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FEEDBACK REGULATED ESCAPE OF IONISING RADIATION FROM HIGH REDSHIFT GALAXIES

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Abstract. Small galaxies are thought to provide the bulk of the radiation necessary to reionise the Universe by $z \sim 6$. Their ionising efficiency is usually quantified by their escape fraction $f_{\rm esc}$, but it is extremely hard to constrain from observations. With the goal of studying the physical processes that determine the values of the escape fraction, we have run a series of high resolution, cosmological, radiative hydrodynamics simulations centred on three galaxies. We find that the variability of the escape fraction follows that of the star formation rate, and that local feedback is necessary for radiation to escape.

Keywords: radiative transfer, methods: numerical, galaxies: dwarfs, galaxies: formation, galaxies: high redshift, dark ages, reionisation, first stars.

1 Introduction

The apparition of the first light sources marks the beginning of the Epoch of Reionisation, during which the intergalactic medium (IGM) transitions from fully neutral to fully ionised around $z \sim 6$. The origin of the bulk of the radiation responsible for reionising the Universe is still subject to debate (e.g. Madau & Haardt 2015; Haardt & Salvaterra 2015): it is unclear that there is enough high-z quasars to provide enough photons, and the contribution of galaxies is poorly constrained. A crucial parameter to account for the galactic contribution to the ionising budget is the *escape fraction* $f_{\rm esc}$, which describe the fraction of photons emitted by stellar sources that can escape from the galaxies to reionise the IGM. The observational determination of $f_{\rm esc}$ is extremely laborious, and is hampered by various selection effects, interloper removals, etc (e.g. Bergvall et al. 2013; Siana et al. 2015). Measurements at low redshift seem to indicate a low value of less than $2-3\%$, but recently Izotov et al. (2016) found Lyman-continuum emitters with $f_{\rm esc} \sim 10\%$. At $z \sim 3$, the IGM is still partially opaque to ionising radiation, which further complicates the measurement of $f_{\rm esc}$, and it will never be possible to directly measure $f_{\rm esc}$ from galaxies during the Epoch of Reionisation, since by definition the Universe is still neutral.

Numerical simulations in the past decade have helped constraining the values of $f_{\rm esc}$ as a function of the redshift and the halo mass $M_{\rm vir}$, but the results are still uncertain. For example, some studies find that $f_{\rm esc}$ increases with $M_{\rm vir}$ (e.g. Gnedin et al. 2008), while some others find the opposite trend (e.g. Yajima et al. 2011; Kimm & Cen 2014; Wise et al. 2014), and Ma et al. (2015) find that there is no clear evolution with the stellar mass of the galaxy. Even within a single study, there is a large scatter in the values of $f_{\rm esc}$ at fixed halo mass. The differences can be accounted by the fact that no two simulations use the same methods: they do not focus on the same galaxies (from minihaloes to Milky-Way progenitors) and do not have the same resolution (from more than 100 pc to subparsec resolution), and more importantly most of the unresolved physical mechanisms like the feedback processes are implemented differently, which is known to lead to different physical properties (e.g. Kimm et al. 2015, for the supernova feedback).

We present here a study of three small galaxies with the goal of understanding the detailed mechanism that can affect the escape of ionising photons during their journey from the star-forming sites to the IGM.

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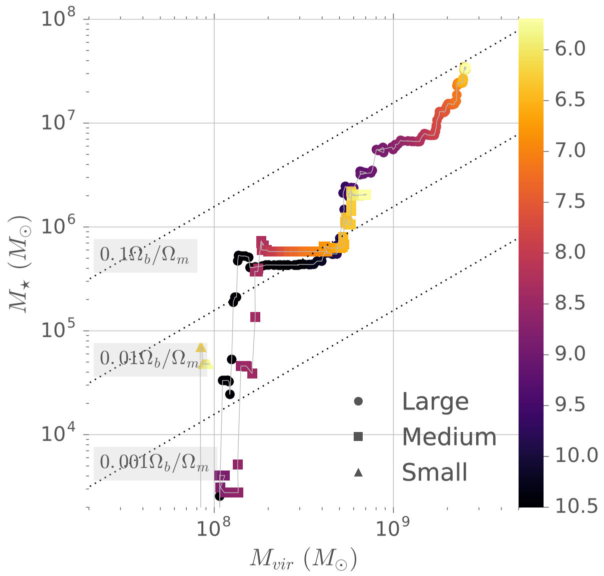
2 Description of the simulations

We performed simulations of galaxies in a cosmological context using the radiative hydrodynamics code RAMSES-RT (Teyssier 2002; Rosdahl et al. 2013). The code follows the coupled evolution of gas and radiation, allowing us to track the ionisation state of the gas in the simulation. We use the zoom technique to achieve the very high resolution that we need to start resolving the structure of the ISM. We focus on the three haloes presented in Trebitsch et al. (2015), with masses $M_{\rm vir} \sim 8 \times 10^7 M_\odot$, $6 \times 10^8 M_\odot$, and $2 \times 10^9 M_\odot$.

The haloes were selected in a dark-matter (DM) only simulation using 512^3 particles in a $10h^{-1}$ Mpc box. We then generated multigrid initial conditions using the MUSIC code (Hahn & Abel 2011), using 3 additional levels of refinement, giving a DM particle mass of $\sim 2000 M_\odot$. We ran the simulation for one billion years, down to $z \sim 5.6$, with a total of 21 levels of refinement, allowing for a cell size of $\Delta x \sim 7$ pc. Radiation is modelled using three photon groups (ionising HI , He I, He II). We use the same supernova (SN) feedback recipe as Kimm & Cen (2014), where after 10 Myr, each star particle deposits in the ISM the amount momentum and metals corresponding to the phase of the SN explosion that can be resolved. We use a new recipe for star formation (Devriendt et al. in prep.), where we account for the turbulence in the star-forming cloud. The stellar particle mass is around $135 M_\odot$, enough to ensure that at least one SN explosion should occur assuming a Chabrier (2003) initial mass function.

3 Properties of the simulated galaxies

We present on Fig. 1 the assembly history of the simulated galaxies: the left panel shows the stellar mass to halo mass for the three simulations, each denoted by a different symbol. The colour of the symbols marks the redshift of the snapshot, and for each galaxy a thin grey line guides the eye through the time evolution. By comparing to the diagonal lines indicating constant baryon fractions, we see that roughly 1% to 10% of the baryons are converted in stars in stars. More important, all galaxies exhibit very similar assembly histories, with a series of plateaus indicating periods of time where the halo grows in mass without star formation.



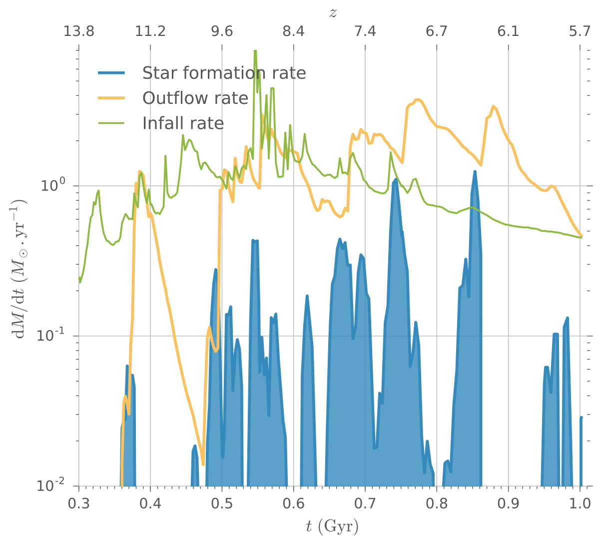


Fig. 1. Left: Stellar mass to halo mass relationship for the three haloes. **Right:** Star formation (in blue), outflow (in yellow) and infall (in green) history of the most massive halo. Each SF episode is followed by a massive outflow.

This can be understood with the right panel of Fig. 1, which compares the star formation rate in blue to the the outflow (inflow) rate in yellow (green) measured at the virial radius for the most massive halo of our sample. Each episode of star formation is followed by a dramatic outflow, expelling considerable amounts of gas out of the halo, effectively shutting star formation until the gas reservoir has been refilled.

4 Escape of ionising radiation

As the massive stars that produces ionising radiation are very short-lived ($\sim$ 5 Myr), the production of ionising photons has a variability that follows that of the star formation rate. However, this is not the end of the story: radiation still needs to escape the halo. We compare on Fig. 2 the time evolution of the escape fraction $f_{\rm esc}$ (in red) to the star formation rate (in blue) and the outflow rate (in yellow). The evolution $f_{\rm esc}$ presents a very bursty behaviour, with values varying quickly from less than 0.1% to more than 60% (e.g. around $t = 850$ Myr). We argue that this can explain the large scatter found in the values of $f_{\rm esc}$ at fixed halo mass in other simulations: in a sample of galaxies of a fixed mass, some will find themselves in a leaking phase while some others will be opaque to ionising radiation.

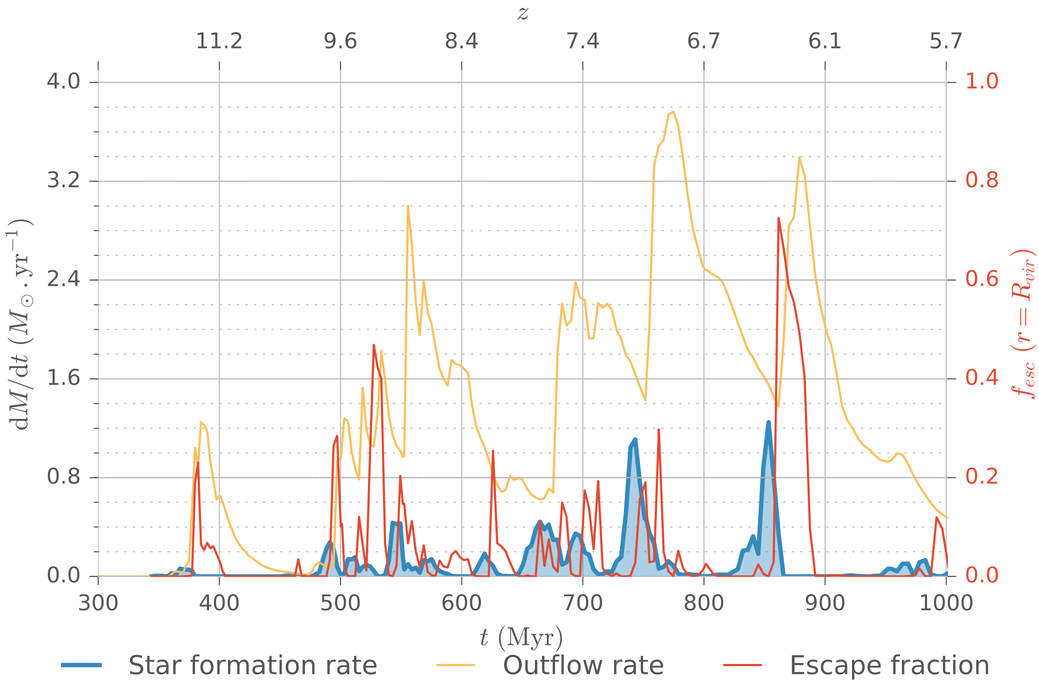


Fig. 2. Evolution of the star formation rate (in red), outflow rate (in blue) and escape fraction (in red) for the most massive halo. The escape fraction starts to rise at the same time as the outflow rate, and typically 10 Myr after the beginning of a star formation event.

Interestingly, we note that the peaks of $f_{\rm esc}$ do not correspond exactly to the peaks of star formation, but rather shifted by approximately 10 Myr. We explain this by the fact that radiation can only escape if the interstellar medium (ISM) has been pierced by a feedback event. In our simulations, radiative feedback is not efficient enough, and radiation is trapped in the star-forming cloud until it has been cleaned by a nearby SN. This can be seen on Fig. 3, which compares $f_{\rm esc}$ for the intermediate mass halo for three runs: the run with SN exploding after 10 Myr is shown in blue, the red line shows a run with only 3 Myr delay before the SN, and the yellow line corresponds to a run without any SN feedback. The two runs with SN feedback exhibit similar behaviour, while in the run without SN only very little radiation can escape. It is only when young stars find themselves in an environment transparent enough to ionising radiation that radiation will escape to the IGM.

5 Conclusions

Using a series of high resolution RHD simulations of three dwarf galaxies at $z \sim 6$, we have studied the mechanisms that regulate the escape of ionising radiation from galaxies. We found that the assembly of these low mass galaxies is regulated by SN feedback, and that the cycle of star formation episodes followed by SN explosions will result in a highly varying escape of ionising radiation that can explain the scatter found in other studies. We showed that the various feedback processes that are at play in the ISM must be modelled correctly to properly account for the local opacity of the ISM, and feedback is needed for radiation to escape in the IGM.

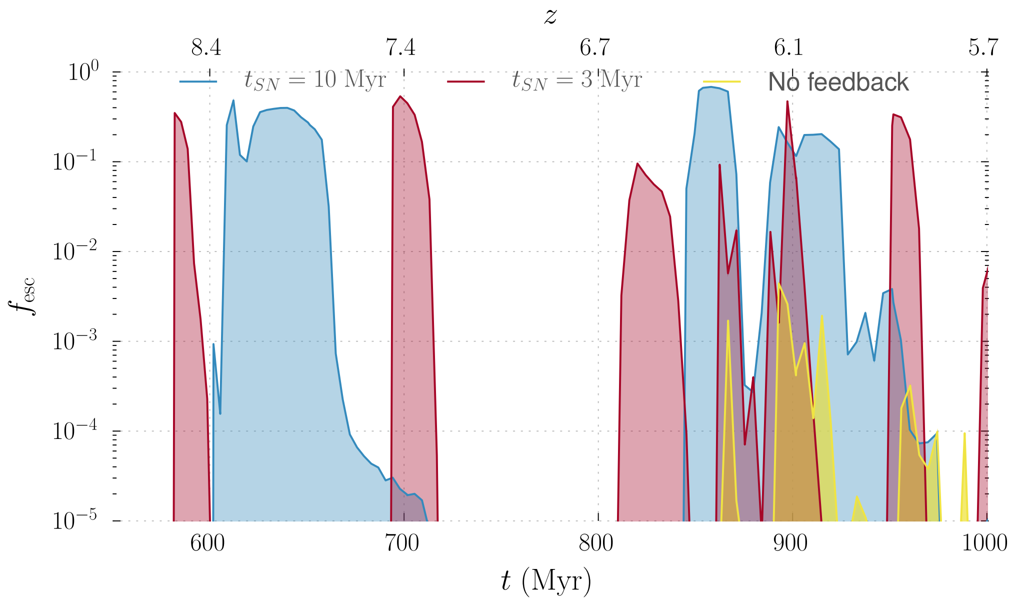


Fig. 3. Evolution of $f_{\rm esc}$ for the medium halo with SN feedback and a 10 Myr (3 Myr) time delay between star formation and the supernova in blue (red), and without feedback in yellow.

We will expand this analysis further in an upcoming work (Trebitsch et al. in prep.), as well as discussing some observational consequences.

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