On the Star Formation Efficiency in High-redshift Lyα Emitters

Arnab Sarkar1,2 and Saumyadip Samui2

1 Department of Physics and Astronomy, University of Kentucky, KY 40508, USA; arnab.sarkar@uky.edu
2 Department of Physics, Presidency University, 86/1 College Street, Kolkata, 700073, India; saumyadip.physics@presiuniv.ac.in

Received 2018 November 12; accepted 2019 March 13; published 2019 June 4

Abstract

We present semi-analytical models of high-redshift Lyα emitters (LAEs) to constrain the star formation efficiency in those galaxies. Our supernova feedback induced star formation model along with Sheth-Torman halo mass function correctly reproduces the shape, amplitude and the redshift evolution of UV and Lyα luminosity functions of LAEs in the redshift range 2 ≤ z ≤ 7.3. We show that the fraction of Lyα emitting galaxies increases with increasing redshifts reaching to unity just after the reionisation. However, we show that star formation efficiency in those LAEs does not show any redshift evolution within the uncertainty in available observations. This would have significant repercussion on the reionisation of the intergalactic medium.

Key words: galaxies; high-redshift – (galaxies:) intergalactic medium – (stars:) supernovae: general

Online material: color figures

1. Introduction

High-redshift galaxies with strong Lyα emission (i.e., Lyα emitters) are detected using narrow band searches with targeted redshifts. Such narrow band technique is successful in detecting Lyα emitters (LAEs) in the redshift range 2 ≤ z ≤ 7.3 (i.e., Taniguchi et al. 2005; Kashikawa et al. 2006; Shimasaku & Kashikawa 2006; Gronwall et al. 2007; Murayama et al. 2007; Dawson et al. 2007; Ouchi et al. 2008, 2010; Ciardullo et al. 2012; Zheng et al. 2013; Konno et al. 2014; Ouchi et al. 2018; Sobral et al. 2017, 2018). However, their detectability depends on the emissivity of Lyα line and the radiative transport of it through the galaxy as well as through the intergalactic medium (IGM). In addition to narrow band searches galaxies are regularly identified using “drop out” technique (i.e., Steidel et al. 2003) even up to a redshift z ∼ 10 (Bouwens et al. 2004; Hopkins & Beacom 2006; Richard et al. 2006; Bouwens et al. 2015; Oesch et al. 2018).

Galaxies detected by this technique are known as Lyman break galaxies (LBGs). Unlike narrow band searches, the drop-out technique is very efficient in selecting galaxies with strong stellar UV continuum and hence biased by the UV luminosity of galaxies. Thus, these two techniques are successful in detecting galaxies with different selection bias and provide useful constraints on different physical properties of such galaxies. Therefore, one should consider both of them together in any theoretical study of galaxy evolution. Even though present day improved observational technology has made an impressive number of observational studies of LAEs available, the theoretical understanding of them is still in preliminary stages. This is because, the Lyα line is a resonant transition and the Lyα emissivity depends on many physical properties of the host galaxy such as amount of star formation, initial mass function of stars, the dust and neutral hydrogen content and the velocity field of the interstellar medium that governs the Lyα escape fraction, the duty cycle of Lyα phase etc. These are still poorly constraint from the present day observations. Several studies of Lyα emitters are available in the literature using simulation (Barton et al. 2004; Davé et al. 2006; Tasitsiomi 2006; Shimizu et al. 2007; Laursen et al. 2009; Zheng et al. 2011; Sadoun et al. 2017; Inoue et al. 2018) and semi-analytical models (Kobayashi et al. 2007; Dayal et al. 2008; Samui et al. 2009; Haiman & Spaans 1999; Dijkstra et al. 2007; Mao et al. 2007; Stark et al. 2007; Fernandez & Komatsu 2008; Dijkstra et al. 2007).

However, recent advancement of observations extending to higher redshifts, especially the constraints on the escape fraction of Lyα photons in high-redshift galaxies (i.e., Hayes et al. 2011) has enabled us to revisit it again. Further, it is well demonstrated that the supernova feedback is very important in determining the star formation in galaxies even in high redshifts (i.e., Samui et al. 2018). Therefore, in this work, we explore the luminosity functions of high-redshift Lyα emitters taking into the supernova feedback in the star formation (Springel & Hernquist 2003; Dayal et al. 2014; Samui 2014; Furlanetto et al. 2017).

Further note that star formation efficiency (SFE) of high-redshift galaxies is a very important physical property as it plays the key role in any processes associated with galaxy evolution (Sun & Furlanetto 2016). Especially it decides galaxy driven processes such as reionisation history and Lyα emitting galaxies are likely to play important role in reionisation. The star formation efficiency is basically defined as the fraction of baryonic gas that is converted to stars in a virialized dark matter halo. In any semi-analytical model it is the most basic parameter that one assumes. Thus it is important to constrain this from
available observations. Some previous works such as (Tilvi et al. 2009), using cosmological simulation, claimed that SFE around 2.5% is enough to fit the observed Lyα luminosity function at z = 3.1. Further, Dijkstra et al. (2007) found a non-evolving nature in SFE and suggesting the SFE be 10% between z = 5.7 and 6.5. By considering early reionization model (ERM) and late reionization model (LRM), Dayal et al. (2008) also provided a constant SFE value for z = 4.5 to 6.56 (10% for ERM and 8% for LRM). In this work we also constrain the star formation efficiency in Lyα emitting galaxies in a wide redshift range of 2 ≤ z ≤ 7.3 using all updated observations.

The paper is organized as follows. In next section, we briefly describe our semi-analytical model. Our results are discussed in Section 3, and conclude in Section 4. Here, we consider the ΛCDM cosmology frame work and use the cosmological parameters of WMAP5 data (e.g., Dunkley et al. 2009) (Ωm = 1, ΩΛ = 0.26, Ωb = 0.74, Ωh = 0.044 and h = 0.71).

2. Lyα Luminosity Function

We first proceed to estimate Lyα luminosity functions of galaxies at different redshifts. To do so, we consider the supernova feedback regulated star formation model of (Samui 2014) for individual galaxies. We briefly describe the model here.

2.1. Star Formation Model

The baryonic gas inside a dark matter halo, after virialization, is heated up to the virial temperature of the halo. The gas then cools down due to radiative cooling and accretes to the center of the halo. Such accretion of cold baryonic gas towards the center of halo enhances the baryonic density at the central part and leads to star formation in a galaxy (Dayal & Ferrara 2018).

On the other hand, massive stars explode as supernovae in relatively short timescale, which drives the cold baryonic gas out of the galaxy. Such outflow reduces the star formation in the host galaxy as availability of cold baryonic gas goes down. We assume that the outflowing mass is proportional to the instantaneous star formation and the star formation is proportional to the available cold gas. Such an assumption is motivated by Kennicutt-Schmidt law (Kennicutt 1998) that says the star formation rate is proportional to gas density. Finally, the star formation rate (M*) in a halo of total mass M evolves as (Samui 2014)

\[ \dot{M}_* = \frac{M_b f_\text{s}}{\kappa \tau T_{\text{eff}}} [e^{-\frac{\kappa T_{\text{eff}}}{M_b}} - e^{-\left(1 + \eta_w\right) T_{\text{eff}}}]. \]  

(1)

Here, f_s governs the star formation efficiency of the galaxy and \( \kappa \) determines the duration of star formation activity in terms of the dynamical timescale, \( \tau \). Throughout this work we have assumed \( \kappa = 4 \), which is determined by constraining UV luminosity functions of LBGs (Samui et al. 2018). Further, \( M_b \) is the total baryonic gas mass in the halo which is taken to be \( M_b = (\Omega_b/\Omega_m)M \). The supernova feedback process is regulated by the parameter \( \eta_w \), defined as \( \eta_w = \eta_w M_b \) (Samui 2014), where \( M_b \) is the baryonic mass driven out from the host galaxy by the outflow and over dot represents the time derivative. Note that, depending on the outflow mechanism, \( \eta_w \) can be related to the circular velocity of the galaxy \( \nu_c = (v_\text{esc}/v_\text{circ})^\alpha \) (e.g., Weaver et al. 1977; Ostriker & McKee 1988; Scannapieco et al. 2002; Veilleux et al. 2005; Samui et al. 2008); \( v_\text{circ}^2 \) is the circular velocity for the galaxy where \( \nu_c = 1 \). Further, if the outflow is driven by the hot gas and/or cosmic rays produced in supernovae shocks, then \( \alpha = 2 \). On the other hand, if the momentum of the gas drives the outflow (Furlanetto et al. 2017; Dayal & Ferrara 2018), \( \alpha = 1 \). It was shown by Samui (2014); also see Samui et al. (2018) that \( \alpha = 2 \) model is preferred by various observations of high-redshift galaxies and hence we use it here along with \( v_\text{circ}^2 = 100 \text{ km/s} \).

Note that, the baryonic gas in halos collapsed in the neutral region of the universe can cool in presence of atomic hydrogen and host star formation, if the virial temperature \( T_v \) of the halo is greater than \( 10^4 \text{ K} \). Below this temperature (and hence in halos with \( T_v < 10^4 \text{ K} \)) gas can cool only in presence of molecular hydrogen. In this work, we only consider galaxies that are cooled via atomic hydrogen cooling. This leads to a minimum halo mass of \( 2.5 \times 10^5 M_\odot \) that can host star formation at \( z = 9 \). Further because of radiative feedback, galaxies collapsed in ionized region of the universe, due to the increased in the Jean’s mass, can host star formation if the circular velocity is \( \geq 35 \text{ km/s} \) (see Bromm & Loeb 2002; Benson et al. 2002; Dijkstra et al. 2004; Samui 2014). For this we assume a complete suppression of star formation in galaxies with \( \nu_c \leq 35 \text{ km/s} \) and no suppression in galaxies with \( \nu_c \geq 110 \text{ km/s} \). In the intermediate halo mass region, i.e., for halo mass with \( 35 \text{ km/s} \leq \nu_c \leq 110 \text{ km/s} \), we have used a linear suppression factor from 0 to 1 by which the star formation is reduced in such halos. Further, AGNs activities in high mass galaxies are likely to produce a negative feedback on star formation in those galaxies (Bower et al. 2006; Best et al. 2006). In order to model that, we also consider a suppression factor of \( [1 + (M/10^2 M_\odot)^{3}]^{-1} \) on star formation in high mass halos due to possible AGN feedback. Such a scenario explains the bright end of the UV luminosity functions of LBGs (Samui et al. 2018).

2.2. Luminosity Functions

The star formation described above will produce stars of different masses (we assume a Salpeter initial mass function of stars in the mass range 1–100 M_\odot). The UV photons coming from massive stars can ionize neutral hydrogen of interstellar medium (ISM). Recombination of those ionized hydrogen can lead to production of Lyα photons. In a case B recombination scenario, ~2/3 of ionizing photons produce Lyα photons (Osterbrock 1989). Thus, the star formation rate (i.e., Equation (1)) can be used to calculate the Lyα luminosity (L_{Lyα}) produced in a star-forming
galaxies, i.e., (Samui et al. 2009),

$$L_{\text{Ly}\alpha}^{\text{int}} = 0.68 \, h \nu_{\alpha} \left( 1 - f_{\text{esc}} \right) N_{\gamma} \, M_\odot.$$  \hspace{1cm} (2)

Here, $h \nu_{\alpha}$ is the energy of a Ly\(\alpha\) photon, i.e., $h \nu_{\alpha} = 10.2$ eV and $f_{\text{esc}}$ is the escape fraction of the hydrogen ionizing photons from the host galaxy. Further, $N_{\gamma}$ represents number of hydrogen ionizing photons produced per unit baryonic mass of star formation and it depends on the initial mass function and the metallicity of the gas. For our work we have taken $N_{\gamma} = 10,840$ per baryonic mass (Leitherer et al. 1999; Samui et al. 2007). Escape fraction of ionizing photon ($f_{\text{esc}}$) from host galaxy is a poorly known quantity from observation (Tilvi et al. 2009; Shapley et al. 2006; Iwata et al. 2009). In our work we have used $f_{\text{esc}} = 0.1$ (Giri et al. 2018) that self consistently reproduces the observational constraints on reionisation. We will also consider how our model predictions differ for a range of $f_{\text{esc}}$ as it is constrained from observation (Matthee et al. 2017; Chisholm et al. 2018).

Note that Equation (2) provides the intrinsic Ly\(\alpha\) luminosity of a galaxy. However, Ly\(\alpha\) luminosity that we observe is less than that because it can be absorbed in the host galaxy ISM as well as in the IGM by the dust as well as neutral hydrogen. We consider a fraction $f_{\text{esc}}$ of the total Ly\(\alpha\) finally reaches to us. Thus the observed Ly\(\alpha\) luminosity of a galaxy is given by

$$L_{\text{Ly}\alpha}^{\text{obs}} = f_{\text{esc}} L_{\text{Ly}\alpha}^{\text{int}}.$$ \hspace{1cm} (3)

To calculate the Ly\(\alpha\) luminosity functions we need the formation rate of halos/galaxies at different redshifts. We use the redshift derivative of Sheth-Tormen (ST) mass function (Sheth & Tormen 1999) to calculate the formation rate of dark matter haloes. Note that redshift derivative of mass function provides the difference of the formation and the destruction rate of halos. Here we assume that redshift derivative of ST mass function closely follows the formation rate of halos (see Samui et al. 2010, for a detail discussion on it). The Ly\(\alpha\) luminosity function $\phi(L, z)$ for luminosity $L$ at a given observed redshift $z$ is given by (Samui 2014)

$$\phi(L, z) \, dL = \int_{M_{\text{low}}}^{\infty} \int_{z_c}^{\infty} \delta M \, n(M, z_c) \, \delta[L - L(M, z, z_c)] \, dL.$$ \hspace{1cm} (4)

Here, $n(M, z_c)$ is the number density of the dark matter halos having masses between $M$ to $M+dM$ and collapsed between $z_c$ and $z + dz_c$, obtained from the ST mass function. The delta function $\delta[L - L(M, z, z_c)]$, ensures that the integral survives only for those galaxies with mass $M$ which formed at $z_c$ greater than the observed redshift $z$ and having observed Ly\(\alpha\) luminosity, $L(M, z, z_c)$. Further, the lower limit of the mass integral, $M_{\text{low}}$, is decided by the cooling criteria discussed above.

Note that not all galaxies are likely to show up as Ly\(\alpha\) emitters. In fact it has been found observationally that only a fraction of galaxies that are found using the Lyman-break technique is detectable as Ly\(\alpha\) emitters (see Shapley et al. 2003; Kornei et al. 2010; Stark et al. 2010). Thus, in our work we assume that a fraction, $G_f$ of all galaxies shows up as Ly\(\alpha\) emitters. We simultaneously fit observed UV luminosity function of Lyman-break galaxies (LBGs) and UV luminosity function of Ly\(\alpha\) selected sample at a similar redshift to obtained the value of $G_f$. In order to obtained UV luminosity functions of LBGs we follow (Samui 2014). Note that Equation (4) can be used to calculate UV luminosity function of LBGs if the luminosity $L$ is the UV luminosity of the galaxy that can be obtained by convolving the star formation rate with UV luminosity of a single burst of star formation (see Samui et al. 2007, for detail). Further, the UV luminosity is also affected by the dust in the galaxies i.e., dust attenuation and like the Ly\(\alpha\) luminosity we assume that only a fraction $1/\eta$ of the intrinsic UV luminosity is finally reached to us. Thus, we use the combination, $f_{\nu}/\eta$ as a free parameter of our model and fit the observed UV luminosity function of LBGs at different redshifts by varying that (Samui et al. 2007). On the other hand we vary $f_{\text{esc}}^{\text{Ly}\alpha}$ combination with redshifts to fit observed Ly\(\alpha\) luminosity functions at different redshifts.

3. Results

In this section we show our model predictions and compare them with the available observations in order to constrain our model parameters. We first concentrate at redshift $z = 3$. In Figure 1 we have shown the UV luminosity functions of LBGs at $z = 3$ as predicted by our model by the solid red line. The corresponding observational data are shown by the red filled triangles with error bars adopted from Reddy & Steidel (2009). We have used $\chi^2$ minimization technique to match our model with observation. It is clear from the figure that a reasonably good agreement is obtained between the model and observed data with value of $f_{\nu}/\eta = 0.144$. We now turn to the UV luminosity function of Ly\(\alpha\) emitters in the similar redshift, i.e., $z = 3.1$. As mentioned above we assume that a fraction $G_f$ of all LBGs shows up as LAEs. Thus we scaled the above fitted UV luminosity function of LBGs by factor $G_f$ to match with the observational UV luminosity function of LAEs keeping all other parameters the same.

The model prediction and the observational data from Ouchi et al. (2008) are also shown in Figure 1 by the dashed red curve and solid magenta filled circles with error bars respectively. We see that a good agreement is obtained with $G_f = 0.10$. Similar values were obtained by Shapley et al. (2003) and Samui et al. (2008). Thus we conclude that only 10% of total galaxies shows up as LAEs at $z = 3.1$. Note that, due to larger uncertainties in the UV luminosity function of LAEs we do not use $\chi^2$-mechanism to obtain the value of $G_f$. Further, due to incompleteness in the observed data points of the two lowest luminosity bins (as shown by open circles) we omitted them from fitting (see Ouchi et al. 2008, for details). This $G_f$ has been used in finding the Ly\(\alpha\) luminosity functions of Ly\(\alpha\) emitters that we consider next.
Figure 1. Above plot shows model predicted UV luminosity function for LBGs and LAEs at redshift 3.1 along with the observational data. Blue solid line indicates the UV luminosity function for LBGs and red dashed line indicates UV luminosity function for LAEs. Red triangles represent (Reddy & Steidel 2009) data of UV LF for Lyman break galaxies and cyan circles (empty and filled) represent the UV LF for Lyman alpha emitters (Ouchi et al. 2008). Empty cyan circles, due to incompleteness in observational data, are excluded from fitting process.

(A color version of this figure is available in the online journal.)

Figure 2 shows our model prediction of Lyα luminosity function at \( z = 3.1 \) by solid line and the observed data points from Ouchi et al. (2008) (filled circles). Here also, we use \( \chi^2 \)-minimization to fit the model with observation by varying \( f^*_{esc} \). We can see that our model well reproduces the shape and amplitude of the Lyα luminosity function of LAEs. Thus, our feedback induced star formation model provides a good description of Lyα emitters at \( z = 3.1 \). The fitted value along with 1σ uncertainty for \( f^*_{esc} \) is 0.047 ± 0.007 at \( z = 3.1 \). Now, as already mentioned Hayes et al. (2011) has measured \( f^*_{esc} = 0.07 \pm 0.04 \) from observations at \( z = 3 \). Using this we estimate \( f_{esc} = 0.67 \pm 0.45 \) where we add the observational uncertainty in \( f^*_{esc} \) and the fitting uncertainty of \( f^*_{esc} \) in quadrature. Note that the bright end of the observed Lyα luminosity function suffer from cosmic variance due to limited survey volume and future large volume survey will help us to understand the nature of such bright LAEs.

The procedure described above for \( z \sim 3 \) has been followed for all other redshift bins, \( z = 2.0, 3.7, 4.5, 5.7, 6.6 \) and 7.3. The resulting values of \( f_{esc} \), \( f^*_{esc} \) and hence the \( f_{esc} \) are tabulated in Table 1. We also provide the best fit \( \chi^2 \) values. The fitted Lyα luminosity functions of LAEs and the observational data are shown in Figure 3. Note that the observed UV luminosity function of LAEs in all these redshifts are not available except for \( z = 3.1, 3.7 \) and 5.7 and hence \( G_f \) can not be estimated at those redshifts (i.e., at \( z = 2, 4.5, 6.6 \) and 7.3) using the procedure describe earlier for \( z = 3 \). In absence of this, at \( z = 2.0 \) we have used \( G_f = 0.10 \) as obtained from near by redshift (i.e., at \( z = 3.1 \) as well as \( G_f = 0.05 \) because of the trend seen from other redshifts that \( G_f \) decreases with decreasing redshift. From the value of \( \chi^2 \) we see that both these values provide similar fit the observed Lyα luminosity function. For \( z = 4.5 \), using \( G_f \) as obtained at \( z = 3.7 \) or 5.7 our model predictions do not provide a good fit to the observational data as can be seen from the value of \( \chi^2 \). An intermediate value \( G_f = 0.30 \) provide the best fit in this redshifts. This is also consistent with the increasing trend of \( G_f \) with increasing redshift. For \( z > 5.7 \) we have used \( G_f = 1.0 \) as obtained at \( z = 5.7 \), and we get good fit of the model predictions with observational data. Thus we conclude that even though the fraction of galaxies, that are detected through narrow band Lyα emission is only \( \lesssim 10\% \) at \( z = 2 \), it increases rapidly with increasing redshift and reaches to unity just after the end of the reionisation process. Hence, during the reionisaton period all galaxies are expected to have strong Lyα emission. Similar results were obtained by Samui et al. (2008) in spite of the fact that they did not take account of supernova feedback in star formation. Further, it is clear from the Figure 3 and the \( \chi^2 \) per degrees of freedom as given in Table 1 that our models provide a good fit to the observed Lyα luminosity function at different redshifts.
luminosity function of LAEs in the entire redshift range from $z = 7.3$ to 2.0. The best fit values of $f_{esc}^\alpha$ along with 1$\sigma$ uncertainty are reported in column 4 of Table 1. Thus we can say that the SNe feedback is operating in the high-redshift galaxies with strong Ly$\alpha$ emission.

The most interesting result of our work is the redshift evolution of star formation efficiency in LAEs as can be seen from the values of $f_*$ at different redshifts (see Table 1). Note that the parameter $f_*$ used here in not exactly the canonically used star formation efficiency. The fraction of total baryonic gas that will eventually convert to stars in the galaxy is $f_*/(1 + \eta_w)$ in presence of supernova feedback and this should be compared with the observations of $M_*/M_\odot$. It is clear from the Table 1 as well as Figure 4 where we have plotted $f_*/(1 + \eta_w)$ as a function of redshift that within the uncertainty the star formation efficiency does not show any evolution in the LAEs for the entire redshift range of $z = 2$ to 7.3. Thus, we conclude that even though the fraction of galaxies that shows up as LAEs changes drastically from reionisation to late universe, the star formation efficiency does not change significantly in those Ly$\alpha$ emitting galaxies. In particular, given the observational uncertainty and hence the uncertainty in derived star formation efficiency, no trend can be identified in the redshift evolution of star formation efficiency.

3.1. Variation of Model Parameters

There are two crucial model parameters that are poorly constraint from observations, namely the escape fraction of UV photon, $f_{esc}$ and the fraction of galaxies that are detected as LAEs, i.e., $G_f$. Here we show how these two parameters affect our results.

First we concentrate on $f_{esc}$ that appear in the Equation (2). Note that this parameter also regulate the reionisation history and hence we show our results only for $z = 6.6$ i.e., $G_f$. Here we show how these two parameters affect our results.

Figure 3. Above plots are for Ly$\alpha$ luminosity function for LAEs as predicted by our model for redshift 2.0, 3.7, 4.5, 5.7, 6.6, 7.3 along with the observational data. In all panels, blue solid line indicates our model predicted luminosity functions. Red filled circles represent the observational data of Ly$\alpha$ luminosity function taken from Ciardullo et al. (2012) for $z = 2$; Ouchi et al. (2008) for $z = 3.7$ and 5.7; Zheng et al. (2013) for $z = 4.5$; Ouchi et al. (2010) for $z = 6.6$; and Konno et al. (2014) for $z = 7.3$. The $G_f$ factors for each redshift are indicated in each panel. In panel (a) we also show our model prediction for $G_f = 0.10$ with dot-dashed line. For $z = 4.5$ (panel c) the model predictions with $G_f = 0.10$ and 1.0 are shown by dashed and dotted-dashed curves respectively.

(A color version of this figure is available in the online journal.)
produce similar fit for the observed data. The $\chi^2$ per d.o.f for these three models are 2.30, 2.00, 2.27 respectively for $f_{\text{esc}} = 0.05$, 0.1 and 0.3. The resulting values of star formation efficiency are $f_\ast = 0.14 \pm 0.07$, $0.15 \pm 0.09$, $0.20 \pm 0.10$.

Thus within the uncertainty, the star formation efficiency does not change significantly for a wide variation in the value of escape fraction of UV photon from the galaxy. We note that similar results are also obtained for any other redshifts that are being considered in this work.
Next we consider the variation of $G_f$. Note that recent observations have resulted very low value of $G_f$ for $z \geq 6$ (Ono et al. 2012; Schenker et al. 2012, 2014). Thus, it is important to see how such variation affect our results. We show in Figure 6 the Ly$\alpha$ luminosity functions at $z = 7.3$ for different $G_f = 1, 0.5$ and 0.3. All three models predict luminosity functions that are consistent with the observation. Fitted values of minimum $\chi^2$ are unable to distinguish between models given the large uncertainty in the observed data. However, for lower value of $G_f = 0.3$ we need unrealistic value of the star formation efficiency parameter, $f_s = 1.0 \pm 0.7$. Thus an improved measurement of the Ly$\alpha$ luminosity functions at $z = 7.3$ is needed in order to understand the physical processes happening inside these Ly$\alpha$ emitting galaxies.

**4. Conclusion**

We have presented semi-analytical models of galaxy formation and evolution to understand the redshift evolution of luminosity functions of LAEs and their physical properties. In particular we have used star formation model regulated by supernova feedback along with Sheth-Tormen halo mass function to obtain simultaneously the UV and Ly$\alpha$ luminosity functions of LAEs in the redshift range $z = 2$ to 7.3. Our models correctly reproduce the shape and redshift evolution of both UV and Ly$\alpha$ luminosity functions of LAEs demonstrating the fact that the supernova feedback is indeed operational in high-redshift Ly$\alpha$ emitters. Finally we derive the average star formation efficiency of the Ly$\alpha$ emitting galaxies at different redshifts using observational constraint of escape fraction of Ly$\alpha$ emission from galaxies.

We show that the fraction of Ly$\alpha$ emitting galaxies increases with increasing redshift, reaching to unity just after the end of reionisation, i.e., at $z = 5.7$. On the other hand the star formation efficiency does not vary significantly before and after reionisation in those Ly$\alpha$ emitting galaxies. This conclusion is independent of the uncertainty in the escape of UV photon from those galaxies. Such a result was also obtained by previous work by Dijkstra et al. (2007) and Inoue et al. (2018) who showed that the change in the Ly$\alpha$ emitter fraction compared to LBGs are due to change in the IGM or surrounding halo gas, not due to change in the physical properties of LAEs. Further, we show that one needs to fit all available data of LAEs in order to constraint the physical properties of LAEs (also see Inoue et al. 2018). Inoue et al. (2018) also showed that a highly fluctuating $f_{Ly\alpha}$ is needed to match recent observations that shows very small fraction of LAEs at $z > 6$. Our models also require unphysical parameters such as star formation efficiency of order unity in order to understand such a low fraction of LAEs while fitting simultaneously the UV and Ly$\alpha$ luminosity functions of LAEs. However, we also wish to point out that this conclusion is highly biased due to large uncertainty in the observed luminosity functions of LAEs and also in the measurements of the escape fraction of Ly$\alpha$ photons from the galaxy. Precise estimation of these in a large volume survey would enable us to more accurately constrain the evolution of the star formation efficiency in the Ly$\alpha$ emitters.

We thank the anonymous referee for suggestions that has improved the paper. We thank V. Tilvi for providing us new data on current Lyman alpha emitter surveys. A.S. thanks to R. Ciardullo for his useful comments on different Lyman alpha survey volume. This work is partially funded by the Physics Incentive programme of the University of Kentucky, Kentucky. SS thanks Presidency University, Kolkata for providing funds through FRPDF scheme. SS also thanks UGC, India for support through UGC Start Up grant.

**ORCID iDs**

Saumyadip Samui \( \text{https://orcid.org/0000-0002-8052-0967} \)

**References**

Barton, E. J., Davé, R., Smith, J. D. T., et al. 2004, ApJ, 604, L1

Benson, A. J., Lacey, C. G., Baugh, C. M., Cole, S., & Frenk, C. S. 2002, MNRAS, 333, 156

Best, P. N., Kaiser, C. R., Heckman, T. M., & Kauffmann, G. 2006, MNRAS, 368, L67

Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015, ApJ, 803, 34

Bouwens, R. J., Thompson, R. I., Illingworth, G. D., et al. 2004, ApJ, 616, L79

Bower, R. G., Benson, A. J., Malbon, R., et al. 2006, MNRAS, 370, 645

Bromm, V., & Loeb, A. 2002, ApJ, 575, 111

(Figure 6. Variation of Ly$\alpha$ luminosity function due to variation of $G_f$ at $z = 7.3$.
(A color version of this figure is available in the online journal.)

We thank the anonymous referee for suggestions that has improved the paper. We thank V. Tilvi for providing us new data on current Lyman alpha emitter surveys. A.S. thanks to R. Ciardullo for his useful comments on different Lyman alpha survey volume. This work is partially funded by the Physics Incentive programme of the University of Kentucky, Kentucky. SS thanks Presidency University, Kolkata for providing funds through FRPDF scheme. SS also thanks UGC, India for support through UGC Start Up grant.

**ORCID iDs**

Saumyadip Samui \( \text{https://orcid.org/0000-0002-8052-0967} \)

**References**

Barton, E. J., Davé, R., Smith, J. D. T., et al. 2004, ApJ, 604, L1

Benson, A. J., Lacey, C. G., Baugh, C. M., Cole, S., & Frenk, C. S. 2002, MNRAS, 333, 156

Best, P. N., Kaiser, C. R., Heckman, T. M., & Kauffmann, G. 2006, MNRAS, 368, L67

Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015, ApJ, 803, 34

Bouwens, R. J., Thompson, R. I., Illingworth, G. D., et al. 2004, ApJ, 616, L79

Bower, R. G., Benson, A. J., Malbon, R., et al. 2006, MNRAS, 370, 645

Bromm, V., & Loeb, A. 2002, ApJ, 575, 111
