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Paper title ... The coolest thing you've ever read

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ABSTRACT

Recap the story...

Keywords: cosmology: theory, early universe – galaxies: high-redshift, evolution – stars: formation, Population III – luminosity function – turbulence

1. INTRODUCTION

intro stuff... Study the effects of radiation in early star and galaxy formation...

The work is structured as follows. In Section 2 we describe our methods, including a brief discussion of the implementation of our subgrid model for following the evolution of the pristine gas fraction, our approach to halo finding, and the spectral energy distribution (SED) models used to compute the luminosity of our stars. In Section 3 we show that ... . We compare nonRT to RT... Next, we focus on an analysis of ... . Conclusions are discussed in Section 4.

2. METHODS

2.1. *Simulations*

We use Ramses-RT (Teyssier 2002; Rosdahl et al. 2013) for this work, a cosmological adaptive mesh refinement (AMR) simulation with coupled radiation hydrodynamics (RHD). Ramses-RT is an extension of Ramses (Teyssier 2002) that models the interactions between dark matter, stellar populations, and baryons via gravity and hydrodynamics. Ramses-RT adds a model for stellar radiation and radiative transfer as well as non-equilibrium radiative heating and cooling. To keep the radiative transfer computations manageable, Ramses-RT groups photon energies into a small number of bins. The simulation also employs a reduced speed of light allowing the time step-size to be reasonable as compared to non-RT codes. The simulation advects photons between cells using a first-order moment method with full local M1 closure for the Eddington tensor (Levermore 1984).

Hydrodynamic flux between cells is computed using a Harten–Lax–van Leer contact (HLLC) Riemann solver (Toro et al. 1994). It is used to advect not only the typical cell-centered gas variables but also the hydro scalars added by Sarmento et al. (2016) that track the turbulent velocity, the pristine gas mass fraction as well as metals generated by Population III (Pop III) supernova (SN). Self-gravity is solved using the multigrid method along with the conjugate gradient method for levels ≥ 12. Stars and DM are modeled with collisionless particles and are evolved using a particle-mesh solver with cloud-in-cell interpolation (Guillet & Teyssier 2011). We assume an ideal gas Equation of State with $\gamma = 5/3$.

The following sections describes the set up for the two simulations, RT and nonRT, used to generate our results. We also review some of the modifications made to Ramses-RT used to track the pristine fraction of gas and the mass fraction of Pop III SN generated metals in each cell.

2.1.1. *Setup*

We again use the following cosmological parameters $\Omega_{\rm M} = 0.267$, $\Omega_\Lambda = 0.733$, $\Omega_{\rm b} = 0.0449$, $h = 0.71$, $\sigma_8 = 0.801$, and $n = 0.96$, based on Komatsu et al. (2011), where $\Omega_{\rm M}$, Ω_Λ, and $\Omega_{\rm b}$ are the total matter, vacuum, and baryonic densities, respectively, in units of the critical density; h is the Hubble constant in units of 100 km/s; σ_8 is the variance of linear fluctuations on the 8 h^{-1} Mpc scale; and n is the "tilt" of the primordial power spectrum (Larson et al. 2011). These and the other relevant simulation parameters are summarized in Table 1.

We use Ramses-RT to evolve a pair of 3 h^{-1} comoving Mpc (cMpc) on-a-side volumes to $z = 6$. The RT simulation models radiative transfer from our stellar populations using *Starburst99* (Leitherer et al. 2011). We have binned stellar photons into 4 groups to account for molecular hydrogen dissociating, hydrogen ionizing and 2 levels of helium ionization.

For both simulations, we set the initial grid to $\ell_{min} =$ 9 corresponding to an coarse grid resolution $\Delta {\rm x}_{\rm max} =$

Table 1. Simulation parameters. All parameters are common to both the RT and nonRT simulations except where noted.

Parameter	Value	Description
	Cosmology	
$\Omega_{\rm M}$	0.267	Total matter density
Ω_Λ	0.733	Dark energy density
$\Omega_{\rm b}$	0.0449	Baryon density
h	0.71	Hubble parameter [100 Mpc/s/kpc]
σ_8	0.801	Amplitude of matter fluctuations
n	0.96	Tilt of the primordial power spectrum
	Setup	
$\ell_{\rm min}$	9	Base grid size - $2^9 = 512$
$\ell_{\rm max}$	15	Max refinement level
$\rm M_{DM}$	17,500	Dark matter particle mass [$\rm M_\odot$]
	Star formation	
$\epsilon_\star$	0.10	Star forming efficiency
$n_\star$	0.05	Star forming density [$\rm n_p$/cc]
$\delta_\star$	200	Star forming density threshold [$\overline{\rho}$]
$m_\star$	2600	Star particle mass resolution [$\rm M_\odot$]
	Feedback	
η_{SNII}	0.10	Pop II SP SN mass fraction at 10 Myr
η_{SNIII}	0.99	Pop III SP SN mass fraction at 10 Myr
	RT Only	
	RT photon bins	
$\rm UV_{H_2}$	11.20 - 13.60	Lyman-Werner photons
$\rm UV_{HI}$	13.60 - 24.59	Hydrogen ionizing
$\rm UV_{HeI}$	13.60 - 24.59	HeI ionizing
$\rm UV_{HeII}$	54.42 - ∞	HeII ionizing

5.86 h^{-1} comoving kpc (ckpc) – a reasonable compromise that provides improved resolution of the intergalactic medium (IGM) without creating an excessive computational load. We adopt a quasi-Lagrangian approach to refinement such that cells are refined as they become approximately 8x over-dense. This strategy attempts to keep the amount of mass in each cell roughly constant as the simulation evolves. Allowing for up to 6 additional levels of refinement results in a best average resolution of 91.6 h^{-1} comoving pc (cpc). However, we stop the simulations at z = 6 where the best average resolution was 18.4 pc physical. Our refinement strategy means that the maximum refinement level reached during the runs, $\ell = 13$, occurred at z $\approx$ 20 in one of the rare over-density peaks. This resulted in a best physical resolution at z $\approx$ 20 approximately 3.3 times that at z = 6 or about 5.4 pc physical.

Star particles (SPs) are created in regions of gas according to a Schmidt law with

$$\dot{\rho_\star} = \epsilon_\star \frac{\rho_{gas}}{t_{\rm ff}} \theta(\rho_{gas} - \rho_{\rm th}) \quad (1)$$

where $\rho_{\rm gas} > n_\star = 0.05\, m_{\rm p}/cc$ is the star forming density threshold. Additionally, the Heaviside step function, $\theta(\rho_{gas} - \rho_{\rm th})$, guarantees star formation occurs only when the gas density exceeds a threshold value $\rho_{\rm th} = 200\,\overline{\rho}$. Here, $\overline{\rho}$ is the mean gas density of the simulation. We set the star forming efficiency to $\epsilon_\star = 0.10$, an empirically derived value that results in reasonable agreement with the observed cosmic star formation rate (**??**). The gas free fall time is $t_{\rm ff} = \sqrt{3\pi/(32G\rho)}$.

SPs represent an initial mass function (IMF) of stars. The SP mass is set by the star-forming density threshold and our resolution resulting in$zm_\star = n_\star \Delta x^3 = 2.6 \times 10^3\, M_\odot$. The final mass of each SP is drawn from a Poisson process such that it is a multiple of $m_\star$.

Each SP represents an initial mass function (IMF) of stars. For normal stars ($Z > Z_{\rm crit}$) we assume a Salpeter a log-normal (for Pop III stars) IMF.

A fraction of each SP's mass is returned to the gas in the form of supernovae (SNe) ejecta and energy. This occurs after the 10 Myr lifetimes for the most massive stars in the IMF (**?**). For regular stars ($Z \geq Z_{\rm crit}$) we assume a Salpeter () IMF so that 10% ($\eta_{SNII} = 0.10$) of the SP's mass represent stars $> 8\, M_\odot$ that go SN on this timescale. For Pop III stars ($Z < Z_{\rm crit}$) we assume a log-normal IMF that results in 99% ($\eta_{SNIII} = 0.99$) of each Pop III SP going SN after 10 Myr.

The impact of these SNe is parameterized by the mass fraction of ejecta, $\eta_{\rm SN}$, and the kinetic energy per unit mass of the explosion, $E_{\rm SN}$. We take $\eta_{\rm SN} = 0.10$ and $E_{\rm SN} = 10^{51}$ ergs/10 $M_\odot$ for all stars formed throughout the simulation. The fraction of new metals in SN ejecta is 0.15 even though metal yields and energy from Pop III stars are likely to have been higher (**??**). We may explore different yields and the subsequent effect on stellar enrichment in future work.

2.2. *Halo Finding*

Nothing yet

3. RESULTS

In this section, we discuss

4. CONCLUSIONS

We have used a large-scale cosmological simulation to study high-redshift galaxies and

At high redshift, radiative feedback from stars reduces the overall/global SFR. However, radiation pressure seems

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Software: RAMSES Teyssier (2010), MUSIC (Hahn & Abel 2013), pynbody Pontzen et al. (2013), Starburst99 Leitherer et al. (2011)

5. APPENDIX

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