Galaxy formation with local photoionization feedback – I. Methods

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ABSTRACT

We present a first study of the effect of local photoionizing radiation on gas cooling in smoothed particle hydrodynamics simulations of galaxy formation. We explore the combined effect of ionizing radiation from young and old stellar populations. The method computes the effect of multiple radiative sources using the same tree algorithm as used for gravity, so it is computationally efficient and well resolved. The method foregoes calculating absorption and scattering in favour of a constant escape fraction for young stars to keep the calculation efficient enough to simulate the entire evolution of a galaxy in a cosmological context to the present day. This allows us to quantify the effect of the local photoionization feedback through the whole history of a galaxy’s formation. The simulation of a Milky Way-like galaxy using the local photoionization model forms 40 per cent less stars than a simulation that only includes a standard uniform background UV field. The local photoionization model decreases star formation by increasing the cooling time of the gas in the halo and increasing the equilibrium temperature of dense gas in the disc. Coupling the local radiation field to gas cooling from the halo provides a preventive feedback mechanism which keeps the central disc light and produces slowly rising rotation curves without resorting to extreme feedback mechanisms. These preliminary results indicate that the effect of local photoionizing sources is significant and should not be ignored in models of galaxy formation.

Key words: atomic processes – hydrodynamics – plasmas – radiative transfer – methods: numerical – galaxies: formation.

1 INTRODUCTION

Within the current paradigm of galaxy formation theory, dark matter first collapses into small haloes, which merge to form progressively larger haloes. Galaxies form out of the gas that cools towards the centres of these dark matter haloes and forms stars (White & Rees 1978; Mo, van den Bosch & White 2010).

Gas collapses into the dark matter haloes by radiating away its energy. Since angular momentum is conserved, the gas settles on to a rotating disc from which stars form. Radiative cooling controls the infall of the gas on to the disc, making it one of the most important processes of galaxy formation. A number of factors slow down the infall of the gas including thermal pressure (Binney 1977; Rees & Ostriker 1977) and the incident radiation field (Rees 1986; Efstathiou 1992; Cantalupo 2010; Gnedin & Hollon 2012). Accurately modelling the cooling rate of halo gas is critical to determining how much fuel is available to form stars in the galaxy.

Gas cooling (Λ) depends most strongly on gas density (Λ ∼ n^2), metallicity and the ionization state. The local gas hydrodynamics determines the gas densities, while chemical enrichment from stellar evolution determines the metallicity. The gas ionization state depends on the temperature of the gas and on the incident radiation field from stars, active galactic nuclei (AGNs) and other radiation sources. In most galaxy formation models (including numerical hydrodynamical simulations), a uniform background is used to represent this radiation field. This background evolves with redshift according to the cosmic star formation and quasar luminosity histories (Haardt & Madau 2012).

Rees (1986) and Efstathiou (1992) showed that photoionization can prevent the gas from cooling into low-mass haloes. Wiersma, Schaye & Smith (2009) presented more detailed results that measured the effect of a uniform photoionization background on individual ion species. Gnat & Ferland (2012) extended this analysis...
to include a variety of radiation fields that could vary due to proximity to galaxies. Oppenheimer & Schaye (2013a,b) explored the problem with a full chemical network including all the ionization states of 30 elements in typical parcels of the gas in the intergalactic medium (IGM) and found that the time it takes for the gas to reach ionization equilibrium can lead to significant changes in the state of the gas in the IGM.

Cantalupo (2010) explored analytically the effect of local sources of radiation on the cooling of the halo gas including the soft X-ray emission produced by star formation events, a component that is absent within typical stellar population synthesis models such as STARSTUDY99 (SB99; Leitherer et al. 1999) that only considers the blackbody radiation from young massive stars. Such low-energy photons do not affect the cooling rate of high-metallicity gas. However, massive stars are also strong X-ray sources due to their stellar winds, supernovae (SNe) remnants and binary interactions. When the high-energy radiation from these sources is included in gas cooling models, their radiation can ionize the metals and can decrease the cooling rate of high-metallicity gas considerably. Gnedin & Hollon (2012) created a general model for cooling in the presence of a radiation field near a galaxy (including both stars and AGNs). They showed that for a sufficiently general variation in the spectral shape and intensity of the incident radiation field, the cooling and heating functions can be approximated based only on the photoionization rates of a few important coolants.

In this paper, we follow the lead of Cantalupo (2010) and Gnedin & Hollon (2012) in an attempt to self-consistently include local ionization sources, in addition to the uniform background of Haardt & Madau (2012), in cosmological simulations of galaxy formation.

One of the great challenges for including the effect of photoionization in simulations is the need to trace the radiation as it propagates through the simulated volume. The radiation field at any given point is dependent on the brightness of and distance to the source as well as the frequency-dependent optical depth of the material between the source and sink. This makes the problem more expensive than the $O(N^2)$ direct calculation of gravity.

Various solutions have been implemented for this complex computational problem. Gnedin (2008) used the local Sobolev approximation that calculates the column density from the density of a resolution element divided by the size of that element. Altay, Croft & Pelupessy (2008, SPIRAY) and Pawlik & Schaye (2008, TRAPIC) both implemented sophisticated ray-tracing schemes in smoothed particle hydrodynamics (SPH) simulations. Altay & Theuns (2013) presented a recent update to SPIRAY. Petkova & Springel (2011) traced radiation through AREPO, a code that solves hydrodynamics on a moving mesh. For a review of how the different schemes perform in a variety of common test cases see Iliev et al. (2009). All the codes show that reionization of the Universe happens in a non-uniform manner. While such radiative transfer schemes are useful tools for studying reionization, these methods are so computationally demanding that it is impossible to evolve a cosmological simulation of galaxy formation much past $z = 4$.

Such models have been used in galaxies simulated to $z = 0$ in a post-process. Fumagalli et al. (2011) solved radiative transfer on a high-resolution grid to find that local radiation helps ionize moderate column density gas and thus reduces the number of Lyman limit and damped Lyman α systems. Rahmati et al. (2013) used TRAPIC post-process and found similar results. However, these studies do not yet explore the impact of the radiation field on the galaxy evolution.

Since it is as yet unclear what is the effect of including local ionization sources on galaxy evolution, we have decided to take a simple approach to the calculation of the radiative transfer, where possible. Our aim is to find a compromise between simulating a galaxy in a cosmological context from high redshift down to $z = 0$ and the precision of an on-the-fly radiative transfer calculation.

In a companion paper, Woods et al. (in preparation) will present the details of the radiative transfer methods, which is summarized here in Section 4.2. This paper describes how we calculate the cooling rates using that radiative transfer method and presents a preliminary simulation based on them. This paper is organized as follows: Section 2 presents the details of the cooling calculation. Section 3 describes the photoionization sources that we explicitly consider in our calculation. Section 4 outlines the approximations used in our radiative transfer approach, while Section 5 describes the construction of the cooling table. Finally, in Sections 6 and 7, we present the results of our implementation of the local photoionization feedback (LPF) on a test gas particle and on a fully cosmological simulation of galaxy formation. Our conclusions are presented in Section 8.

2 GAS COOLING

A number of processes determine the internal heating ($H$) and cooling ($\Lambda$) rates in the hydrodynamic energy equation:

$$\frac{D\rho}{Dt} = -\frac{P}{\rho} \nabla \cdot \mathbf{u} - \frac{1}{\rho} \nabla \cdot \mathbf{F} + \frac{1}{\rho} \Psi + \frac{H - \Lambda}{\rho},$$

where $\rho$ represents the specific internal energy of a parcel of gas, $-\nabla \cdot \mathbf{u}$ gives the change in internal energy due to PdV work, represents the adiabatic work done on that gas, $\mathbf{F}$ represents the flux of heat that is conducted out of the parcel and $\Psi$ represents the viscous dissipation rate.

Both the heating and cooling rates are a function of the density, $n_i$, of each ion species present in the gas parcel, as well as the parcel’s temperature, $T$, and incident radiation field, $J_i$:

$$H - \Lambda = f(n_i, T, J_i).$$

The density of each ion species is subject to a number of creation and destruction processes, which in turn also depend on $n_i$, $T$ and $J_i$:

$$n_i = f(n_j, T, J_i), j \neq i.$$  

The densities of the ion species can be obtained using networks of differential equations that account for all the electrons that are made available when atoms are ionized. Such networks can become arbitrarily complicated depending upon how many elements are included (Ferland et al. 1998; Gnat & Ferland 2012; Oppenheimer & Schaye 2013b). In simulations, it is possible to carry the ionization state of every species from timestep-to-timestep to keep the non-equilibrium ionization state of each element rather than making the assumption of ionization equilibrium (e.g. Oppenheimer & Schaye 2013a).

2.1 Primordial cooling: non-equilibrium

Since these differential equations need to be solved for each particle during every timestep in a simulation, it becomes necessary to limit the calculation of non-equilibrium ionization states to hydrogen and helium. We use the implementation of Shen, Wadsley & Stinson 2010 (also see Vogelsberger et al. 2013). Hydrogen and helium are the most abundant elements in the Universe, so their temperature and ionization state are important in determining the dynamics and cooling of gas in simulations.
Primordial gas contains various ionization states of hydrogen and helium: \( i \in (\text{H}^+, \text{H}^0, \text{He}^+, \text{He}^0, \text{e}^-) \). The rate of change of densities of these species is obtained by solving the following set of differential equations:

\[
\frac{dn_{\text{H}^+}}{dt} = \alpha_{\text{He}^+} n_{\text{He}^+} n_e - \gamma_{\text{H}^+} n_{\text{H}^+} n_e - \gamma_{\text{e}^-} n_{\text{e}^-} n_{\text{H}^+} \\
\frac{dn_{\text{He}^+}}{dt} = (\alpha_{\text{He}^+} + \alpha_{\text{e}^-}) n_{\text{He}^+} n_e - \gamma_{\text{e}^-} n_{\text{e}^-} n_{\text{He}^+} + \gamma_{\text{He}^+} n_{\text{He}^+} n_e, \\
\frac{dn_{\text{He}^0}}{dt} = \alpha_{\text{He}^0} n_{\text{He}^0} n_e - \gamma_{\text{e}^-} n_{\text{e}^-} n_{\text{He}^0} + \gamma_{\text{He}^0} n_{\text{He}^0} n_e,
\]

where \( \alpha_i \) is the radiative recombination coefficient for ion species \( i \), \( \alpha_{\text{e}^-} \) is the dielectric recombination coefficient, which only applies to He \( ^+ \), \( \gamma_{\text{H}^+} \) is the collisional ionization rate for each species, while \( \gamma_{\text{e}^-} \) is the photoionization rate defined as

\[
\gamma_{\text{e}^-} = \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{\hbar \nu} \sigma_{\text{e}^-} \, d\nu,
\]

where \( \sigma_{\text{e}^-} \) is the frequency-dependent photoionization cross-section of the species \( ^- \).

These equations are closed when combined with the following set of conservation equations:

\[ n_{\text{H}^+} + n_{\text{He}^+} = n_{\text{H}} \] \hspace{1cm} (8)
\[ n_{\text{He}^+} + n_{\text{He}^0} + 2n_{\text{e}^-} = n_e. \] \hspace{1cm} (9)

The cosmic production of helium was constrained by Jimenez et al. (2003) using K dwarfs from Hipparcos catalogue with spectroscopic metallicities, and they found that the amount of helium produced compared to heavier elements in stars follows the relation \( \Delta Y/\Delta Z = 2.1 \pm 0.4 \). In accordance with this result, we compute the helium abundance in the following manner:

\[
Y_{\text{He}} = \begin{cases} 
(0.236 + 2.1Z)/4.0 & \text{if } Z \leq 0.1 \\
(-0.446Z - 0.1)/0.9 + 0.446)/4.0 & \text{if } Z > 0.1 ,
\end{cases}
\]

with the density of hydrogen being

\[ Y_{\text{H}} = 1.0 - 4Y_{\text{He}} - Z, \] \hspace{1cm} (11)

where

\[ Y_i = \frac{n_i M_i}{\rho}, \] \hspace{1cm} (12)

where \( M_i \) is the mass of the hydrogen atom and \( \rho \) is the total density of the gas. Most of the radiative processes discussed above along with collisional excitation that causes the gas to cool, and the coefficients and the cooling rates are enumerated in Anninos et al. (1997).

In addition to determining the ionization state of gas, the incident radiation field also injects energy into the gas when a high energy \((\hbar \nu > \hbar \nu_\gamma)\) photon transfers the rest of its energy to the electron it frees from the atom. The photoheating rate is thus given by

\[ H = n_{\text{He}^+} e_{\text{He}^+} + n_{\text{He}^0} e_{\text{He}^0} + n_{\text{e}^-} e_{\text{e}^-}, \] \hspace{1cm} (13)

where

\[ e_i = \int_{\nu_\gamma}^{\infty} \frac{4\pi J_\nu}{\hbar \nu} \sigma_{\text{e}^-}(\hbar \nu - \hbar \nu_\gamma) \, d\nu. \] \hspace{1cm} (14)

### 2.2 Metal cooling: equilibrium

A significant amount of cooling also occurs via elements heavier than hydrogen and helium. For these elements, we refrain from solving the entire non-equilibrium ionization network due to its computational complexity. Instead, we assume that equilibrium conditions hold and interpolate values in a look-up table as implemented in Shen et al. (2010). The table consists of heating and cooling rates as a function of total gas density, temperature, redshift and the radiation fields from local sources, described in Section 3. Metallicity does not need to be a dimension in our table, since the cooling rate scales linearly with metallicity and can thus be easily calculated from the cooling rate of solar metallicity gas (see also Shen et al. 2010 and Vogelsberger et al. 2013).

Thus, our total cooling calculation is the summation of three components: (i) non-equilibrium primordial – calculated on the fly in the code; (ii) equilibrium metals – values tabulated from CLOUDY (v10.00, last described in Ferland et al. 1998) and (iii) Compton scattering of cosmic microwave background photons,

\[ \Lambda_{\text{tot}} = \Lambda_{\text{H,He}} + \frac{Z}{Z_{\odot}} \Lambda_{\text{Z,He}} + \Lambda_{\text{e}^-}. \] \hspace{1cm} (15)

This division neglects some sources of free electrons in the cooling calculation. CLOUDY calculates the cooling rates of metals using the free electrons created in ionization equilibrium primordial cooling. This number of free electrons may be different from the non-equilibrium primordial cooling in our code. Additionally, our non-equilibrium primordial cooling calculation assumes that the number of free electrons released from metals is negligible. Thus, our cooling calculation is a first approximation that can be improved by tracking non-equilibrium metal cooling in addition to H and He. It is worth noting that this assumption is used in practically all current numerical implementations of metal-dependent gas cooling (Shen et al. 2010; Vogelsberger et al. 2013).

### 3 IONIZING STELLAR RADIATION SOURCES

There are many radiation sources which produce high-energy photons and ionize gas in the galaxy. In the following sections, we outline the sources that we consider in our photoionization model. One source of radiation not included in our model is quasars, since we do not follow the formation or gas accretion on to supermassive black holes in our cosmological simulations. However, Vogelsberger et al. (2013) showed that the low-frequency duty cycle of radiation from AGNs results in a minimal impact on the large-scale gas dynamics in galaxies.

#### 3.1 UV background

Nearly all simulations include the effect of photoionization from a uniform background. This UV background accounts for the UV radiation that all stars and AGN emit throughout the evolution of the Universe attenuated by the Lyman \( \alpha \) forest (Haardt & Madau 2012). Our refined method is an attempt to account for more local ionizing radiation. The spectral energy distribution (SED) from Haardt & Madau (2012, henceforth HM) is shown as the cyan curve in Fig. 1. Since the HM SED incorporates the emission from AGNs, it contains photons up to X-ray energies, but the photon flux can be lower than local sources at energies less than 10 Rydbergs. We consider the HM SED as the minimum ionizing flux seen by the gas particles in our simulations, at low redshift (\( z < 9 \)).
Figure 1. The incident photon flux from the photoionization sources considered in our simulations. These fluxes are reported at 10 kpc from the source. The blue curve shows the photon flux as a function of energy from a population of young stars forming at the rate of $10 \, M_\odot \, yr^{-1}$. The young stars have the highest photon flux at the hydrogen edge but decreases quickly at higher energy. The black curve shows the spectrum of young stars including the X-ray luminous cooling of shock-heated gas after an SNe event. The SED of a $10^{11} \, M_\odot$, old ($\sim 200$ Myr) stellar population is shown in red. Old stars emit fewer photons than young stars at the hydrogen edge but have higher flux at higher energies ($\nu > 4$ Rydberg). The cyan curve shows the UV background at $z = 2$. Compared to the plotted ionization fields, this background flux is lower than local sources at low energies ($\nu < 100$ Rydberg) but dominates at higher energies due to the hard photons emitted by AGN.

3.2 Young stars

Our initial SED for young stars comes from sb99 (Leitherer et al. 1999) using an SED taken 10 Myr after stars start forming at a constant rate of $1 \, M_\odot \, yr^{-1}$ using the ‘present-day’ (equation 6) initial mass function (IMF) from Kroupa (2001) (blue curve in Fig. 1). The SED has a relatively high photon flux at the hydrogen edge (13.6 eV), but the flux drops precipitously to higher energies, with almost no flux above the helium edge (4 Rydbergs = 54.4 eV).

Fig. 2 shows how the cooling (solid curves) and heating (dashed curves) rates change in the presence of various levels of the radiation field (SFR = $1 \, M_\odot \, yr^{-1}$, blue curve; SFR = $100 \, M_\odot \, yr^{-1}$, black curve) from young stars compared to the cooling and heating rates in the presence of the peak HM radiation field (red) at $z = 2$. The gas used to make these cooling curves has a density of $n_H = 0.01 \, cm^{-3}$, a metallicity of $Z = 0.01 \, Z_\odot$ and is at a distance 10 kpc from the star-forming region. The cooling curve is calculated using the assumption that the gas in between the source and the gas test particle is optically thin. Thus, the flux is inversely proportional to the distance squared. All test cooling curves presented in this section were calculated using the code CLOUDY, which assumes photoionization equilibrium for all elements.

The sb99 young star SED suppresses hydrogen cooling that dominates in $\sim 10^4$ K gas. The spectrum also partially ionizes some helium in strong radiation fields. It also slightly changes the equilibrium temperature of the gas. The equilibrium temperature is defined as the temperature where cooling transitions to heating because of the incident radiation file. Practically, it corresponds to the temperature at which the heating and cooling rates are equal. At temperatures above equilibrium, the gas cools, while at lower temperatures, it heats up. So, the equilibrium temperature depends on the shape of the heating and cooling curves.

Radiation fields change the heating and cooling curve depending on the energy of the photons they possess. HM has the most high-energy photons, whose extra energy results in heating, so it has the highest heating rates, but it has a low flux at low energies ($\nu < 10$ Rydbergs) causing minimal impact on the cooling of low-metallicity gas. The young star blackbody spectrum includes mostly photons around the hydrogen ionization edge, so it results in minimal heating, but a large reduction in the cooling rate. The net result is that the radiation from new stars, for typical values of radiation field in the galaxy, is more effective at raising the equilibrium temperature of the gas than the background HM UV spectrum.

Fig. 3 shows the effect of metallicity on the cooling function at a fixed star formation rate of $10 \, M_\odot \, yr^{-1}$. While this radiation field eliminates hydrogen cooling at solar metallicity (note the lack of a peak around 10$^4$ K in the red curve), heavier elements make cooling rates more than an order of magnitude higher than in the low-metallicity gas (blue) at all temperatures. The higher cooling rates mean that the equilibrium temperature of the gas is also an order of magnitude lower in solar metallicity (red curve) gas because the heating rate does not change. Fig. 3 shows that cooling is most easily suppressed in low-metallicity gas irradiated with a soft UV spectrum from young stars.

3.3 X-rays from young stars

Cantalupo (2010) considered the radiation from young stellar populations, including both the blackbody radiation from hot young stars and the X-rays that SNe remnants emit. Using analytic calculations, Cantalupo (2010) showed that while stellar photons ionize hydrogen, soft X-rays ionize other significant metal coolants. The X-ray photoionization increased the equilibrium temperature, which consequently slowed the accretion of gas on to the disc.

X-rays are produced in a number of ways. Rapidly outflowing gas from stellar winds or SN explosions shocks against the interstellar medium (ISM) and thermalizes (Heckman et al. 1995; Strickland et al. 2004). Non-thermal processes associated with SNe explosions
and high-mass X-ray binaries also emit X-ray radiation (Grimm, Gilfanov & Sunyaev 2003; Persic et al. 2004).

We use the SED for a 5 Myr old stellar population (Fig. 1, black curve) from Cerviño, Mas-Hesse & Kunth (2002). The Cerviño et al. (2002) SEDs are derived from models of young O and B stars and the X-rays that their stellar winds and SN explosions produce. Their models are calibrated to match the observed relationship between SFR and soft X-rays (e.g. see Heckman et al. 1995). In their models, the X-ray emission peaks when the stellar population is ~5 Myr old and continues for ~100 Myr. To simplify our calculation, we use the SED of a 5 Myr old stellar population for all stars younger than 10 Myr, so we pick the maximum emission SED, but only use it for one-tenth of the time that X-rays are emitted. Following Cantalupo (2010), we assume that 5 percent of the mechanical energy from the SNe is emitted as X-rays.

The Cerviño et al. (2002) models assume a Salpeter IMF, but our simulations use a Chabrier (2003) IMF that has more stars with \( M_\ast > 8 \, M_\odot \). So, we renormalize the Cerviño et al. (2002) SED to make the flux from O and B stars, and the number of subsequent SNe events consistent with the Chabrier IMF.

There is significant absorption of Lyman continuum photons in the galaxy due to the abundance of hydrogen. To include this effect, we assume an escape fraction of 5 percent around Lyman-limit frequencies to mimic the highly absorptive nature of their birth molecular clouds (e.g. Bergvall et al. 2006, see Section 4.1 for a more thorough discussion on the escape fraction).

Fig. 4 shows how including X-rays in the young star SED affects the cooling curve in \( Z = Z_\odot \) gas at \( 10^{-2} \, \text{cm}^{-3} \) density at 1 kpc from the star formation site. At high metallicity, the young star SED without X-rays (thin curves) only eliminates hydrogen cooling, independent of the star formation rate of the galaxy. The harder X-ray spectrum (thick curves) ionizes heavier elements such as oxygen, neon and some ions of iron to lower the gas cooling rate and also raise the heating rate of the gas. These effects combine to increase the equilibrium temperature by an order of magnitude. X-rays thus remain an important ionization source at low redshifts, where the halo gas has been metal enriched by continuous bursts of star formation. For this reason, we use an SED that combines the blackbody emission of young stars with the X-ray emission that massive stars produce in stellar winds and SN explosions in our simulations. Henceforth, flux from young stars includes X-rays along with their blackbody spectrum.

### 3.4 Old stars

Naively, old stellar populations seem like they should not be sources of ionizing photons. Since all the hot young stars have exploded as SNe, all that are left are cool, old stars. However, a UV upturn was observed coming from the old stellar population at the centre of M31 (Code 1969) and was determined to be light from extreme horizontal branch stars. Subsequently, UV radiation has been detected from many quiescent, early-type galaxies (Kaviraj et al. 2007). What fraction of this radiation is from young stars, forming at low rates, compared to how much is from old stars is still a question waiting to be answered with better observations. Additionally, recent UV telescopes like GALEX have only been able to detect relatively soft UV radiation sources. However, stellar population synthesis models predict that stars that have shed their outermost envelopes, so-called post-AGB stars, should emit a hard UV spectrum.

Bruzual & Charlot (2003) include such stars in the SED of a simple stellar population (SSP). The SED of SSPs older than 200 Myr is harder, though much fainter (at the hydrogen edge), than the UV SED for a young SSP. In the model, the photon flux increases near the helium edge, due to the accumulation of post-AGB stars. The shape of the SED remains fairly constant from 200 Myr to 13 Gyr because low-mass stars evolve within a narrow temperature range all the way from the main sequence to the AGB phase. This implies that a constant SED can be used for old stars irrespective of their age (Fig. 1, red curve). We choose the 2 Gyr SED since it is near the mean of the SEDs.

Fig. 5 shows the effect of the old star SED on the cooling function of the gas as a function of intensity of the incident radiation field. The gas has the same conditions as that studied in Section 3.2 (\( n_H = 0.01 \, \text{cm}^{-3}, \, Z = 0.01 \, Z_\odot, \, d = 10 \, \text{kpc} \)). The radiation with energies higher than the helium edge can eliminate helium cooling in the gas.
A galaxy with $M_\star = 10^{10} M_\odot$ has less effect on the cooling function than the peak HM UV background ($z = 2$) because its ionizing flux is so low. $10^{10} M_\odot$ stars produce a strong enough radiation field to reduce cooling below the HM level. Thus, radiation from old stars starts to play a role in massive galaxies, where the radiation field is strong, and at lower redshifts, once the HM background has decreased from its peak. Thus, they might help limit star formation in massive elliptical galaxies.

The consequences of photoionization that are most critical for galaxy formation are the decrease in the cooling rate of the gas and the increase in the equilibrium temperature, which is the minimum temperature to which gas can cool. Moreover, the equilibrium temperature sets the minimum pressure a gas parcel can reach. More intense and harder radiation fields shift the equilibrium temperature higher, while higher densities and metallicities shift the equilibrium temperature lower.

### 4 Calculating the Radiation Field

In the previous section, the different sources of local ionizing radiation were enumerated and shown to be important in the calculation of gas cooling in galaxies. However, propagating the radiation from the sources to the gas particles can become computationally expensive (e.g. Altay et al. 2008). This necessitates the use of some simplifying, albeit physically motivated, assumptions. We plan to relax these assumptions in future work in order to present a more complete implementation of radiative transfer.

#### 4.1 Escape fractions

Our strongest assumption is that the gas is optically thin to photons so that the optical depth is determined simply by the escape fraction of ionizing photons from the ISM. Given the abundance of neutral hydrogen in the Universe, Lyman continuum photons with around 1 Rydberg of energy will generally see optical depths and thus have short travel distances and low escape fractions. In future work, we will try to improve our model to make more physical calculations for the optical depth. For now, we assume that since young stars form embedded in molecular clouds, the photoionizing escape fraction, $f_{esc}$, is low ($f_{esc} \sim 5\%$). This number is an upper limit, motivated by a number of observations (Steidel, Pettini & Adelberger 2001; Bergvall et al. 2006; Shapley et al. 2006; Siana et al. 2007; Grimes et al. 2009; Nestor et al. 2013). The escape fraction we use is frequency dependent ($f_{esc}^\nu$), similar to Cantalupo (2010),

$$f_{esc}^\nu = \left[ f_{esc}^{LL} + (1 - f_{esc}^{LL}) e^{-\tau_\nu} \right],$$

where $f_{esc}^{LL}$ is the absolute escape fraction at the Lyman limit, $\tau_\nu = \sigma_\nu N(H^0)$ is the neutral hydrogen optical depth and $\sigma_\nu$ the corresponding cross-section. Our 5 per cent escape fraction means that we fix $f_{esc}^{LL} = 0.05$. The value of $N(H^0)$ determines the hardening of the spectrum around the Lyman limit. We anticipate that this parameter has a little effect on our results and we fix $N(H^0) = 10^{20}$ cm$^{-2}$.

Escape fractions are a strong function of the distance from the source. $f_{esc} = 5\%$ represents the mean escape fraction at our spatial resolution of $\sim 300$ pc. For old stars, we assume that they have left their dense birth locations and that the escape fraction of their ionizing photons is 100 per cent.

#### 4.2 Combining sources

Each parcel of gas will receive an ionizing flux from all the radiation sources (stars in our case) with an intensity proportional to the inverse of the distance square. In order to reduce the computational cost of the distance calculation, we exploit the tree algorithm used to compute the gravitational force, which already groups sources according to their distance from the gas particle.

Our grouping scheme is a first rough attempt at calculating radiative transfer. Woods et al. (in preparation) will present the radiation transfer method in more detail. Our initial attempt takes little account of absorption except for the constant escape fraction used for young stars described above.

Combining sources of the same kind is an algebraic operation, since the SEDs do not evolve with time, so the summation of SEDs only affects their normalization. In this manner, the radiation field incident on a gas particle is calculated using two separate components, one from young stars ($\phi_{SFR}$) and one from old stars ($\phi_{os}$).

Young stars in our scheme are all those with an age $< 10$ Myr, while old stars have an age $> 200$ Myr. For each gas particle, the effective flux, $\phi_{eff}$, is the sum of the sources normalized by the distance from the gas particle squared, as follows:

$$\phi_{SFR} = \frac{1}{10^7 \text{ yr}} \sum_{i=1}^{N} M_i(t < 10 \text{ Myr}) \left( \frac{r}{r_i \text{ kpc}^2} \right)^2,$$

$$\phi_{os} = \sum_{i=1}^{N} M_i(t > 200 \text{ Myr}) \left( \frac{r}{r_i \text{ kpc}^2} \right)^2,$$

with the total photoionization and heating rates, for each species ‘$\gamma$’, given by

$$\Gamma_{\gamma, i} = \phi_{SFR} \Gamma_{\gamma, SFR} + \phi_{os} \Gamma_{\gamma, os} + \Gamma_{\gamma, HM},$$

$$\epsilon_i = \phi_{SFR} \epsilon_{SFR} + \phi_{os} \epsilon_{os} + \epsilon_{HM}.$$
of high-redshift galaxies. For 

As shown in equation (15), the total gas cooling is divided into primordial, metal and Compton cooling. The primordial and Compton cooling is calculated on-the-fly as described in Section 2.1. However, to reduce the complexity of the cooling calculation as the simulation runs, the metals are assumed to be in ionization equilibrium and their heating and cooling rates are tabulated across a range of physical conditions using CLOUDY. This look-up table is used in the simulations.

The table has four dimensions at \( z > 9 \) and five dimensions thereafter. The four common dimensions are density, temperature, \( \phi_{\text{SFR}} \) and \( \phi_{\text{os}} \). After \( z = 9 \), the UV background turns on, so a redshift dimension is added to track how the HM SED shape changes. We make the division at \( z = 9 \), even though HM tabulate the UV background to \( z = 15 \), in order to limit the size of the cooling table. The mean free path of photons at high redshift is low because the Universe is not yet reionized, so the flux of the background UV field is relatively low. There is never a metallicity dimension in the table as cooling is assumed to scale linearly with metallicity as discussed in Section 2.2.

In both parts of the cooling table, the density ranges from \( 10^{-9} \) to \( 10^{16} \text{ cm}^{-3} \) with a spacing of 0.5 dex in log space. The temperature ranges from \( 10^{2} \) to \( 10^{8} \text{ K} \) with a resolution of 0.1 dex. At \( z > 9 \), \( \phi_{\text{SFR}} \) ranges from \( 10^{-11} \) to \( 10^{2} \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \) with a resolution of 0.5 dex and \( \phi_{\text{os}} \) ranges from \( 10^{-12} \) to \( 10^{10} \text{ M}_\odot \text{ kpc}^{-2} \) also with a resolution of 0.5 dex. These minimum values correspond to the collisional ionization equilibrium (CIE) cooling rates, while the maximum values correspond to the maximum star formation rate and mass of high-redshift galaxies. For \( z \leq 9 \), \( \phi_{\text{SFR}} \) covers a smaller range, from \( 10^{-1} \) to \( 10^{2} \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \) with a resolution of 0.5 dex. \( \phi_{\text{os}} \) ranges from \( 10^{0} \) to \( 10^{4} \text{ M}_\odot \text{ kpc}^{-2} \) with 0.5 dex spacings. The minimum values are higher at \( z \leq 9 \) because the HM UV background sets the minimum rather than CIE. The maximum SFR and mass are increased to reflect observations. The redshift dimension that accounts for the UV background ranges from 9.0 to 0.0 with a resolution of 0.5. The resolutions were motivated by Gnedin & Hollon (2012).

To create the table, cooling and heating rates are calculated at every point for solar and primordial metallicity gas using CLOUDY. The difference between the solar and primordial metallicity values is stored as the heating and cooling rates due to the metals only. The values are stored as natural logarithms with single point precision, which provides accurate values and limits the size of the table to 78 MB, a size well within the memory capacity of modern computer hardware.

6 TEST PARTICLE EVOLUTION

The methods described in the previous sections are implemented in the SPH code GASOLINE first described in Wadsley, Stadel & Quinn (2004). As a first test of the cooling implementation, we calculate the evolution of the temperature and ionization state of a single isolated particle over the course of 350 Myr. The particle stays at a constant density and metallicity since it is not part of a fully dynamic simulation. The effects of dynamics are explored in a full simulation in Section 7.

Fig. 6 shows the evolution of a gas particle with a density \( n_H = 0.001 \text{ cm}^{-3} \) in a young star radiation field that includes X-rays as described in Section 3.3. Unlike for the cooling curves in Section 3 that showed the effect of the stellar fields and HM separately, now their fields are combined as described in Section 4.2. The effect of the background UV field alone is shown as the blue curve. The distance from the source to the test gas particle is 10 kpc. The left-hand column shows how the particle cools when its metallicity is 0.01 \( \text{Z}_\odot \), similar to unenriched gas falling for the first time into a galactic halo (Brook et al. 2013). The right-hand column shows the particle cooling time when its metallicity is 0.1 \( \text{Z}_\odot \). The gas that has cooled into the disc and has been ejected into the halo (Brook et al. 2013).

A comparison of the top two panels shows that cooling times are longer and the equilibrium temperatures are higher in low-metallicity gas. Compared to the HM line, the top right-hand panel shows that X-rays also prolong cooling at 0.1 \( \text{Z}_\odot \), though to a lesser extent than at 0.01 \( \text{Z}_\odot \). The lower four panels show that the young star radiation fields keep hydrogen and helium ionized even after the gas cools. What is not shown in the ionization plots is that they can also ionize other potential metal coolants.

For each metallicity, stronger radiation fields reduce the neutral hydrogen and He II fractions (middle and bottom panels). In the
0.01 \solarmass case, the lack of metals means that the delayed cooling is primarily due to the ionization of hydrogen and helium. While the fractions of neutral hydrogen and He ii are similar between the 0.01 and 0.1 \solarmass with the same ionization field, the cooling rate in 0.1 \solarmass is higher. The faster cooling is due to metal coolants more prevalent in the 0.1 \solarmass gas. Since metal cooling is computed using equilibrium gas in CLOUDY, it is impossible to show the ionization state of the metal coolants in our current test particle runs (but see Oppenheimer & Schaye 2013b).

Fig. 7 shows the evolution of the same particles in the old star radiation field. Old stars have a smaller effect than young stars that include X-rays, especially in high-metallicity gas. The He ii fractions (bottom panels) are systematically lower in the old star radiation field (Fig. 7) than in the young star field (Fig. 6) because the flux at energies just above the helium ionizing edge is higher. While old stars ionize helium, they do not ionize metals, so the gas cools faster at high metallicities than it does in young star radiation field.

### 7 COSMOLOGICAL SIMULATION USING LOCAL PHOTOIONIZATION FEEDBACK

We want to study the effect of local ionizing radiation on the whole process of galaxy formation in a cosmological context. For this purpose, we implement LPF in GASOLINE. The version of GASOLINE is the same as described in Stinson et al. (2013) with the changes to cooling that have been described in the previous section.

#### 7.1 Simulation physics

We select a galaxy from the McMaster Unbiased Galaxy Simulations (Stinson et al. 2010) that has a halo mass of $6.4 \times 10^{11} \solarmass$. With the feedback prescription used in Stinson et al. (2013), the star formation rate of the galaxy increases steadily to 12 \solarmass yr$^{-1}$ at $z = 0$. This galaxy was chosen to show the maximum effect of the local photoionization field. The galaxy has a gas mass resolution of $2 \times 10^5 \solarmass$ with a gravitational force softening of 310 pc.

The star formation and feedback model is the same as the fiducial simulation from the Stinson et al. (2013) parameter study. The star formation efficiency, $\epsilon_*$, is 0.1, and the density threshold is 9.3 cm$^{-3}$. The stellar population that forms follows a Chabrier (2003) initial stellar mass function. Stellar feedback comes from Type II supernovae (SNII) and pre-SN energy (early stellar feedback, ESF hereafter). Each SNII explosion ejects $E_{SN} = 10^{51}$ erg of thermal energy into the surrounding ISM, which has its cooling delayed according to the blastwave solution presented in Stinson et al. (2006). This cooling delay typically lasts several Myr. SNe II and Ia chemically enrich the ISM according to a detailed stellar evolution model as described in Stinson et al. (2013). Energy injection before SNII explosions (‘ESF’) is modelled using 10 per cent of the bolometric luminosity from young stars, an amount comparable to the UV flux. This energy is deposited directly into the gas surrounding the young stars as thermal energy and then is rapidly radiated away.

We add our LPF to these stellar feedbacks. As outlined in Section 4.2, the contribution from stars are summed based on their distance from the gas particle for which we want to compute the incoming radiation. Close sources (stars) are treated as individual sources, while distant ones are grouped based on the gravity tree. A detailed description of this method will be provided in Woods et al. (in preparation).

We emphasize that the simulations presented here are preliminary. One concern is that we include the radiation energy from young stars twice, both as a photoionization source and as a source of thermal energy for the ESF. Though the details of the pre-SN thermal energy input would change, the energy could also be the hot gas created by stellar winds. In future models, we hope to present a more consistent picture. For now, we leave our model as similar as possible to our previous simulations so that the effect of including local photoionizing radiation on the formation of the disc is apparent.

A second concern is that the effect of low-energy photons in our simulations may be overestimated because the outer regions of high-density gas clouds will shield the inner regions from the radiation field. This ‘self-shielding’ is important in gas with a density higher than 0.1 cm$^{-3}$ (Ceverino et al. 2013). However, we have shown that the X-ray photons have the largest effect on cooling and these photons have a very small interaction cross-section. So, ignoring self-shielding effects may be a reasonable first approximation.

#### 7.2 Simulation results

We perform two simulations of the galaxy, one including the HM UV background only (hereafter, HM) and another adding LPF to the UV background (HM+LPF).

Fig. 8 shows the star formation history of the two simulations. The star formation histories are nearly identical until $z \sim 1.5$, after which they diverge. The star formation rate in the HM run (red curve) steadily increases to 12 \solarmass yr$^{-1}$ at $z = 0$. The HM+LPF simulation (blue curve) maintains a steady star formation rate of $\sim 4 \solarmass$ yr$^{-1}$ from $z = 1.5$ until 0. The reduced star
formation results in ∼40 per cent less stellar mass than in HM at $z = 0$.

To understand the physics behind the lower star formation rate in HM+LPF, Fig. 9 shows a comparison of the distribution of the gas in temperature–density phase space of the two simulations at $z = 0$. Three differences are apparent between the simulations: the mean temperature of low-density halo gas, the amount of gas cooling out of the halo on to the disc and the absence of very low temperature gas in the disc of the galaxy.

The difference between the hot, diffuse halo gas in the region bounded by $10^5 < T(K) < 10^6$ and $\log(n/m_p \, cm^{-3}) < -3.5$ is striking. With LPF, most of the low-density gas mass is between $10^5$ and $10^6$ K. Without LPF, a large fraction of the halo gas has cooled to a phase that is intermediate between the cool, dense disc and the hot, diffuse halo, and the gas temperature lies between $10^4$ and $10^5$ K. Even a small amount of ionizing radiation from the local sources has a big effect on the gas cooling rate, so that gas stays hot longer. The high temperature of the hot halo gas provides pressure support against the galaxy’s gravitational potential and hence reduces the gas accretion rate on to the disc. Thus, there is less gas in the region between the hot, less-dense halo gas and the cold dense disc in HM+LPF than in HM.

Another factor that causes more cooling in HM is the positive feedback that the metal enrichment from the higher star formation rate in HM causes. HM starts with a marginally higher accretion rate than HM+LPF, which ejects more metals into the hot halo, which cause the gas to cool faster further enhancing the accretion rate, and consequently makes more stars. The higher halo gas temperature indicates the global nature of LPF and underlines the importance of propagating the radiation field from the local sources throughout the entire volume of the simulation box.

Fig. 10 shows the reduction in gas accretion rate on to the disc more explicitly. The baryonic disc mass evolves similarly in the two simulations until ∼4 Gyr when they diverge as HM adds mass at a faster rate, leaving HM+LPF lighter than HM. The slope of the baryonic disc mass evolution gives a rough gas accretion rate on to...
Local photoionization feedback

Figure 11. The face-on projection view of the stellar (top panels) and gaseous (bottom panels) components of the MW-like galaxy simulations with the HM (left-hand panels) and HM+LPF (right-hand panels) models.

The disc (modulo outflows and stellar accretion). The dot–dashed line represents a best linear fit of the gas accretion rate after $\sim 4$ Gyr. For the HM simulation the slope of this line is $7.25 \, M_\odot \, \text{yr}^{-1}$, while the HM+LPF simulation has a slope of $4.10 \, M_\odot \, \text{yr}^{-1}$.

The increased cooling rate and equilibrium temperature of the halo gas due to LPF affects star formation by reducing the gas accretion onto the disc. This is different from feedback mechanisms local to star-forming events that rely on blowing gas out of the disc. LPF is rather a preventive feedback mechanism which reduces the need for artificially high levels of feedback that can destroy the galaxy disc (Agertz, Teyssier & Moore 2011; Roškar et al. 2013). LPF also provides a natural and non-violent mechanism to keep the disc lighter and prevent disc instabilities from driving the gas to the centre.

Fig. 11 shows face-on images of the stellar and gaseous components of the simulated galaxies. The top panels show the stellar distribution and the bottom panels the gas distribution for the HM (left-hand panels) and HM+LPF (right-hand panels) simulations. The HM simulation shows a large stellar bulge and a high concentration of gas in the centre. The HM+LPF simulation has a smaller stellar bulge with generally less mass in stars in the disc. The gas distribution in the HM+LPF simulation is more extended and less concentrated than in the HM simulation.

The central concentration of stars and gas in the HM simulation is reflected in the 300 km s$^{-1}$ central peak of the galaxy rotation curve shown in Fig. 12. The HM+LPF simulation creates a slowly rising rotation curve that has a rotation velocity of 200 km s$^{-1}$ from near the centre to the edge of the disc, clearly showing that it is much lighter than the HM disc.

Figure 12. The rotation curves of the galaxy in the HM (red) and HM+LPF (blue) runs at $z = 0$. 
The difference in stellar and gaseous distributions and subsequently in the rotation curves can be explained in part due to the reduced gas accretion on to the disc but also with the reduction in amount of cold gas in the HM+LPF. The HM simulation has a tail of gas at low temperatures (<1000 K) and high densities (n > \(1 \text{ cm}^{-3}\)). This tail is absent from the HM+LPF run since the additional radiation fields raise the equilibrium temperature of the dense gas. Thus, the average temperature of the disc gas is higher and has higher pressure that stops the disc from fragmenting and forming stars. However, we reiterate that the effect of low-energy photons might be overestimated, because we do not impose any criterion for self-shielding in high-density gas present in the disc.

8 CONCLUSIONS

We tested a novel method for including the effects of local photoionizing radiation fields in galaxy formation simulations. Previously, the expense of including detailed radiative transfer meant that simulations that tried to include the effect of photoionization could only be evolved until \(z \sim 4\). While such simulations are extremely useful to study the early evolution of the Universe and the reionization epoch, they are not able to address the effect of a local radiation field on galaxy evolution. The local radiation field should have a significant importance in regulating how much gas cools on to discs and fuels star formation. Currently, in many simulations, the only radiation field considered is the UV background against which the galaxy might otherwise be self-shielded (Pontzen et al. 2007; Faucher-Giguère et al. 2009). The local field might be very different from the uniform background and must be included in realistic cosmological simulations of galaxy formation.

Our method uses the existing optimizations that quickly solve gravity to include the \(r^{-2}\) attenuation effect, a more detailed description of our method will be presented in Woods et al. (in preparation). Our current treatment uses the optically thin limit, which provides an upper limit on the effect of radiation. The optically thin approximation is valid for the X-ray photons that we include in our model of the young star radiation field. X-ray photons are not strongly absorbed in typical ISM conditions. However, we will relax the optical thin approximation in future work.

Our radiation field includes the blackbody emission from young stars, along with the X-rays that massive stars produce in their winds and SN explosions, as well as UV flux from post-AGB stars in old stellar populations. Our simple treatment of absorption assumes that 5 per cent of the flux around the Lyman limit escapes from clusters of young stars, while old stars have an escape fraction of unity since they likely moved out of their birth cocoons into an optically thinner environment. Otherwise, the radiation field is only attenuated as an inverse square of distance. These physically motivated assumptions allow us to study the effect of a local ionizing radiation field on cooling rates of gas within the galaxy, throughout cosmic time.

As a test of the cooling and to develop physical intuition about how photoionization affects the cooling rate, we provide simple examples of the evolution of a single gas parcel embedded in the radiation field. We show that a radiation field from young stars that includes soft X-rays can increase the equilibrium temperature of the gas significantly and prolong cooling times (Cantalupo 2010).

We then use our local photoionization scheme in the SPH code GASOLINE to investigate the effect of local ionizing radiation fields in full cosmological simulations of a Milky Way-like (MW-like) galaxy. We simulate the galaxy with and without the local radiation field. We find that the radiation field reduces star formation after \(z \sim 1.5\) and results in \(\sim 40\) per cent less stellar mass. The reduced star formation is due to a combination of factors. The hot, diffuse halo gas surrounding the disc has a higher temperature when the local photoionizing field is considered because a small amount of ionizing radiation from local sources has a big effect of the gas cooling and heating rates at low densities, which in turn raises the equilibrium temperature of the gas. This increased temperature of the hot halo gas provides pressure support to the halo gas against the gravitational potential of the galaxy and hence reduces the gas accretion rate on to the disc. This coupling of the local radiation field to the gas cooling in the host galaxy provides a preventive feedback mechanism that reduces the gas accretion to the central regions of the galaxy, regulating star formation.

The local ionizing radiation field also eliminates high-density low-temperature gas by raising the equilibrium temperature of the dense gas in the disc. The higher average temperature of the disc gas provides pressure support to the gaseous disc that stops the disc from fragmenting and forming stars. All these effects on the gas distribution by the local radiation field cause the HM+LPF run to form a light and more stable stellar disc, which has a slowly rising rotation curve which peaks at 200 km s\(^{-1}\), consistent with observations of MW-like galaxies.

We plan to extend this initial study to a broader galaxy mass range (from dwarfs to massive ellipticals) and to improve the parametrization of our radiative transfer scheme in forthcoming work(s). While this result is still preliminary and based on a single simulation, it shows the importance of self-consistently including LPF in simulations aimed at reproducing realistic galaxies.

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