The MaGICC volume: reproducing statistical properties of high-redshift galaxies

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ABSTRACT
We present a cosmological hydrodynamical simulation of a representative volume of the Universe, as part of the Making Galaxies in a Cosmological Context (MaGICC) project. MaGICC uses a thermal implementation for supernova and early stellar feedback. This work tests the feedback model at lower resolution across a range of galaxy masses, morphologies and merger histories. The simulated sample compares well with observations of high-redshift galaxies (z ≥ 2) including the stellar mass–halo mass (M⋆ − Mh) relation, the galaxy stellar mass function (GSMF) at low masses (M⋆ < 5 × 10^10 M_☉) and the number density evolution of low-mass galaxies. The poor match of M⋆ − Mh and the GSMF at high masses (M⋆ ≥ 5 × 10^10 M_☉) indicates that supernova feedback is insufficient to limit star formation in these haloes. At z = 0, our model produces too many stars in massive galaxies and slightly underpredicts the stellar mass around L⋆ mass galaxy. Altogether our results suggest that early stellar feedback, in conjunction with supernova feedback, plays a major role in regulating the properties of low-mass galaxies at high redshift.

Key words: methods: numerical – galaxies: abundances – galaxies: evolution – galaxies: formation – galaxies: star formation – galaxies: stellar content.

1 INTRODUCTION
Gravitational assembly of structure in a Lambda cold dark matter (ΛCDM) Universe is well understood and mostly consistent with observations. However, the evolution of galaxies inside dark matter haloes presents many challenges for modellers. The baryonic physics in haloes is complicated, involving various processes, such as gas cooling, star formation, radiative transfer, stellar and active galactic nucleus (AGN) feedback. These processes are highly non-linear and modelling them accurately is the major challenge for galaxy formation theory.

Fortunately, there are now large catalogues of galactic data available from the local Universe to as far back as z = 4. They make it possible to compare galaxy formation models with observations, throughout their evolution. These catalogues include observations that present full spectral energy distributions of the galaxies from 1.4 GHz radio continuum observations with the VLA (Karim et al. 2011), to infrared imaging with Hubble/WFC3, Spitzer/MIPS and VLT/HAWK-I (Kajisawa et al. 2010; Santini et al. 2012). These observations give a complete picture of star formation even when it is dust obscured.

From these observations, one can construct a cosmic star formation history (SFH) to compare with models (Lilly et al. 1996; Madau et al. 1996; Hopkins 2004; Wilkins, Trentham & Hopkins 2008; Bouwens et al. 2012). The shape of the cosmic SFH has a steep rise from z = 0 to z = 1 before flattening off and then steadily decreasing from z = 2 to higher redshift.

It is also possible to compare the star formation rate (SFR) of individual galaxies with their stellar mass (M⋆) determined from infrared photometry. In observations, SFR and M⋆ show a tight correlation that is sometimes called the star-forming main sequence (Brinchmann et al. 2004; Noeske et al. 2007; Wuyts et al. 2011). The slope of the relationship does not evolve significantly with redshift, but the normalization increases at higher redshifts (Kajisawa et al. 2010; Whitaker et al. 2011).

Dividing the SFR by M⋆ gives the specific star formation rate (sSFR), which provides a test of the star formation efficiency (SFE) compared to prior star formation. Similar to the rise of the...
star-forming main sequence, the sSFR rises with redshift (Kajisawa et al. 2010; Karim et al. 2011). Above $z = 2$, some observations show that the evolution of the sSFR flattens, though Stark et al. (2013) found that when corrected for nebular line emission, the sSFR continues increasing up to $z = 7$.

The primary constraint used for many models is the number density of galaxies as a function of their stellar mass, the galaxy stellar mass function (hereafter GSMF). The GSMF is a Schechter type function characterized by a power law at low masses and an exponential cutoff. At $z = 0$, the exponential cutoff is at $M_\ast \sim 5 \times 10^{10} M_\odot$ (Li & White 2009). The GSMF evolves as a function of redshift: Santini et al. (2012) find that the low-mass slope increases with redshift while Peng et al. (2010) finds that the slope remains constant, but the normalization increases.

Three types of models are commonly used to understand how stars populate galaxies:

(i) Statistical models: compare statistics of simulations with observations.

(ii) Semi-analytic models: populate dark matter haloes with stars based on halo mass, merger history, and single zone physics.

(iii) Cosmological simulations: model a volume of the Universe with hydrodynamics.

1.1 Statistical models

The statistical models are based on comparing the GSMF with the dark matter halo mass function and lead to an understanding of how efficiently stars form as a function of dark matter halo mass. A set of cosmological parameters makes explicit predictions about the mass function (Press & Schechter 1974; Sheth, Mo & Tormen 2001; Reed et al. 2005) of dark matter haloes and how those haloes are distributed throughout the Universe. The observed GSMF has a different shape than the dark matter halo mass function found in simulations. The GSMF low-mass slope ($\alpha$) is shallower than the low-mass dark matter mass function slope. $M_\ast \sim 5 \times 10^{10} M_\odot$ cutoff is at a lower mass than the dark matter mass function exponential cutoff.

Halo occupation models make the reasonable assumption that the distribution of galaxies in the Universe is similar to the distribution of dark matter haloes, modulo some bias (Peacock & Smith 2000). Halo occupation model attempt to match the correlation function statistics of galaxies and dark matter haloes to determine the stellar mass of galaxies that are most likely to be present in a particular dark matter halo. Using halo occupation modelling, one can construct a conditional luminosity function that can be compared with the real luminosity function (Yang, Mo & van den Bosch 2003; van den Bosch et al. 2007).

Conroy, Wechsler & Kravtsov (2006) realized that if one used satellite masses at their time of accretion, then the clustering statistics of mass-ordered dark matter halo samples matches galaxies. This realization lead to the abundance matching technique in which galaxies are placed in dark matter haloes with the same stellar mass ranking as that of the dark matter halo mass rank (Conroy & Wechsler 2009; Behroozi, Conroy & Wechsler 2010; Guo et al. 2010; Moster et al. 2010). Such a match leads to the stellar--halo mass ($M_\ast - M_h$) relationship, the key constraint for our model. The $M_\ast - M_h$ relation consists of two power laws with a steep slope at low masses and shallow slope at high masses. Stars form most efficiently at the break mass. The SFE drops quickly to both higher and lower masses. The characteristic mass of the break in the power law is $M_b \sim 10^{12} M_\odot$ at $z = 0$ (Moster, Naab & White 2013).

The availability of luminosity functions at high redshifts means that we can trace the evolution of the $M_\ast - M_h$ relation. Abundance matching indicates that the $M_\ast - M_h$ relation evolves surprisingly little (Behroozi, Wechsler & Conroy 2013a). The SFE evolves most significantly to higher halo masses at higher redshift from $M_h \sim 10^{12} M_\odot$ at $z = 0$ to $M_h \sim 10^{12.5} M_\odot$ at $z = 3$ (Behroozi, Wechsler & Conroy 2013b; Moster et al. 2013).

The key finding of the abundance matching models is that the star formation peaks earliest in the highest mass galaxies whereas, in the lowest mass galaxies, the SFR increases monotonically with time. This is a reflection of galaxy downsizing (Fontanot et al. 2009). This represents a delay of star formation in low-mass haloes and is the most important feature that must be reproduced in models in order to get the evolution of low-mass galaxies right.

1.2 Semi-analytic models

Semi-analytic models (SAMs) try to match the GSMF at $z = 0$ using physical prescriptions based on the mass and merger history of dark matter haloes taken from simulations (Kauffmann, White & Guiderdoni 1993). SAMs show that supernovae can limit star formation in low-mass galaxies (White & Rees 1978; White & Frenk 1991; Somerville & Primack 1999; Benson et al. 2003) and that AGN can limit star formation in high-mass galaxies (e.g. Bower et al. 2006; De Lucia et al. 2006).

While SAMs do well matching the evolution of the high-mass luminosity function, they do not match the evolution of low-mass galaxies at high redshift. (Guo et al. 2011). Current SAMs include strong stellar feedback to reproduce the GSMF at $z = 0$ (e.g. Guo et al. 2011; Bower, Benson & Crain 2012), but the low- and intermediate-mass galaxies build their stellar mass at early times ($z > 2$) following the assembly of the dark matter mass, because the feedback mechanism in these SAMs do not delay star formation in low-mass haloes. That means that there is little evolution in the SAM luminosity functions after $z = 2$, in contrast with observations (e.g. Fontanot et al. 2009; Marchesini et al. 2009; Guo et al. 2011). The early star formation means that the SAM galaxies have low sSFR at $z < 2$ (e.g. Daddi et al. 2007; Damen et al. 2009) and high values at $z > 3$ (e.g. Bouché et al. 2010; Dutton, van den Bosch & Dekel 2010; Weinmann, Neistein & Dekel 2011) although this picture might change at high redshifts due to refinement in the observational estimates of sSFR (Stark et al. 2013). This discrepancy has been looked at in detail by Weinmann et al. (2012), who use the number density evolution of low-mass ($9.27 < \log(M_\ast/M_\odot) < 9.77$) galaxies as a diagnostic to find that the observed evolution of the number density is not reproduced in any SAMs or simulations. They argue that the simple supernova feedback mechanism used in these models that gets the present-day GSMF correct does not decouple star formation from the parent DM halo growth.

1.3 Simulations

Hydrodynamical simulations differ from SAMs in that they include self-consistent interaction of dark matter and baryon evolution. Although the efficiency of computational calculations has increased, it is still not possible to resolve many important physical processes, so they must be modelled at the ‘sub-grid’ level. These processes include gas cooling, star formation and stellar feedback.

Since relatively little is known about star formation and feedback, the models include free parameters, which are constrained by observations. Star formation model parameters are constrained using...
local observations of the Kennicutt–Schmidt gas density–star formation density relation (Springel & Hernquist 2003; Stinson et al. 2006; Schaye & Dalla Vecchia 2008). The energy feedback from stars is modelled either by adding velocity to gas, called kinetic feedback, or adding thermal energy as thermal feedback. These models have been constrained based on observations (Springel & Hernquist 2003; Oppenheimer & Davé 2006; Dalla Vecchia & Schaye 2008; Crain et al. 2009; McCarthy et al. 2012). The model used in this paper instead constrains stellar feedback to match the evolution of $M_{\star} - M_{\text{halo}}$ relation.

There has been a lot of research on the optimal velocity for winds driven using kinetic feedback. The original models used a fixed wind velocity (Springel & Hernquist 2003; Crain et al. 2009; McCarthy et al. 2012), however, they had difficulties reproducing the GSFM at $z = 0$. Observations of metal absorption lines in outflows show that wind velocities are not constant, but are correlated with star formation rate, $v_{\text{w}} \approx SFR^{0.35}$, at $z = 0$ (Martin 2005) and $v_{\text{w}} \approx SFR^{0.3}$ at $z \approx 1.4$ (Weiner et al. 2009). These observations motivated using momentum conserving wind models in which mass loading depends on the mass of the host galaxy such that $M_{\text{wind}}/M_{\star} \propto V_{\text{circ}}^2$ (Oppenheimer & Davé 2006; Oppenheimer & Davé 2008; Davé, Oppenheimer & Finlator 2011a; Davé, Finlator & Oppenheimer 2011b). Momentum conserving winds successfully reproduce the GSFM and many other observed galaxy properties at $z = 0$ (Oppenheimer et al. 2010; Davé et al. 2011a,b; Puchwein & Springel 2013), but has similar shortcomings with the low-mass end of the luminosity function as the SAMs at high redshift. Weinmann et al. (2012) conclude that the current models of stellar feedback (in both SAMs and simulations) are unlikely to decouple the galaxy and DM halo growth due to its fundamental dependence on host halo mass and accretion history. An alternative to the momentum driven wind model is the energy conserving approximation for driving outflows from galaxies in which the mass loading factor scales as $M_{\text{wind}}/M_{\star} \propto V_{\text{circ}}^2$. Puchwein & Springel (2013) find that using this approximation of a stronger scaling of mass loading with galaxy size results in a shallower slope of the GSFM at $z = 0$. The energy-driven wind model also suppresses star formation at high redshift, reducing the cosmic SFR density to observed levels and shifting its peak to $z \sim 2.5$. This model is also successful in reproducing the GSFM at $z = 1$ and $z = 2$ reasonably well.

In thermal stellar feedback, stars heat the surrounding gas particles adiabatically, which creates pressure that can push gas out of galaxies (Gerritsen & Icke 1997; Thacker & Couchman 2000; Kawata & Gibson 2003; Stinson et al. 2006). SN energy can only efficiently drive outflows if the Sedov–Taylor phase of gas expansion is resolved. Such resolution is infeasible even with modern computer hardware, so two techniques have been employed to model this sub-grid physics. Stinson et al. (2006) delay cooling within the blast region that a supernova would create. Dalla Vecchia & Schaye (2012) integrate all the supernova energy that a stellar population creates and put it in a single gas particle. This raises the temperature to lengthen the cooling time enough so that the hot gas particle has a dynamical effect.

Simulations using thermal feedback have so far focused on disc structure using high-resolution zoom in simulations (Governato et al. 2010; Agertz, Teyssier & Moore 2011; Brook et al. 2011; Guedes et al. 2011; Sawala et al. 2011). Some recent simulations of a handful of galaxies have indicated that adiabatic feedback produces galaxies that follow $M_{\star} - M_{\text{halo}}$ below $M_{\text{halo}} < 10^{12} M_{\odot}$ (Brook et al. 2012; Munshi et al. 2013).

In most models of stellar feedback, only feedback from supernovae is considered, but Murray, Quataert & Thompson (2010) recognized the amount stars can disrupt molecular clouds before any stars explode as supernovae. Hopkins, Quataert & Murray (2011) and Agertz et al. (2013) implemented early stellar feedback schemes that rely on IR radiation pressure and tested them on isolated galaxy simulations. Lopez et al. (2011) and Pellegrini, Baldwin & Ferland (2011) found that when they mapped the pressure in different phases of the gas in the 30 Doradus region of the Large Magellanic Cloud, UV photoheating provides more pressure than IR radiation pressure.

In Stinson et al. (2013), we assume that photoheating from massive stars is thermalized by the time it reaches the spatial scales resolved in cosmological simulations. So, we inject thermal energy equal to the fraction of the bolometric luminosity emitted in the UV in the time between the formation of the star and the first supernova explosion. This early stellar feedback limits star formation to the amount prescribed by the $M_{\star} - M_{\text{halo}}$ relationship and delays star formation in an $L_{\star}$ galaxy, so that the galaxy follows the evolution of the $M_{\star} - M_{\text{halo}}$ relationship. This is a major improvement over previous galaxy formation models, as the delayed star formation means that star formation is decoupled from DM halo mass growth. Some sideeffects of using early stellar feedback include transforming DM cusps to cores in galaxies up to $L_{\star}$ mass (Macciò et al. 2012) and populating the circumgalactic medium with hot metal enriched gas, matching OVI observations (Stinson et al. 2013).

In this paper, we explore how the early stellar feedback model, described in Stinson et al. (2013), affects the global properties of galaxies on a large scale. To study this, we simulate a large volume of the Universe, 114 Mpc on a side, as part of the Making Galaxies in a Cosmological Context (MaGICC) project. This simulation tests the effectiveness of our model at low resolution across a wide range of galaxy masses, environments and merger histories. We compare the properties of the galaxies in our simulations with observed statistical properties of high-redshift galaxies like the GSFM, stellar to halo mass relationship, SFR and the number density evolution of low-mass galaxies through cosmic time. In Section 2, we briefly outline the star formation and stellar feedback mechanisms used in our simulations, in Section 3 we present our results at $z \geq 2$ and compare them to the current observational estimates. In Section 5, we summarize our results and discuss future challenges.

2 SIMULATION METHOD

We simulate a cosmological volume, 114 Mpc on a side, from $z = 99$ to $z = 2$. It is created using Wilkinson Microwave Anisotropy Probe 7 initial conditions with $(h, \Omega_{\text{M}}, \Omega_{\Lambda}, \Omega_{\text{b}}, \sigma_{8}) = (0.702, 0.2748, 0.7252, 0.0458, 0.816)$ (Komatsu et al. 2011; Larson et al. 2011). The simulation includes 512$^3$ dark matter and 512$^3$ gas particles. The dark matter particle has mass of $3.4 \times 10^{6} M_{\odot}$ and a softening length of $\sim 3.7$ kpc. The initial gas particle mass is $6.9 \times 10^{7} M_{\odot}$ and the initial star particle mass is $1.3 \times 10^{4} M_{\odot}$. Gas and star particles have a softening length of $\sim 2.17$ kpc. Section 4 describes lower resolution simulations that were used to test the resolution dependence of our model.

All the simulations use the smoothed particle hydrodynamics (SPH) code GASOLINE (Wadsley, Stadel & Quinn 2004). The smoothing length is calculated using 32 nearest neighbours. Details of the physics used in the MaGICC project are detailed in Stinson et al. (2013). Briefly, stars are formed from gas cooler than $T = 10^{4} K$, and denser than $8.7 \text{ cm}^{-3}$ according to the Kennicutt–Schmidt Law as described in Stinson et al. (2013) with the SFE parameter $\epsilon_{s} = 0.1$. The cooling used in this paper is described in detail in Shen, Wadsley & Stinson (2010). It was calculated using CLOUDY (version 07.02; Ferland et al. 1998) including photoionization and heating...
from the Haardt & Madau (unpublished) ultraviolet (UV) background, Compton cooling, and hydrogen, helium and metal cooling from 10 to 10^7 K.

The star particles are massive enough to represent an entire stellar population consisting of stars with masses given by the Chabrier (2003) initial mass function. 20 per cent of these have masses greater than 8 M⊙ and explode as Type II supernovae from 4 until 35 Myr after the stellar population forms according to the Padova stellar lifetimes (Alongi et al. 1993; Bressan et al. 1993). Each supernova ejects E_SN = 10^51 erg of purely thermal energy into the surrounding gas (~1 kpc at the resolution of our simulations). The supernova energy would be radiated away before it had any dynamical impact because of the high density of the star-forming gas. Thus, the supernova feedback relies on delaying the cooling based on the sub-grid approximation of a blast wave as described in Stinson et al. (2006).

The supernova feedback does not start until 3.5 Myr after the first massive star forms. However, nearby molecular clouds show evidence of being blown apart before any SNII exploded (Murray, Ménard & Thompson 2011). Lopez et al. (2011) and Pellegrini et al. (2011) found that UV photoheating is the dominant feedback mechanism in early phases of star formation by mapping out the pressure in different phases of the gas. In simulations in the MaGICC project, like those here, 10 per cent of the UV luminosity of the stars is injected into the surrounding gas over this 3.5 Myr period without disabling the cooling, at the rate of 4.45 × 10^48 erg/Myr/M⊙. Stinson et al. (2013) showed that this energy limits star formation to the amount prescribed by the M_*,−M_⊙ relationship at all redshifts. The current work is our attempt to explore how this star formation and feedback prescription works at lower resolutions over a wide range of galaxy masses.

2.1 Halo identification

For each snapshot, we find all the virialized haloes within the high-resolution region using a spherical overdensity algorithm. Candidate groups with a minimum of N = 100 particles are selected using an FoF algorithm with linking length d = 0.2d_c ≈ 22 kpc (d is the mean interparticle separation). We then: (i) find the point C where the gravitational potential is a minimum; (ii) determine the radius r of a sphere centred on C, where the density contrast is Δ_ν =r, with respect to the critical density of the Universe. Using all particles in the corresponding sphere of radius r, we iterate the above procedure until we converge on to a stable particle set. This stable particle set is then defined as a 'halo'. A galaxy is all stars within the particle set defined as a 'halo'. This does not affect the definition of stellar mass in low-mass galaxies, the focus of this paper, because their sub-structures contain very little amount of stars. We use a constant virial density contrast Δ_ν =200, in order to be consistent with Moster et al. (2013). We include in the halo catalogue all the haloes with more than 100 particles (see Macciò et al. 2007; Macciò, Dutton & van den Bosch 2008 for further details on our halo finding procedure).

3 RESULTS

We compare the simulated galaxy population in a 114^3 Mpc^3 volume with a set of basic properties derived from the most recent observational estimates. These include the GSMF, stellar mass–halo mass (M_*,−M_⊙) relationship, cosmic SFH, star-forming main sequence and sSFRs. Individual galaxies have been shown to match observations well (Brook et al. 2012; Stinson et al. 2013), so the volume provides an opportunity to test the accuracy and effectiveness of this feedback model at low resolution and high redshift. All the observational estimates of stellar masses and SFRs, that our results have been matched to, have been corrected to a Chabrier (2003) IMF. The results presented in this paper have all been presented in comoving units where ever applicable.

3.1 Stellar mass–halo mass (M_*,−M_⊙) relation

Fig. 1 shows the M_*,−M_⊙ relation for all the galaxies in the simulated volume (black points) that contain a minimum of 20 star particles, or a stellar mass of ~3 × 10^10 M⊙. The galaxies trace (red solid line) the slope of the M_*,−M_⊙ (green line) up to M_⊙ = 10^{12} M⊙ at all redshifts where it has been examined. The scatter of the simulated galaxies, quantified by the 10 and 90 percentile limits of the distribution (red dotted lines), also matches the variation in the relation as obtained by Moster et al. (2013) (grey shaded area). The agreement points to the fact that the stellar feedback effectively regulates star formation to produce the right amount of stellar mass in a given halo mass at all times.

Above a halo mass of 10^{12} M⊙, abundance matching (green dotted line) shows a decrease in SFE. This is not reproduced in the simulation. The SFE actually increases at M_⊙ ∼ 4 × 10^{12} M⊙, before decreasing slightly as represented by the slightly shallower slope of the simulation points. The reduced SFE is due to the reduced gas accretion because of the high virial gas temperature of the halo. However, this slight decrease in SFE does not reduce the star formation in these high-mass haloes to the extent observed. The implemented stellar feedback model is insufficient in these high-mass haloes. Some other quenching mechanism is required such as feedback from a central supermassive black hole (AGN feedback; e.g. Springel, Di Matteo & Hernquist 2005; Fanidakis et al. 2011).

3.2 The galaxy stellar mass function (GSMF)

The GSMF measures the number of galaxies of a certain stellar mass in a given volume of the Universe. The era of deep, high-redshift surveys has provided detailed GSMFs out to z = 3. We compare our simulation results to Santini et al. (2012), who use deep WFC3 near-IR data complemented by deep Hawk-I Ks band data to derive accurate stellar masses in an ~33 arcmin^2 area located in the GOODS-South field, to study the low-mass end of the GSMF. The observed GSMFs are presented for various redshift ranges. To compare with them, we use the simulated GSMF from the middle of the observed redshift range. Fig. 2 shows that the simulated galaxies from the fiducial run (blue line) trace the intermediate-mass (10^9.5 < M_*/M⊙ < 10^{11}) slope of the observed GSMF (red points) very well. There is a slight discrepancy at M_⊙ < 10^{9.5} M⊙ at z = 2.15. This discrepancy might arise due to the difficulty in determining the properties of low-mass galaxies at such large distances or due to cosmic variance, as their data set has a small sky coverage. The feedback model makes the slope of the GSMF as shallow as the observed value, which is non-trivial and is a major improvement over previous attempts to match the GSMF at high redshift (e.g. Guo et al. 2011). A small discrepancy remains, as the simulated number density of high-mass galaxies continues to decrease at the same rate, whereas the observations show an exponential cutoff. This again indicates that stellar feedback is insufficient to limit star formation in these high-mass haloes. The green and red curves are control test runs, which will be discussed in Section 4.
Figure 1. $M_* - M_h$ relation at different redshifts. The black points are simulated galaxies, with the red solid line tracing the mean of the distribution and the red dotted lines indicate the 10 and 90 percentile limits of the distribution. The green dotted line is the Moster et al. (2013) relation derived from abundance matching techniques and the grey shaded area is the scatter derived for the relation. Our simulated galaxies match the relation below $M_h < 10^{12} M_{\odot}$, but star formation is too efficient in high-mass haloes.

Figure 2. GSMF at $z \sim 2$ and $z = 3$ compared to observational data taken from Santini et al. (2012) for three different simulations. The fiducial simulation with $512^3$ particles is shown in blue, the corresponding low-resolution run ($256^3$) is shown in green, while the low-resolution simulation without ESF is coloured red.

3.3 Number density evolution of low-mass galaxies

Weinmann et al. (2012) used the number density evolution of low-mass ($9.27 < \log(M_*/M_{\odot}) < 9.77$) galaxies to show that SAMs or cosmological hydrodynamic simulations do not correctly model low-mass galaxies. They argue that the simple supernova feedback mechanism changes the stellar mass at $z = 0$, but renormalizes the SFH and thus does not decouple star formation from DM.
The blue line is the SFR density for $\sim$ error bars. The simulated curve falls in the middle of The evolution of the SFR density. The blue points are a com-
z = 3 galaxies. There is a clear trend of decreasing star formation at $z \leq 3.5$ in the highest mass galaxies.

the excess star formation in galaxies with $(\log(M_{\ast}/M_\odot) > 11.5)$ because even though the galaxies in that mass range form too many stars at $z \leq 3.5$, they are not the dominant population of galaxies at those redshifts.

3.5 Star-forming main sequence

Observations show that star-forming galaxies have a tight correlation between their SFR and $M_\ast$ (e.g. Elbaz et al. 2007; Pannella et al. 2009; Wuyts et al. 2011; Whitaker et al. 2012). This correlation has been called the ‘star-forming main sequence’.

We compare the SFRs of our simulated galaxies with observational estimates by Kajisawa et al. (2010) and Whitaker et al. (2012). Kajisawa et al. (2010) studied SFR as a function of $M_\ast$ for galaxies at $0.5 < z < 3.5$ in the GOODS-North field, using the $K$-selected sample from Subaru-MOIRCS. They determined SFRs from rest-frame, dust-corrected UV luminosity and the Spitzer-MIPS 24 $\mu$m flux. The depth of their data allowed them to constrain the slope of the SFR–$M_\ast$ relation down to $M_\ast = 10^{8.9} M_\odot$ at $z \sim 3$. The median SFR as a function of stellar mass (green curve) from their sample of galaxies is plotted in the top panels of Fig. 5 at $z = 2$ and 3. The slope of their relation is close to unity for low-mass galaxies at these high redshifts. Our simulated galaxies match these observations well at $z = 3$, but have nearly two times less star formation at $z = 2$. This discrepancy at $z = 2$ presents a challenge for all hydrodynamic simulations and SAMs (Weinmann et al. 2011). Davé (2008) suggested that an evolving stellar IMF is required to reduce the discrepancy in this relation out to $z = 2$.

Whitaker et al. (2012) measure SFRs using the NEWFIRM Medium-Band Survey from MIPS 24 $\mu$m fluxes. At $z > 2$ their detection limit is $(\log(M_{\ast}/M_\odot) > 10.7)$. For these galaxies, they find a shallower, sub-linear, slope for their star-forming main sequence, SFR $\propto M_\ast^{0.44}$, with a constant scatter of 0.34 dex. Above their detection limit, our simulated galaxies (black points) lie below the observations (red line) as seen in the top-left panel of Fig. 5.

3.4 Star formation history

We can also compare our simulation with the total number of stars formed in the Universe as a function of time. Fig. 4 shows how the cosmic SFR evolves as a function of redshift (‘Lilly–Madau plot’) in our simulated volume. The observed points used for comparison are taken from Moster et al. (2013) and include star formation estimates derived from rest-frame UV (Salim et al. 2007; van der Burg, Hildebrandt & Erben 2010; Bouwens et al. 2011; Robotham & Driver 2011; Cucciati et al. 2012), Hα (Ly et al. 2011), combined UV and IR (Zheng et al. 2007; Kajisawa et al. 2010), far-IR (Rujopakarn et al. 2010) and radio observations (Dunne et al. 2009; Smolčič et al. 2009; Karim et al. 2011). The total SFR density (black line) passes through the observations from $z = 2$ to 5.

The total SFH can be divided into separate lines based on the stellar mass of the halo at $z = 2$ in which the stars are formed. The lowest mass galaxies ($9.5 < \log(M_{\ast}/M_\odot) < 10.5$) contribute little to the overall SFR density, while the intermediate ($10.5 < \log(M_{\ast}/M_\odot) < 11.5$) and high mass ($\log(M_{\ast}/M_\odot) > 11.5$) contribute equally up to $z = 3$. Below this redshift, the SFR flattens out in the highest mass galaxies. This flattening is not sufficient to explain the quenching of high-mass galaxies as shown by the failure of the simulated $M_{\ast} - M_h$ and GSMF relations at the high-mass end. We note that our match of the SFH is not greatly affected by accretion. Stinson et al. (2013) showed for a high-resolution $L^*$ simulation that early stellar feedback can break the coupling of star formation to dark matter accretion. Fig. 3 shows the number density evolution of low-mass galaxies at high redshifts in our simulation volume compared to observations taken from fig. 1 of Weinmann et al. (2012), as well with the SAM described in Guo et al. (2011). The simulation matches the observational results much better and lies well below the values obtained by the SAM. The difference between the observations of González et al. 2010 (blue points) and Lee et al. 2012 (red points) is larger than the González et al. 2010 error bars. The simulated curve falls in the middle of these observations in contrast with the SAM that lies an order of magnitude above the observations. We note that the slope obtained from our model is still slightly steeper than observed, indicating that the simulation is building low-mass galaxies faster than observed.
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Figure 5. Top panels: the star-forming main sequence (black points) at different redshifts. The $z = 2$ result for galaxies with $\log(M/M_\odot) > 10.7$ is matched to the observational results of Whitaker et al. (2012) (red line). The slope of the main sequence is much steeper at lower masses. This matches well with the observational estimates derived by Kajisawa et al. (2010) at $z = 2$ and 3 (green curve). Bottom panels: the simulated sSFR (black points) matched to observational results matched from Karim et al. (2011) (red points) and Kajisawa et al. (2010) (green curve). The simulated sSFR lies below the observed values for low-mass galaxies at $z = 2$ by a factor of $\sim 2$, but matches very well at $z = 3$.

Galaxies above a stellar mass of $10^{11} M_\odot$ show a slight reduction in SFR from the trend at lower masses. This reduction is likely the result of the high temperatures of the gas haloes surrounding these galaxies, which has a long cooling time, so gas accretion on to the disc is slightly reduced. However, observations of such galaxies show a much more dramatic decrease in star formation that is not captured in these simulations.

3.6 sSFR evolution

Another common way to compare SFRs with galaxy stellar masses is the sSFR, which gives the amount of star formation in haloes for a unit stellar mass of material. As one would expect from the star-forming main sequence, the bottom panels of Fig. 5 show that the simulated galaxies (black points) match the Kajisawa et al. (2010) (green curve) observed sSFRs at $z = 3$ but have $\sim 2$ times lower sSFR at $z = 2$. We also compare our simulated results with 1.4 GHz radio continuum observations from Karim et al. (2011) of star formation in galaxies in the 2 deg$^2$ COSMOS field. The simulated galaxies in our volume (black points) are in good agreement above $\log(M/M_\odot) > 10.7$, but are 2–3 times lower below this mass range at both $z = 2$ and 3.

Karim et al. (2011), like other authors before them (Stark et al. 2009; González et al. 2010), found that sSFR increases for galaxies in a given stellar mass range from $z = 0$ to $z \sim 2$, but then does not evolve much from $z = 2$ to $z \sim 7$. Weinmann et al. (2011) shows that such observations are contradictory with most models in which higher gas accretion rates at higher redshift and lower galaxy stellar masses translate into larger sSFR in galaxies within a fixed stellar mass range.

Stark et al. (2013) re-examined their data and found that their Spitzer-IRAC photometry was contaminated by nebular emission. They use the photometric excesses in the contaminated [3.6] filter to estimate the equivalent width distribution of H$\alpha$ emission at $3.8 < z < 5.0$. The corrected sSFRs increase from $z = 4$ to $z = 7$ by a factor of $\sim 5$ similar to model predictions. Fig. 6 shows the evolution of the sSFR in simulated galaxies (black line) within a narrow stellar mass range around $\sim 5 \times 10^9 M_\odot$ (blackline). We compare the simulations with the observational estimates of Stark et al. (2013). The evolution of sSFR matches well at $z \leq 3$, but is below the observed value at lower redshifts.

Many other authors also find lower than observed sSFRs in their models (Davé 2008; Weinmann et al. 2012). The higher observed sSFRs again indicates delayed star formation in low-mass galaxies. Although our model does a better job of delaying the star formation at early times than most SAMs and hydrodynamic simulations,
below $z = 3$ the simulated haloes may still be forming too few stars. This suggests the importance of some other physical mechanism, not modelled in our simulation, like the dependence of the star formation on gas metallicity (Krumholz, Leroy & McKee 2011; Krumholz & Dekel 2012), that could further delay star formation at earlier times and increase the sSFR of these galaxies at $z = 2$.

3.7 Results at $z = 0$

Galaxies in the local Universe are the easiest to observe and compare with our model. Unfortunately, it is too computationally demanding to simulate the full cosmological volume to $z = 0$. So, we select a $16 \ h^{-1}\text{ Mpc}$ sub-volume from the fiducial simulation at $z = 2$. The region was selected to limit the number of high-mass haloes present in the region. The lack of massive haloes reduces the computational cost but also reduces the density of the region by $\sim 10$ per cent compared to the mean density for full volume. This kind of volume selection also impairs our ability to compare the volume-weighted properties of galaxies like the GSMF. On the other hand, the individual properties of galaxies like the stellar mass compared to the halo mass of the galaxy ($M_\star - M_h$ relation) and the SFR compared to their stellar mass (star formation main sequence) are expected to remain similar irrespective of the surrounding density field. Sheth & Tormen (2004) showed that halo formation weakly depends on the surrounding density field. So, only the $M_\star - M_h$ relation and the star formation main sequence obtained from the selected region are shown at $z = 0$ in Figs 7 and 8.

We include gas particles only inside the $16 \ h^{-1}\text{ Mpc}$ sub-volume. Outside this region the particles are re-binned to a lower resolution in order to save computing time. The simulation was then restarted from $z = 2$ and allowed to continue to $z = 0$, with all the other parameters unchanged from the fiducial run. This region contained enough galaxies for us to make a statistical comparison at $z = 0$ with observations.

Fig. 7 shows the ($M_\star - M_h$) relation for the galaxies in the selected cube at $z = 0$. The black points are simulated galaxies, the red solid line traces the mean of the distribution and the red dotted lines indicate the 10 and 90 per cent confidence intervals of the distribution. The green dotted line is the Moster et al. (2013) relation derived from abundance matching techniques and the grey shaded area is the scatter derived for the relation. The simulation still provides a fair match to the observations at $M_h \sim 10^{11}\ M_\odot$, though the galaxies at $z = 0$ have half the stellar mass of the observed galaxies. The overcooling problem also remains in higher mass galaxies ($M_h > 10^{12}\ M_\odot$).

As mentioned in Section 1, previous studies using momentum-driven wind SN feedback recipes (e.g. Crain et al. 2009; Oppenheimer et al. 2010) also tend to overproduce the stellar mass of massive galaxies and slightly under predict the stellar mass at the knee of the stellar mass function. Energy-driven variable wind models seem to be capable of reproducing the low-$z$ GSMF (for e.g. see Puchwein & Springel 2013). Our model is more successful in reproducing the GSMF at high redshift ($z > 2$) in the low-mass galaxy regime, while the previous studies largely overpredict the number of low-mass galaxies at these high redshifts (as shown in fig. 1 of Weinmann et al. 2012) and the differences between observations and our model at $z = 0$ is pretty small and comparable to previous works.

Observations of the star-forming main sequence are also more complete at $z = 0$. Fig. 8 shows how the simulated galaxies compare to those observations (grey contours from Brinchmann et al. 2004). The median SFRs of the simulated galaxies are $\sim 0.5$ dex higher than the locus of the observed star-forming main sequence, but are still within the observed range of SFRs. This is a change from high redshift where the simulated galaxies had systematically lower SFRs than observations.

No simulated galaxies populate the quiescent-high stellar mass corner of the plot. Even at $z = 0$, the simulation cannot produce red, dead galaxies most likely due to the lack of AGN feedback.

While the simulations have trouble at high masses, this sample of galaxies at $z = 0$ suggests that the simulations model the statistical
properties of low-mass galaxies well throughout the history of the Universe.

4 EFFECT OF RESOLUTION AND EARLY STELLAR FEEDBACK

To test the effect of resolution and early stellar feedback, we simulated the fiducial volume at a lower resolution containing 256$^3$ 2.76 $\times$ 10$^6$ M$_\odot$ dark matter and 256$^3$ 5.5 $\times$ 10$^6$ M$_\odot$ gas particles. Star particles form with masses of 1.83 $\times$ 10$^4$ M$_\odot$. The dark matter particles use a softening length of $\sim$ 3.7 kpc, while the gas and star particles use a softening length of $\sim$ 2.17 kpc. All the other simulation parameters are the same as used in the fiducial run. The low-resolution simulation was performed with two different feedback models, one with SN feedback only, and the other adding early stellar feedback to the SN feedback.

Fig. 2 shows the GSMF’s for these simulations (green and red lines) in addition to the fiducial run (blue curve). The low-resolution volume with the same physics as the fiducial run (green curve) matches the fiducial run and observations for $M_\star > 10^{12}$ M$_\odot$. The simulation without early stellar feedback has too many galaxies with $M_\star > 10^{12}$ M$_\odot$. The decrease in the number of $M_\star > 10^{12}$ M$_\odot$ in the low-resolution simulations is caused by the resolution limit. These galaxies consist of only a couple star particles, so star formation is not well sampled and the results cannot be trusted. Fig. 2 shows that our model is fairly well converged as well as the need for early stellar feedback to produce realistic galaxies.

5 DISCUSSION AND CONCLUSIONS

We examine the effect of early stellar feedback used in the MaGICC project on a broad sample of galaxies in a cosmological volume of 114$^3$ Mpc$^3$. The stellar feedback used is exactly the same as that used for a high-resolution $L_*$ galaxy (Stinson et al. 2013). We compare the simulated galaxies with the observed $M_\star - M_h$ relation, the GSMF, the cosmic SFH, the star-forming main sequence and the sSFR. The simulated galaxies do a good job matching each observation to $z = 2$, the time when previous models have most deviated from observations. Our use of early stellar feedback is the key difference between our simulation and ones run previously. The way that it delays star formation in $M_h < 10^{12}$ M$_\odot$ galaxies allows the simulations to match many observed statistical properties of high-redshift galaxies.

At $z \geq 2$, the simulated galaxies not only follow the $M_\star - M_h$ for $M_h < 10^{12}$ M$_\odot$ at all the redshifts examined but also match the scatter in the relation. Correspondingly, the simulated galaxies match the shallow slope at the low-mass end of the GSMF. The slope of the GSMF relationship was not a constraint for the simulation, but is a natural by-product of the stellar feedback recipe used. It is a major improvement over previous attempts to match the GSMF at high redshift. The early stellar feedback decouples the growth of stellar mass from DM mass by effectively blowing the gas away from the disc either into the circumgalactic medium or entirely out of the halo. This helps regulate the number density of low-mass galaxies to the observed values by delaying star formation in these haloes.

The simulated SFH of the Universe also matches a variety of different observations. The model predicts that the lowest mass galaxies ($9.5 < \log (M_\star / M_\odot) < 10.5$) contribute little to the overall SFR density, while the intermediate- ($10.5 < \log (M_\star / M_\odot) < 11.5$) and high-mass ($\log (M_\star / M_\odot) > 11.5$) galaxies contribute equally up to $z = 3$. After $z = 3$, the star formation slows in the highest mass galaxies.

At $M_h > 10^{12}$ M$_\odot$, too many stars form, which is shown by the presence of galaxies above the abundance matching $M_\star - M_h$ relation and the lack of an exponential cutoff in the GSMF. These indicate that the thermal stellar feedback is unable to quench star formation like is observed in massive galaxies.

Comparing SFR with stellar mass, the simulated galaxies lie along a tightly correlated ‘star-forming main sequence’. The simulated galaxies match observations by Kajisawa et al. (2010) at $z \geq 3$, but there is a slight discrepancy at $z = 2$ between simulations and observations. At a given stellar mass, the simulated SFRs and correspondingly, the sSFRs, are $\sim$ 2 times lower than the observed values at $9.5 < \log (M_\star / M_\odot) < 10.5$. The high sSFRs in low-mass haloes at $z = 2$ suggests that there needs to be a significant amount of cold gas still present in these galaxies at $z = 2$. Although our model does a better job of delaying the star formation at early times than most SAMs and hydrodynamic simulations, after $z = 3$ the simulated galaxies are forming too few stars.

Davé (2008) showed that the higher observed SFRs at $z \leq 2$ can be explained by an evolving stellar IMF, which becomes increasingly bottom-light at high redshift. However, Marchesini et al. (2009) showed that when such a bottom light IMF was used to model observations, the resulting observed high-redshift GSMF contained less galaxies, making the discrepancy with model GSMFs worse.

Regarding the evolution of sSFRs at $z > 3$, our simulation results are consistent with the revised Stark et al. (2013) observations for a sample of galaxies with stellar masses centred around $5 \times 10^9$ M$_\odot$. The increasing sSFR at $z \geq 4$ is consistent with increasing baryon accretion rates at larger redshift translating into larger sSFR in galaxies of fixed stellar mass. However, our simulated galaxies have lower sSFR values than observed at $z = 2$. Weinmann et al. (2012) argued that the correct sSFR evolution should follow naturally from the correct evolution of the GSMF. We see a slight deviation from the observed sSFR relation even though we match the GSMF. It must be noted that Weinmann et al. (2012) performed their analysis at $z < 2$, while our simulation has only reached at $z = 2$, where the observational estimates are less robust and might show some internal inconsistency among different galaxy properties (e.g. sSFR and GSMF).

There may also be another physical mechanism delaying star formation. Krumholz et al. (2011) and Krumholz & Dekel (2012) argue that star formation depends sensitively on a metallicity threshold. Until gas reaches this threshold, which coincidentally also delays the formation of H$_2$, star formation is delayed in low-mass galaxies at $z > 3$, which leaves sufficient cold gas at $z = 2$ to increase the sSFR of these galaxies to the observed values.

To compare the model with observations of the local Universe, the inner 16 h$^{-1}$ Mpc of the fiducial run was simulated with gas to $z = 0$. The $M_\star - M_h$ relation is reproduced at low masses ($M_h = 10^{11}$ M$_\odot$) and an over cooling problem still exists at high masses ($M_h = 10^{12}$ M$_\odot$). In the intermediate-mass regime, we are below the relation by a factor of 2. We also match the observed star-forming main sequence quite well, although we are a bit above the relation throughout the entire mass range. These results indicate that our model does not fare so well at $z = 0$ as at high redshifts but the errors are low when compared to many SAMs and simulations (Davé 2008; Guo et al. 2011).

Two low-resolution ($2 \times 256^3$ particles) realizations of the fiducial volume were simulated to test the effect of resolution and importance of Early Stellar Feedback (ESF). Both volumes used the same the same physics as the fiducial volume, but one had ESF
turned off. The low-resolution volume fiducial simulation compares well with the high-resolution fiducial run and observations for galaxies with $M_\star > 10^{10.5} \, M_\odot$ (20 star particles). However, the re-simulation without ESF has too many galaxies with $M_\star > 10^{10} \, M_\odot$.

Altogether, our results suggest that stellar feedback is one of the most important factors regulating star formation in $M_\star < 10^{11} \, M_\odot$ galaxies. What is most important is when the feedback occurs rather than simply the amount of feedback energy. Simply increasing and decreasing the feedback energy will only set the normalization, i.e. the total stellar mass of present at $z = 0$, but the key is delaying star formation in low-mass galaxies. When we include stellar feedback immediately after a star forms until supernovae stop exploding after 30 Myr, star formation is significantly delayed in low-mass galaxies. In this way, we account for the downsizing in galaxy populations by delaying the star formation in low-mass galaxies with our stellar feedback model and thus reconcile a couple key aspects of a Λ-CDM cosmology with observations.

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