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Star formation in high redshift galaxies including supernova feedback: Effect on stellar mass and luminosity functions

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HIGHLIGHTS

- Closed form of star formation rate in a galaxy from first principle with SNe feedback.
- Explain the stellar mass content of different populations of galaxies.
- Understand the stellar mass–Metallicity relation in high redshift galaxies.
- Luminosity functions of galaxies at $1.5 \leqslant z \leqslant 8$ is well explained by the model.

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ABSTRACT

We present a semi-analytical model of high redshift galaxy formation. In our model the star formation inside a galaxy is regulated by the feedback from supernova (SNe) driven outflows. We derive a closed analytical form for star formation rate in a single galaxy taking account of the SNe feedback in a self-consistent manner. We show that our model can explain the observed correlation between the stellar mass and the circular velocity of galaxies from dwarf galaxies to massive galaxies of $10^{12}\,M_{\odot}$. For small mass dwarf galaxies additional feedback other than supernova feedback is needed to explain the spread in the observational data. Our models reproduce the observed 3-D fundamental correlation between the stellar mass, gas phase metallicity and star formation rate in galaxies establishing that the SNe feedback plays a major role in building this relation. Further, the observed UV luminosity functions of Lyman-Break Galaxies (LBGs) are well explained by our feedback induced star formation model for a vast redshift range of $1.5 \leqslant z \leqslant 8$. In particular, the flattening of the luminosity functions at the low luminosity end naturally arises due to our explicit SNe feedback treatment.

1. Introduction

Presently we possess a wealth of observations regarding the high redshift universe, thanks to present day technology. The galaxies are regularly being detected till redshift $z \sim 10$ using Lyman break technique (Steidel et al., 2003). The UV luminosity functions of Lyman Break Galaxy (LBG) are well constrained up to redshift $z \sim 8$ using Hubble Ultra deep field observations (Bouwens et al., 2007, 2008, 2011; Reddy and Steidel, 2009; Oesch et al., 2010). The faint end slope of the UV luminosity functions is well established for $z \lesssim 6$ and it shows flattening of the luminosity function at low luminosity end. The presence of Gunn–Peterson (Gunn and Peterson, 1965) absorption in the spectrum of high redshift quasars tells us a transition from highly ionised inter galactic medium (IGM) to partially ionised IGM around redshift $z \sim 6$ (Wyithe et al., 2005; Fan et al., 2006; Mortlock et al., 2011). Also the electron scattering optical depth (τ_e) measured in the Cosmic Microwave Background Radiation (CMBR) by Wilkinson Microwave Anisotropy Probe (WMAP) constrains the reionisation redshift to be $z_{re} = 10.4 \pm 1.2$ (Komatsu et al. 2011) for a step reionisation scenario.

Further, the high resolution absorption spectra of quasars show the presence of metals in very low density IGM far away from galaxies. Metals are produced inside galaxies and believed to be transported by outflows produced by the supernova (SNe) explosions in the galaxy. The outflows are routinely being observed in low redshift galaxies as well as in high redshift galaxies (Martin, 1999; Pettini et al., 2001; Martin, 2005). These outflows are likely to expel metals along with a large amount of inter stellar medium (ISM). This, in turn, reduces the star formation in galaxies by reducing the available gas to form new generation of stars. Thus the supernovae give a negative feedback to the star formation by throwing out gas from galaxies in the form of galactic winds.

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Not only that, outflows also regulate the amount of metals in galaxies. Starting from very early days, a tight correlation has been observed between luminosity and metallicity of galaxies (Lequeux et al., 1979). Later, a more fundamental correlation has been found between the stellar mass and gas phase metallicity of galaxies in the local universe (Garnett, 2002; Tremonti et al., 2004; Lee et al., 2006; Kewley and Ellison, 2008) as well as in high redshift galaxies (Savaglio et al., 2005; Erb et al., 2006; Mannucci et al., 2009, 2010). It has been observed that galaxies with higher stellar mass trend to have more metals compared to their lower stellar mass counter parts. Further observations of local as well as high redshift universe show that the luminosity–metallicity or mass metallicity relation observed in galaxies is due to a more general relationship between stellar mass, metallicity of the gas and star formation rate (Mannucci et al., 2010; Cullen et al., 2013). Since, the outflows from galaxies throw metal enrich gas it is most likely that outflows play an important role in building up this correlation (Kobayashi et al., 2007; Scannapieco et al., 2008).

It has been seen from observations that the amount of gas/ISM expelled from a galaxy due to outflows is inversely proportional to the mass of the galaxy (Martin, 1999; Martin, 2005). This is expected if the hot gas produced in SNe explosions drives the outflow. Roughly 10% of total SNe energy would be available for driving the outflow when the SNe remnants started to overlap with each other (Cox, 1972). The conservation of SNe energy available to drive the outflow to the kinetic energy of outflowing gas would lead to a mass outflow rate inversely proportional to the square of the circular velocity (v_c) of the galaxy. Even if the hot gas loses its thermal energy due to radiative cooling the momentum of the gas and/or the cosmic rays produced in the SNe shocks can still drive the outflow (Samui et al., 2010; Ostriker and McKee, 1988). In such cases as well the inverse relation between outflowing mass and the circular velocity of the galaxy still holds with a different scaling. Thus due to supernova explosions small mass galaxies would lose more gas and experience a strong negative feedback to the star formation compare to higher mass galaxies.

Hence, it is important to build a complete model of high redshift galaxy formation taking account of all the observational evidences, particularly the SNe feedback driven star formation in high redshift galaxies and their metal transport to the IGM. Numerical simulations are the best way to study all these together and a tremendous effort is going on (for example, Scannapieco et al., 2005, 2006, 2012; Dave et al., 2008; Dave et al., 2011). However, present state of art hydrodynamic simulations are far from reality. They are constrained by the resolutions as well as the amount of physical processes that they can take account together (Scannapieco et al., 2012; Stringer et al., 2012). Here, we build an analytical model of star formation in the high redshift galaxies regulated by the feedback from SNe driven winds and try to explain the amount stellar mass and metals detected inside galaxies and the high redshift UV luminosity functions of Lyman-Break Galaxies (LBGs). In past, several authors have proposed semi-analytical models in order to understand the high redshift as well as low redshift galaxy formation process (White and Frenk, 1991; Kauffmann et al., 1993; Cole et al., 1994; Baugh et al., 1998, 2005; Somerville and Primack, 1999; Chiu and Ostriker, 2000; Granato et al., 2000; Choudhury and Srianand, 2002; Shankar et al., 2006). These works clearly demonstrated the power of such semi-analytical modelling by predicting various observations regarding high redshift universe. However, they have not derived a universal closed analytical form for the time evolution of star formation rate (SFR) in a single galaxy. Chiu and Ostriker (2000) and Choudhury and Srianand (2002) and some of our earlier works (Samui et al., 2007, 2008; Jose et al., 2011) have used such a closed form without considering the SNe feedback and also not deriving their star formation model from first principle. Others have just considered star formation rate to be proportional to the available cold gas and not derived a single evolution equation for the evolution of the star formation rate including feedback. Here, we solve for the star formation rate in a closed form starting from very basic physics governing the star formation and taking account of the negative feedback from galactic outflows on the star formation in a self-consistent manner. This closed form will be very useful while fitting the photometric observations of high redshift galaxies in order to find their star formation history, stellar mass etc. Moreover, the new data are extended to much lower in stellar mass/luminosity and higher redshift where the process of reionisation is still going on. In one hand these low mass systems are the dominating sources of reionisation. On the other hand they are much likely to prone to SNe feedback. Hence, it is timely to revisit feedback induced star formation in high redshift galaxies in the light of new improved data sets. Further, semi-analytical models are always useful as they are computationally inexpensive and help to understand the average universe very well. Also it is important to explore vast range of parameters that regulates the physical processes happening inside a galaxy.

The paper is organised as follows. In Section 2 we clearly state our feedback induced star formation model in galaxies and how well it explains the stellar mass detected in dwarf galaxies to high mass galaxies. The mass-metallicity-SFR relation of galaxies is discussed in Section 3. We present our model of UV luminosity function in Section 4. We show our model predictions of UV luminosity functions of LBGs and compare that with observations in Section 5. Finally we draw our conclusions with some discussions in Section 6. Through out this paper we assume a Λcold dark matter (ΛCDM) cosmology with the cosmological parameter as obtained by recent WMAP observation,[1] i.e. $\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$, $\Omega_b = 0.045$ and Hubble parameter $H_0 = 70$ km/s/Mpc.

2. Feedback induced star formation in individual galaxy

We model the star formation rate including the feedback from SNe driven outflows in a galaxy as follows. We assume that the instantaneous star formation rate at a given time is proportional to the amount of cold gas present in the galaxy. Once the dark matter halo virialises it accretes baryonic matter and a fraction, f_*, of that becomes cold and available for star formation. The f_* can be thought of as star formation efficiency and is a free parameter in our model. The baryon accretion rate in a galaxy of total mass M at time t after the formation of dark matter halo is taken as

$$\frac{dM_g}{dt} = \left(\frac{M_b}{\tau}\right) e^{[-t/\tau]}. \tag{1}$$

where M_g is the gas mass and $M_b = (\Omega_b/\Omega_m)M$ is the total baryonic mass in the halo. Further, τ is the dynamical time of the galaxy (Barkana and Loeb, 2001). We assume that the total gas mass in the galaxy is equal to the dark matter mass times the universal dark matter to baryon mass ratio. Note that integrating Eq. (1) from $t = 0$ to ∞ results $M_g = M_b$. The exponential form of the baryon accretion rate can be understood as follows. Once the dark matter halo virialises, the baryons are captured in the potential well and heated to virial temperature of the dark matter potential. In order to form stars the gas needs to cool and fall into the centre of the galaxy. If one assumes the rate of hot gas becoming cold is proportional to the amount of hot gas present, the increase in cold gas mass would follow an exponential form with time scale governed by the cooling time ($t_{\rm cool}$). However, as already mentioned, this cold gas has to collapse into the centre of the galaxy in order to form stars. The collapse of the gas into the centre of dark matter halo is

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[1] For a list of Cosmological Parameters based on the latest observations see http://lambda.gsfc.nasa.gov/product/map/current/parameters.cfm.