The First Billion Years simulation project. Galactic outflows and metal enrichment

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Abstract. The *First Billion Years* is one of the largest and most comprehensive cosmological, hydrodynamical simulation of the early Universe to date. It studies the formation of the first proto-galaxies down to redshift 6, and provides the path of the evolution from proto-galaxies to the observed galaxy population at redshift 4. It also provides predictions for future observations.

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1. Introduction

In the last decade, deep observations of the Universe have been providing high quality data in the redshift range $4 < z \lesssim 6$. In the near future, the *James Webb Space Telescope* will be probing even higher redshifts with observations of proto-galaxies formed when the Universe was less that one billion years old. Providing a detailed, theoretical framework of the formation of these proto-galaxies will help to predict, as well as to interpret, what will be observed. The *First Billion Years* simulation project (*FiBY*) has been conducted with this aim.

FiBY is one of the largest and most comprehensive cosmological, hydrodynamical simulation of the early Universe to date. A volume of $(8 \text{ Mpc})^3$ containing 2×1368^3 dark matter and gas particles is evolved down to redshift $z = 6$. The gas mass resolution is 1250 $M_\odot$, whereas the spatial resolution is a few tens of physical parsecs. Such high resolution is necessary to resolve the collapse of the first structures—the mini-haloes that host the first generation of stars (population-III stars, hereafter pop-III).

The collapse of gas of primordial composition into mini-haloes is driven by molecular hydrogen cooling. This gas is the fuel for the formation of pop-III stars. These stars are responsible for the early enrichment of the inter-galactic medium (IGM) through very energetic pair-instability supernova (PISN) explosions, creating the conditions for the formation of the metal-enriched, second generation stars (population-II stars, hereafter pop-II). Therefore, molecular formation and molecular cooling, pop-III and pop-II star formation and stellar feedback are the main ingredients for building the first galaxies.

A set of simulations with increasing volume and decreasing resolution have been performed to provide a larger range of galaxy masses, to study the effect of numerical resolution, and to test variations of the physics and parameters in the model. When combined, these simulations extend the low mass end of the simulated galaxy mass function down to 10^5 $M_\odot$. This corresponds to resolving galaxies with masses two orders of magnitude smaller than in simulations that are currently state-of-the-art (e.g. Finlator *et al.* 2011).

Table 1. Summary of simulation parameters: simulation name; co-moving box length, L; number of particles, N_{tot}; gas particle mass, m_{b}; dark matter particle mass, m_{DM}; co-moving gravitational softening, ϵ.

Simulation	L (h^{-1} Mpc)	N_{tot}	m_{b} (h^{-1} M$_\odot$)	m_{DM} (h^{-1} M$_\odot$)	ϵ (h^{-1} kpc)
FiBY08XL	5.68	2×1368^3	8.87×10^2	4.36×10^3	0.17
FiBY04M	2.84	2×684^3	8.87×10^2	4.36×10^3	0.17
FiBY08M	5.68	2×684^3	7.10×10^3	3.48×10^4	0.33
FiBY16M	11.36	2×684^3	5.68×10^4	2.79×10^5	0.66
FiBY32M	22.72	2×684^3	4.54×10^5	2.23×10^6	1.33

The list of *FiBY* simulations is in Table 1. A brief description of the code employed in the project is in the next section.

2. Numerical tool

The code used for the project is an extension of that employed in the *OWLS* project (Schaye *et al.* 2010). The *OWLS* code is a modified version of GADGET (Springel 2005) with a novel treatment of star formation (Schaye & Dalla Vecchia 2008), stellar evolution (Wiersma *et al.* 2009b), metal line cooling (Wiersma *et al.* 2009a) and black hole feedback (Booth & Schaye 2009). It was updated by introducing molecular hydrogen formation and cooling, gas shielding from the UV background (e.g. Nagamine *et al.* 2010), pop-III star formation and feedback, and stellar dust yields. Stellar feedback has been improved by adopting the model of Dalla Vecchia & Schaye (2012), where thermal energy from SN explosions is injected in the surrounding gas. As shown by these authors, the effect
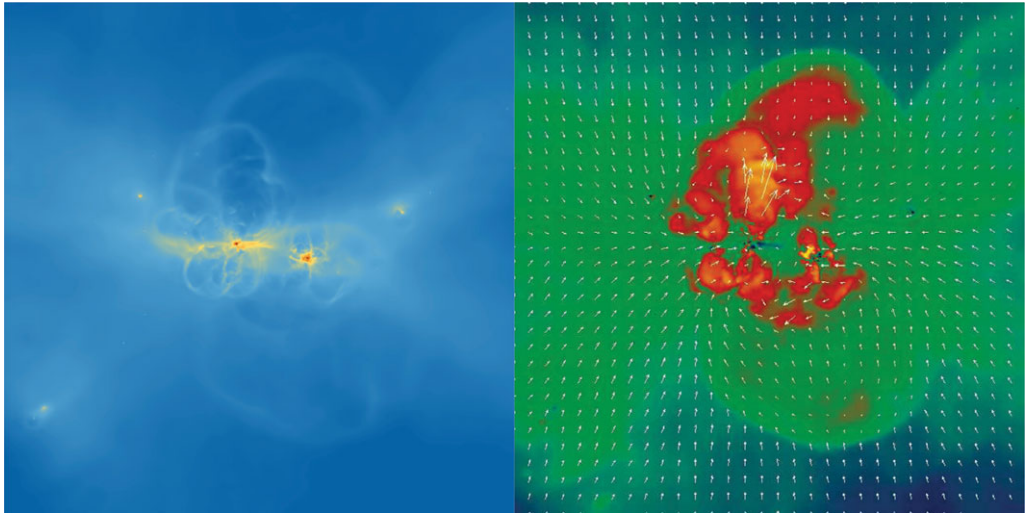

Figure 1. Projected density (left panel) and mass-weighted temperature (right panel) maps of a box of 900 co-moving kpc centred on the most massive halo in *FiBY04M*. The colour scale is logarithmic. Two interacting galaxies are in a filament which is horizontal in the picture. Several shock fronts surrounding underdense bubbles are clearly visible in the density map and are the result of several stellar feedback episodes. The temperature of the gas inside the bubbles (right panel) is larger than the background temperature and can be as high as 10^{5-6} K. The over-plotted velocity field shows the accretion along the filament as well as the galactic outflow.
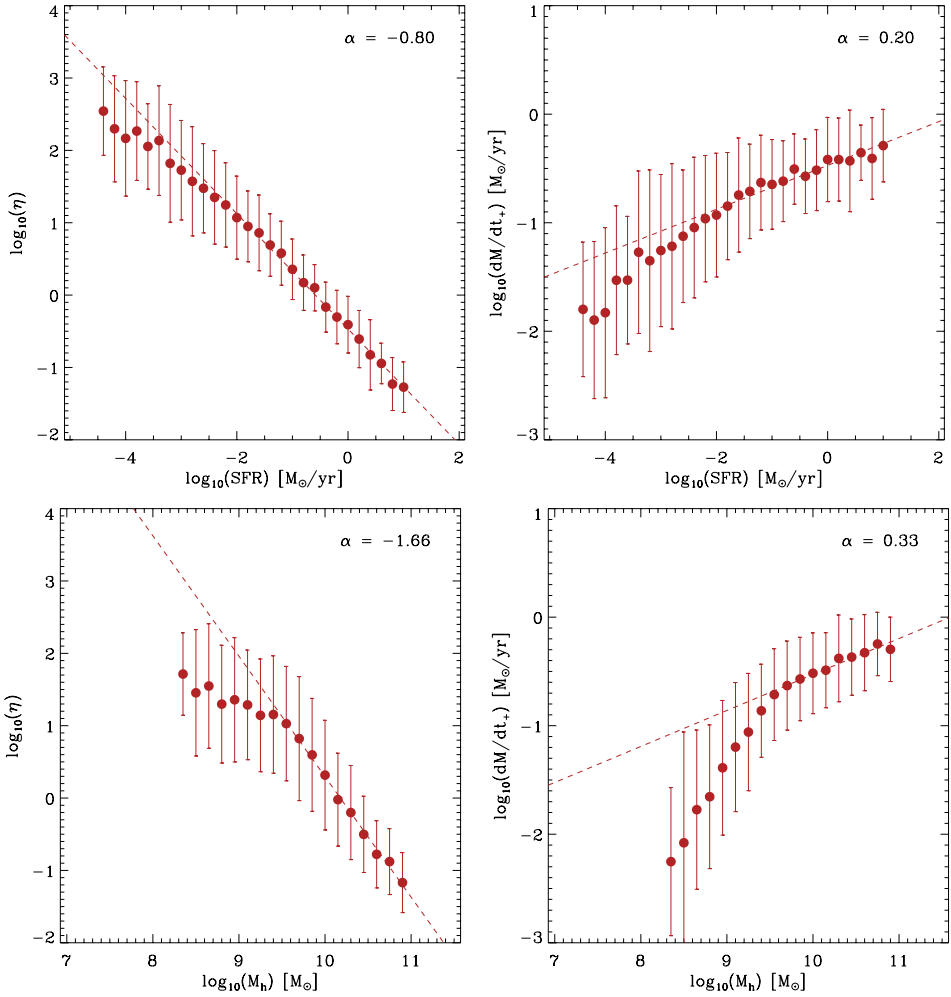
Figure 2. Outflow mass loading (left panels), η, and rate (right panels) as function of star formation rate (top row) and halo mass (bottom row). The dashed lines are fits of the bin averages for halo masses $M_{\rm h} > 10^{9.5}$ M$_\odot$. The slope of the fitting relations is reported in the top-right corner of each plot. The break in the relations is evident when plotting the values against halo mass.

of feedback depends on resolution. The resolution criterion they propose is matched in all but the largest volume simulations. The effect of feedback in creating large galactic outflows is depicted in Fig. 1. Hot and metal-rich bubbles extend well into the IGM contributing to the enrichment of a large volume. The metal volume-filling factor at $z = 6$ is $\sim 10^{-3}$ (Johnson *et al.* 2013).

3. Preliminary results

Fig. 2 shows outflow properties as function of star formation rate (SFR) and halo mass. The mass loading (the ratio between mass outflow rate and SFR), η, is plotted in the left panels, whereas the mass outflow rate is plotted in the right panels. All gas particles at the virial radius that are moving with (positive) radial velocity larger than the halo

escape velocity are considered to be outflowing. There is a clear break in the relations at halo masses $M_{\mathrm{h}} \simeq 10^{9.5}$ M$_\odot$. This is not present in the galaxies mass and luminosity functions which match the observed data at $z \sim 6$. Therefore, the stellar mass of haloes does not seem to play a role.

What plays a role in defining the break is the stellar feedback. Feedback is more effective in removing gas from small haloes. Haloes in a low density environment cannot accrete gas efficiently, therefore, after feedback has removed a large part of their gas content, their stellar mass does not grow further. This becomes clear when plotting the ratio of stellar mass to gas mass, $f_* = M_*/M_{\mathrm{g}}$, where, for $M_{\mathrm{h}} < 10^{9.5}$ M$_\odot$, the ratio flattens. The flattening of f_* is in the numerically resolved mass range.

Okamoto *et al.* (2008) showed that the same characteristic halo mass (the so called filtering mass) is imprinted by re-ionisation processes, and galaxies in halos smaller than $10^{9.5}$ M$_\odot$ cannot grow efficiently. However, in *FiBY*, the flattening of f_* is observed well before re-ionisation happens in the simulations. The conclusion is that stellar feedback may be the main driver defining the filtering mass at any redshift before re-ionisation.

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