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How does inhomogeneous reionization impact the gas content of galaxies?

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Abstract. The reionization of the intergalactic medium (IGM) was likely inhomogeneous and extended. By heating the IGM and photo-evaporating gas from the outskirts of galaxies, this process can have a dramatic impact on the growth of structures and suppress the observed number of dwarf galaxies. We tackle this problem using a tiered approach: combining parameterized results from suites of single-halo collapse simulations with large-scale models of reionization. We present an expression for the halo baryon fraction which is an explicit function of: (i) halo mass; (ii) an ionizing UV background (UVB) intensity; (iii) redshift; (iv) redshift at which the halo was exposed to a UVB. The latter has been shown to significantly impact the observed abundance of local dwarf galaxies. We then fold-in our parametrized results into large-scale simulations of reionization, such that the ionizing emissivity of galaxies depends on the local values of the reionization redshift and the UVB intensity, evolving in a self-consistent manner. We present a physically-motivated analytic expression for the resulting average minimum mass of star-forming galaxies, $M_{\rm min}$, which can be readily used in modeling galaxy formation, as well as interpreting observations of dwarf galaxies at all redshifts.

Key words. cosmology: theory – early Universe – galaxies: formation – high-redshift – evolution

1. Introduction

As the first galaxies formed, their ionizing UV radiation carved-out HII regions from the neutral intergalactic medium (IGM). As structures continued to form, these HII regions grew and overlapped, eventually permeating the entire Universe. This global phase change, known as reionization, is expected to be fairly extended and inhomogeneous (e.g. Furlanetto et al. 2004). The resulting ionizing ultraviolet background (UVB) heated the IGM to temperatures of $\sim 10^4$ K, photo-evaporating gas out of shallow potential wells and affecting its cooling properties (e.g. Shapiro et al. 1994; Miralda-Escudé & Rees 1994; Hui & Gnedin 1997). Therefore the gas reservoir available for star formation is decreased for low-mass galaxies in the ionized IGM (e.g. Couchman & Rees 1986; Rees 1986; Efstathiou 1992). This UVB feedback mechanism can suppress the baryon content of local dwarf galaxies, explaining the apparent dearth of observed satellite galaxies in the Milky Way (e.g. Klypin et al. 1999; Moore et al. 1999) and dwarf galaxies in the field (as inferred from the HI ALFALFA survey; Papastergis et al. 2011; Ferrero et al. 2012).

Since semi-analytic calculations (e.g. Shapiro et al. 1994; Gnedin & Hui 1998) were used to motivate a suppression of star formation in galaxies with $M \lesssim 10^9 M_\odot$, several attempts have been made to further quantify this effect, both using spherically symmetric simulations (Thoul & Weinberg 1995; Dijkstra et al. 2004) and three-dimensional cosmological hydrodynamic simulations (e.g. Quinn et al. 1996; Gnedin 2000; Hoeft et al. 2006; Okamoto et al. 2008). Unfortunately, quantifying UVB feedback is challenging. Semi-analytic approaches do not include all of the relevant physics (e.g. non-linear growth of perturbations, cooling processes of the gas). On the other hand, cosmological simulations often focus on a particular reionization history, fixing the UVB evolution and/or the reionization redshift. Our poor understanding of the details of reionization motivates a flexible approach that is not dependent on a particular model, and can therefore be broadly applied.

As an intermediate approach, in this paper we run suites of fast, 1D cosmological collapse simulations, exploring a wide parameter space motivated by the inhomogeneity of reionization. Fitting these results, we present an expression for the halo baryon fraction, f_b, and the critical mass M_{crit}, defined as the halo mass which retains half of its baryons compared to the global value. In this work, we focus on halos with masses of $10^8 \lesssim M/M_\odot \lesssim 10^{10}$, which are relevant in the advanced stages of reionization (e.g. Haiman et al. 1997). These halos are massive enough to host gas collapsing via the atomic cooling channel, and yet small enough to be susceptible to UVB feedback.

The paper is organized as follows. In §2 we describe the collapse simulations we use. In §3 we use results from these simulations to fit formulae for M_{crit} and f_b; then we fold-in our results in a large-scale simulation of reionization. Finally, in §4 we present the conclusions of the work. Throughout we assume a flat ΛCDM cosmology with parameters (Ω_m, Ω_Λ, Ω_b, h, σ_8, n) = (0.27, 0.73, 0.046, 0.7, 0.82, 0.96), consistent with WMAP results (Komatsu et al. 2011).

2. Hydrodynamical collapse simulations

We use a 1D simulation to study collapsing, cosmological perturbations (Sobacchi & Mesinger 2013b). The code evolves a mixture of dark matter (DM) and baryon fluids by moving concentric spherical shells of fixed mass in the radial direction. It includes cooling through excitation, ionization, recombination and free-free emission and by Compton scattering with CMB photons (relevant at $z \gtrsim 7$; Dijkstra et al. 2004). For more details on the code please see Thoul & Weinberg (1995).

As in previous works (e.g. Thoul & Weinberg 1995; Dijkstra et al. 2004; Mesinger & Dijkstra 2008) we start with typical profile around a 2-σ peak in a Gaussian random field (Bardeen et al. 1986), sampled by 6000 (1000) shells for the DM (baryons). To set-up the runs, we fix the total halo mass M collapsing at redshift z when UVB feedback is neglected. We include an isotropic UVB instantaneously turned on at redshift z_{IN} and parametrized as $J(\nu) = J_{21}\,(\nu/\nu_H)^{-\alpha} \times 10^{-21}$ erg s^{-1} Hz^{-1} cm^{-2} sr^{-1}, where ν_H is the Lyman limit frequency and $\alpha = 5$ corresponds to a stellar-driven UV spectrum (e.g. Thoul & Weinberg 1996). We consider a range of z_{IN}= 9–16, as well as three different intensities: $J_{21} = 0.01$, $J_{21} = 0.1$ and $J_{21} = 1$, spanning the expected range of interest (e.g. Bolton & Haehnelt 2007; Calverley et al. 2011; McGreer et al. 2011).

3. Results

Armed with our suite of collapse runs, we now present the two main results of this paper: a formula for the critical mass $M_{crit}\,(J, z, z_{IN})$ (defined as the halo mass retaining half of its baryons; §3.1), and its generalization to the halo baryon fraction $f_b\,(M, J, z, z_{IN})$ (§3.2). We then fold-in our parametrized results into large-scale simulations of reionization, presenting a physically-motivated analytic expression for the resulting average minimum mass of star-forming galaxies, $\bar{M}_{min}$ (§3.3).

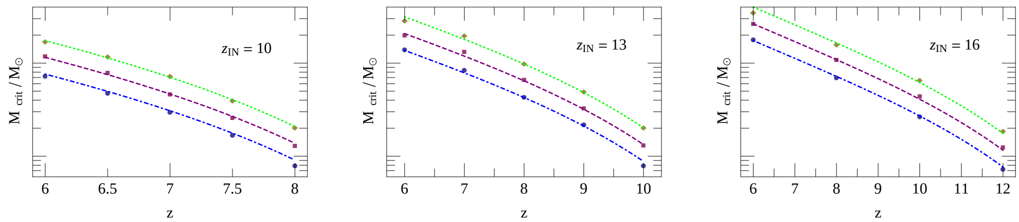

Fig. 1. Critical mass versus redshift with different choices of $z_{\rm IN}$; points show the output of the simulations and curves show the best fit of Eq. 1 with three different values of J_{21}: *Dot-dashed*: $J_{21} = 0.01$. *Dashed*: $J_{21} = 0.1$. *Dotted*: $J_{21} = 1$.

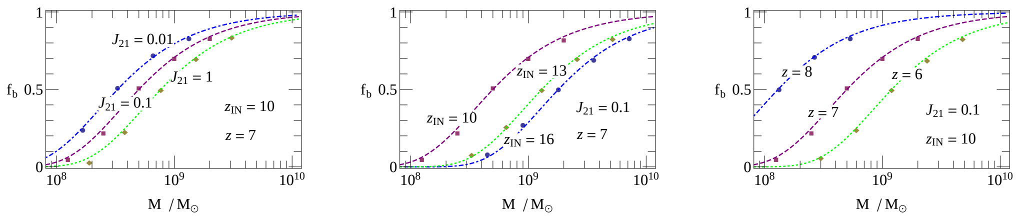

Fig. 2. The baryon fraction, f_b, versus M for halos with different reionization histories. Points show the output of the simulations and curves show our fitting formula in Eq. 3. We choose a "fiducial" parameter combination: $(z, z_{\rm IN}, J_{21}) = (7, 10, 0.1)$ and show variation with J_{21}, $z_{\rm IN}$, z in the left, middle and right panels (respectively).

3.1. Critical mass

As an ionization front sweeps through a patch of the IGM at $z = z_{\rm IN}$, the temperature of the gas is expected to jump from $T_{z>z_{\rm IN}} \sim 0$, to $T_{z<z_{\rm IN}} \sim 10^4$ K (e.g. Barkana & Loeb 2001), roughly within a sound-crossing time. We expect that the asymptotic limit of $M_{\rm crit}(z \ll z_{\rm IN})$ is approached independently of the precise value of $z_{\rm IN}$. Therefore we can write $M_{\rm crit}(J, z, z_{\rm IN}) = J_{21}{}^a g_1(z)\, g_2(z, z_{\rm IN})$, with $g_2(z, z_{\rm IN}) \sim 1$ if $z \ll z_{\rm IN}$. Since the Jeans mass before reionization is much lower than the mass scales we are studying, we assume the additional limiting behaviour of $g_2(z, z_{\rm IN}) \to 0$ at $z \to z_{\rm IN}$.

Mindful of these trends and motivated by the linear theory (Gnedin & Hui 1998), we assume the functional form:

$$M_{\rm crit} = M_0 J_{21}{}^a \left(\frac{1+z}{10}\right)^b \left[1 - \left(\frac{1+z}{1+z_{\rm IN}}\right)^c\right]^d \quad (1)$$

where we treat M_0, a, b, c and d as fitting parameters. A χ^2 minimization fitting to our simulation outputs results in $(M_0, a, b, c, d) = (2.8 \times 10^9 M_\odot, 0.17, -2.1, 2.0, 2.5)$.

Values of $M_{\rm crit}$ from our simulation runs are shown as points in Fig. 1, together with the curves corresponding the analytic expression above (Eq. 1). Note that our results are not very sensitive to the intensity of the UVB: increasing J_{21} by two orders of magnitude increases $M_{\rm crit}$ only by a factor $\sim$ 2–3. This weak dependence is expected given that the post-ionization collapse in this regime proceeds isothermally, and $T_{z<z_{\rm IN}} \sim 10^4$K is only weakly dependent on J (Dijkstra et al. 2004).

Star-forming galaxies need to be massive enough to both: (i) host gas in the presence of a UVB ($M > M_{\rm crit}$); and (ii) allow this gas to efficiently cool, collapse and form stars ($M > M_{\rm cool}$). Therefore, a reasonable choice is:

$$M_{\rm min} = \max\left[M_{\rm cool}, M_{\rm crit}\right] \ , \quad (2)$$

where $M_{\rm cool}$ corresponds to the effective cooling threshold (Barkana & Loeb 2001).

3.2. Halo baryon fraction

We now generalize the expression for the critical mass, obtaining the halo baryon fraction,

f_b, normalized to the global mean, Ω_b/Ω_m. By definition, $f_b(M = M_{crit}) = 1/2$, with the asymptotic behaviour: $f_b(M \ll M_{crit}) = 0$ and $f_b(M \gg M_{crit}) = 1$. Our results are well-fit by:

$$f_b(M) = 2^{-M_{crit}/M} . \quad (3)$$

We note that this expression is a relatively steep function of M, thus justifying the common, step-function simplification of $f_b = 0 \rightarrow 1$ at M_{crit}.

In Fig. 2 we show the baryon fraction of halos with different masses and reionization histories. Points show the output of the simulation and curves show our fitting formula. We present a "fiducial" model, $(z, z_{IN}, J_{21}) = (7, 10, 0.1)$, varying one parameter in each panel. In the left panel, we show the variation of f_b with J_{21}. As we have already discussed this dependence is weak. In the middle panel, we show the variation of f_b with z_{IN}. This dependence is stronger. In particular, regions only recently exposed to a UVB do not exhibit significant baryonic suppression. This is qualitatively supportive of earlier claims (Mesinger & Dijkstra 2008) that UVB feedback does not significantly impact the progress of the advanced stages of reionization (note that this panel shows a "maximal" $z_{IN} - z$ case of halos collapsing towards the very end of reionization, $z = 7$). These results also suggest that a potentially large scatter in the reionization redshift of halos (e.g. Alvarez et al. 2009) may have an important impact on the evolution of their gas. Finally, in the right panel we show the variation of f_b with z. The formation redshift has a very strong impact on the baryon fraction, consistent with claims that UVB feedback can be important in suppressing star formation post-reionization (e.g. Thoul & Weinberg 1996).

3.3. UVB feedback in reionization

We use a large-scale simulation of reionization (Sobacchi & Mesinger 2013a) to study the impact of inhomogeneous reionization on the gas content of galaxies. It would therefore be reasonable to expect $\bar{M}_{min}$ to evolve from M_{cool} at high redshifts to some M_0 (at virial temperature $T_{vir} \approx$ const) at low redshifts, with the transition occurring at $z \sim z_{re} - \Delta z_{sc}$ (where Δz_{sc} is the redshift interval corresponding to a sound-crossing time-scale $2R_{vir}/c_s$; c.f. Shapiro et al. 2004), roughly over a time-scale scaling with the duration of reionization, Δz_{re}. Indeed, we find that our results for $\bar{M}_{min}$ are well fitted by:

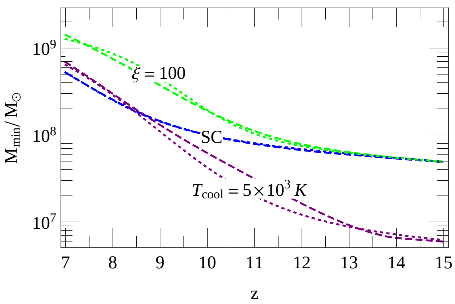

Fig. 3. Average value of M_{min} versus redshift. We compare our fiducial model with the standard parameter choice (SC), with $T_{cool} = 5\times10^3$ K and with $\xi = 100$. *Dashed*: results of the simulation. *Dotted*: expression in Eq. 4.

$$\bar{M}_{min}(z) = M_{cool} \times \left(\frac{M_0}{M_{cool}}\right)^g , \quad (4)$$

with the transition function

$$g(z) = \frac{1}{1 + \exp\left[\frac{z-(z_{re}-\Delta z_{sc})}{\Delta z_{re}}\right]} . \quad (5)$$

We take $M_0(z)$ to correspond to $T_{vir} = 5 \times 10^4$ K (e.g. Okamoto et al. 2008) and define Δz_{re} to correspond to the redshift interval between $\bar{x}_{HI} = 0.6$ and $\bar{x}_{HI} = 0.4$.

In Fig. 3 we compare this approximation (dotted lines) with the results from our simulation (dashed lines). We show our fiducial model with the standard choice of the parameters (SC): a threshold M_{cool} corresponding to efficient atomic hydrogen cooling ($T_{vir} = 10^4$ K); a ionizing efficiency per baryon $\xi = f_* f_{esc} N_\gamma = 30$ (f_* is the fraction of baryons collapsed in stars, f_{esc} is the escape fraction from galaxies, N_γ is the number of photons emitted per stellar baryon; c.f. Mesinger & Furlanetto 2009). To test the robustness of the above approximation, we also include two "extreme" models: (i) with molecular hydrogen cooled halos significantly contributing to reionization: $T_{\rm cool} = 5 \times 10^3$ K (*magenta curves*); (ii) with a significantly higher emissivity $\xi = 100$ (*green curves*). These runs correspond to $z_{\rm re}$ = (9.3, 9.9, 12.0), $\Delta z_{\rm re}$ = (1.0, 1.3, 0.8) and $\Delta z_{\rm sc}$ = (2.0, 0.9, 2.5), for the fiducial, $T_{\rm cool} = 5 \times 10^3$ K, and $\xi = 100$ models, respectively. Even in the extreme cases, our formula provides a good fit.

4. Conclusions

Using a spherically symmetric simulation, we study the baryonic content of atomically-cooled galaxies exposed to a UVB. Since the details of reionization are unclear, we explore a large parameter space of (i) halo mass; (ii) UVB intensity; (iii) redshift; (iv) redshift of UVB exposure. The last is especially important given that reionization is likely very inhomogeneous. We present an analytic expression for the characteristic or critical mass $M_{\rm crit}$, defined as the mass scale of halos retaining half their gas mass compared to the global mean. We also generalize these results, obtaining a simple formula for the baryonic content of galaxies as a function of (i)–(iv) above. We then fold-in our parametrized results into large-scale simulations of reionization, presenting a physically-motivated analytic expression for the resulting average minimum mass of star-forming galaxies which depends on: (i) redshift of reionization; (ii) extension of inhomogeneous reionization; (iii) sound-crossing time scale for the relevant halos.

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