller than the factor $s_w \equiv \rho_s/\rho_{s,w}$ by which the SFR is suppressed due to kinetic feedback. As expected, the simultaneous inclusion of photoheating and feedback from SNe leads to a suppression of the SFR by a factor $s_{wh} \equiv \rho_s/\rho_{s,wh}$ that is larger than the factors $s_h$ and $s_w$ by which the SFRs are suppressed due to the sole inclusion of either photoheating or SN feedback.

Interestingly, the factor by which the SFR is suppressed due to photoheating is larger in the presence (set of dashed curves) than in the absence (set of solid curves) of SN feedback. Conversely, the factor by which the SFR is suppressed due to SN feedback is larger in the presence (set of red curves) than in the absence (set of blue curves) of photoheating.

Photoheating and SN feedback thus mutually amplify each other in suppressing the SFR. This amplification probably arises because the inclusion of photoheating keeps the gas diffuse, which makes it easier for the winds to drag it out of haloes. Winds, on the other hand, move gas from the central to the outer parts of haloes, where it is more susceptible to the photoevaporation process. Models that implicitly ignore this interaction between photoheating and SN feedback, like for example (semi-) analytic models of galaxy formation (e.g. Somerville 2002; Benson et al. 2002, 2006; Croton et al. 2006; Monaco, Fontanot & Taffoni 2007; Khochfar & Ostriker 2008), thus may underestimate the strength of the feedback these processes exert.

We now define the feedback amplification factor $\chi \equiv s_{wh}/(s_hs_w)$. A value $\chi = 1$ would indicate that photoheating and SN feedback suppress the SFR independently of each other. A value $\chi > 1$ ($\chi < 1$) would indicate that photoheating and SN feedback amplify (weaken) each other’s ability to suppress the SFR. The evolution of the amplification factor $\chi$ is shown in the bottom panel of Fig. 1, together with that of $s_{wh}$ and $s_w s_h$. The fact that $\chi > 1$ for $z < 9$ implies that photoheating and SN feedback amplify each other in suppressing star formation.

To demonstrate that this amplification is indeed mutual, we write $s_{wh} = s_{wh} s_h$ and $s_{wh} = s_{wh} s_w$. Thus, $s_{wh}$ is the factor by which SN feedback suppresses the SFR in simulations that include photoheating and $s_{wh}$ is the factor by which photoheating suppresses the SFR in simulations that include SN feedback. We have

$$s_{wh} = \frac{\rho_s/\rho_{s,wh}}{\rho_s/\rho_{s,w}} = \frac{\rho_s/\rho_{s,wh}}{\rho_s/\rho_{s,h}} = \frac{s_{wh}}{s_h} s_w.$$  

This shows explicitly that the amplification of the suppression of the SFR due to photoheating in simulations that include SN feedback is equal to the amplification of the suppression of the SFR due to SN feedback in simulations that include photoheating. It implies that we cannot determine whether photoheating amplifies the effect of SN feedback or vice versa.

Fig. 2 shows, for our set of reference simulations, the dependence of the suppression of the SFR due to photoheating and/or SN feedback on halo mass. The top panel shows the cumulative SFR at $z = 6$ in dark matter haloes less massive than $M_{\text{dm}}$. The bottom panel shows, similar to the bottom panel of Fig. 1, the feedback amplification factor $\chi$ obtained from analogous definitions of the suppression factors $s_h$, $s_w$ and $s_{wh}$ applied to the cumulative SFR at $z = 6$ shown in the top panel. The vertical dotted lines indicate the dark matter mass corresponding to a virial temperature $T_{\text{vir}} = 10^4$ K.

While photoheating strongly decreases the SFR in haloes with virial temperatures $T_{\text{vir}} \lesssim 10^4$ K, the inclusion of SN feedback leads to a strong decrease in the SFR in haloes with $T_{\text{vir}} \gtrsim 10^4$ K. Radiative and kinetic feedback thus act mostly over complementary mass ranges. This dichotomy arises because photoevaporation mainly affects the gas fractions of haloes with masses that correspond to virial temperatures that are of order of or smaller than the thermal

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2 Note that in our simulations $s_h = 1 = \chi$ for $z \geq 9$ because there is no photoheating at these redshifts.
temperature to which the gas is photoheated, $T_{\text{vir}} \lesssim 10^4$ K. In contrast, star formation and the associated SN feedback become only efficient for haloes with masses corresponding to $T_{\text{vir}} \gtrsim 10^4$ K because our simulations do not include radiative cooling from metals and molecules (and because of our limited resolution), which could potentially enable star formation in haloes of much smaller virial temperatures.

The left-hand (right-hand) panels of Fig. 3 show the evolution (mass-dependence) of the feedback amplification factor $\chi$ obtained from simulations for which we have varied the size of the simulation box and/or the resolution. Note that the solid, black curves in the left- and right-hand panels are identical to the solid, black curves shown in the bottom panels of Figs 1 and 2, respectively.

Changing the size of the simulation box by a factor of 2 (at fixed resolution; solid curves) has little effect. On the other hand, increasing the resolution by a factor of 2 (while keeping the size of the simulation box fixed; red curves) significantly increases $\chi$. The increase in $\chi$ with increasing resolution is likely due to both an increase in the fraction of galaxies that are subject to photoevaporation and an increase in the SFR (and thus associated SN feedback) of all galaxies.

4 DISCUSSION

Photoheating from reionization and SN feedback are key processes that determine the SFR in the high-redshift Universe. Using a set of cosmological SPH simulations that include radiative cooling and star formation, we analysed the $z \geq 6$ star formation history in the presence of photoionization heating from a uniform UV background and/or kinetic feedback from core-collapse SNe. The inclusion of photoheating and SN feedback both lead to a suppression of the SFR.

We showed that the factor by which the SFR is suppressed due to photoheating is larger in the presence than in the absence of SN feedback. We also showed that the factor by which the SFR is suppressed due to the inclusion of SN feedback is larger in the presence than in the absence of photoheating. This mutual amplification of SN feedback and reionization heating is the central result of the present work.

We caution the reader that our simulations have not fully converged with respect to resolution and that we have ignored some potentially important physical processes. This result will therefore need to be confirmed and quantified with future simulations. In what follows, we briefly discuss the most important physical effects that our analysis ignored.

We computed photoheating rates from a uniform UV background in the optically thin limit. Our simulations therefore do not account for the self-shielding of gas from ionising radiation. This may lower the fraction of the gas that is photoevaporated (e.g. Kitayama et al. 2000; Dijkstra et al. 2004; Susa & Umemura 2004). Iliev et al. (2005) (extending the work of Shapiro et al. 2004) have, however, pointed out that regions that are initially self-shielded will eventually also be photoevaporated: as subsequent layers of gas are photoevaporated, previously self-shielded regions become exposed to ionising radiation and are eventually stripped away. Moreover, the evaporation of the initially self-shielded gas may proceed at a speed comparable to the speed predicted by simulations that compute photoheating rates in the optically thin limit (fig. 3 in Iliev et al. 2005). Note also that because SN explosions decrease the gas density, the effects of self-shielding may be less prominent in simulations that include this type of feedback. Clearly, the importance of self-shielding and the applicability of the optically thin limit to the present problem need to be critically assessed using cosmological radiation-hydrodynamical simulations.

Although all of our simulations employ a sufficiently high resolution to resolve all haloes with virial temperatures $T_{\text{vir}} \gtrsim 10^4$ K with at least 100 particles, none of them has the resolution to properly reproduce the properties of the multi-phase medium associated with the star-forming regions these haloes host. The factors by which photoheating and SN feedback suppress the SFR are therefore not yet converged. We have, however, demonstrated that the effect of mutual amplification of photoheating and SN feedback becomes only stronger with increasing resolution.

Because we have assumed the presence of a photodissociating background, the formation of molecular hydrogen is suppressed in our simulations. In reality, the gas may contain a significant fraction of molecular hydrogen before reionization (but see, e.g. Haimean, Rees & Loeb 1997). Star formation and the associated kinetic feedback would then already be efficient in haloes with virial temperatures much smaller than $10^4$ K (e.g. Tegmark et al. 1997). Because the gas fraction in these haloes would be affected by both photoheating and SN feedback, we expect that the inclusion of molecular hydrogen would only strengthen our main result.

We have also ignored the existence of atoms and ions heavier than helium. SN explosions may, however, quickly enrich the interstellar and intergalactic gas with metals (e.g. Bromm, Yoshida & Hernquist 2003), which would increase its ability to cool. Metal enrichment thus provides a positive feedback that may partially offset the negative kinetic feedback from SN explosions.

None of the caveats we discussed seems, however, likely to invalidate our main qualitative conclusion that photoheating and SN explosions amplify each other’s effect on the cosmic SFR. Galaxy formation models that treat the effects of photoheating and SN explosions independently of each other, like for example (semi-) analytic models, may therefore significantly underestimate the effect of these feedback processes on the SFR. Because photoheating and SN feedback are important processes that affect the gas in low-mass haloes at all epochs, our findings may...
also have implications for the understanding of the properties of low-redshift galaxies, for example in the context of the missing satellite problem (for a recent discussion see, e.g. Koposov et al. 2009).

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