Models for Dusty Lyα Emitters at High Redshift

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ABSTRACT

Models are presented for the Lyα emission of dusty high–redshift galaxies by combining the Press–Schechter formalism with a treatment of the inhomogeneous dust distribution inside galaxies. It is found that the amount of Lyα radiation escaping from the galaxies strongly depends on the time over which the dust is produced through stellar activity, and on the ambient inhomogeneity of the HII regions that surround the ionizing OB stars. Good agreement is found with recent observations, as well as previous non–detections. Our models indicate that the dust content builds up in no more than ∼ 5 × 10^8 yr, the galactic HII regions are inhomogeneous with a cloud covering factor of order unity, and the overall star formation efficiency is at least ∼ 5%. It is predicted that future observations can detect these Lyα galaxies upto redshifts of ∼ 8.

Subject headings: cosmology:theory – early universe – galaxies:evolution – galaxies:star formation – galaxies:ISM

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1. Introduction

One expects that the ionizing radiation from young stars leads to prominent Ly\textsc{\(\alpha\)} emission through the recombination of hydrogen in the interstellar medium (Meier 1976). Because the Ly\textsc{\(\alpha\)} line is narrow and strong, it stands out against the continuum background and should provide a signature of primeval high–redshift galaxies (Partridge & Peebles 1967). Until a decade ago, the search for these high–redshift Ly\textsc{\(\alpha\)} galaxies had enjoyed no compelling successes (e.g. Djorgovski 1992; Thompson et al. 1995). A large class of high redshift radio galaxies was discovered in recent years (c.f. Chambers & Miley 1990), but their numbers are still significantly below the theoretical predictions of about $10^{3-5}$ of such primeval galaxies per square degree (cf. Pritchet 1994). As was pointed out in the above paper, the lack of detections was becoming a source of confusion and concern. However, in the last couple of years, with improved sensitivity on large area telescopes, these young galaxies are finally being detected (e.g. Hu, Cowie, & McMahon 1998; and references therein). Clearly, this population is of great interest to the field of galaxy formation and the early evolution of the universe. It is mandatory to understand why earlier surveys have been unsuccessful, how many objects are still expected to be found, and what physical conditions pertain in these early systems so that the Ly\textsc{\(\alpha\)} radiation may escape.

On galactic scales, the spatial distribution and the amount of stellar dust are crucial ingredients for the radiative transfer effects in the Ly\textsc{\(\alpha\)} line, such as resonant scattering and dust attenuation, and will determine the emerging Ly\textsc{\(\alpha\)} luminosity (e.g. Neufeld 1991). Indeed, for a homogeneous dusty HII region it is well known that only a negligible fraction of the Ly\textsc{\(\alpha\)} photons can escape the medium (c.f. Spitzer 1978). Observations by e.g. Hartmann, Huchra, & Geller (1984) and Terlevich et al. (1993) have firmly established the strong decrease in Ly\textsc{\(\alpha\)} equivalent width with increasing oxygen abundance.

The presence of dust in galactic HII regions therefore needs to be studied in detail. In a cosmological context, the formation of dust requires the presence of metals, and is therefore intimately related to the star formation process itself (Miralda-Escudé & Rees 1998). Connected to this metal production is the question of the early enrichment of the intergalactic medium (IGM) as seen in damped Ly\textsc{\(\alpha\)} systems, as well as that of the hot cluster gas observed in lower redshift systems. The interplay between the IGM and the galactic environment likely plays an important role in the distribution of metals and dust through galactic wind expulsion and accretion (Ferrara 1998). These effects are particularly important in the light of recent observations by Pettini et al. (1998). Although their signal–to–noise ratio should be improved, these observations suggest that damped Ly\textsc{\(\alpha\)} systems do not trace compact dense regions, i.e. primordial galaxies, but reflect the more diffuse IGM enriched by these same primeval structures. As such, the metal content of a
galaxy or the IGM may show two quite different sides of the same star formation process.

The importance of dust has been encountered in the past both observationally and theoretically. Obscuration effects have been studied for quasars by Fall & Pei (1993) and galaxies by Charlot & Fall (1993). The latter authors perform a study somewhat similar to the present paper, but here we have included the effects of inhomogeneity and large amounts of dust, and also utilized the physically motivated Press–Schechter formalism for the star–formation history. Local starbursts are known to emit the bulk of their energy in the infrared through dust absorption and re–emission. The evolution of the universal average star–formation rate (Madau et al. 1996) must likely be modified for dust extinction to reflect the true star formation history of the universe. Finally, recent SCUBA (JCMT) results indicate the presence of extremely dusty galaxies (Smail et al. 1998) at high redshifts ($z \sim 3$), which could also be related to the production of the recently discovered cosmic infrared background radiation (Puget et al. 1996; Hauser et al. 1998).

The aim of this paper is to investigate the importance of dust for the recently discovered Ly$\alpha$ emitters; to show that it is possible to derive constraints from the observational data on the formation of galactic structure, and on the first generation of stars; and finally to make predictions for higher, previously unexplored redshifts. It is assumed that the bulk of the Ly$\alpha$ photon production is driven by stars, and that the contribution of type II supernova shocks or non–thermal emission is negligible (Charlot & Fall 1993). An issue which will not be addressed here in detail is the formation of Ly$\alpha$ galaxies (e.g. Primack et al. 1998). Although this is clearly an important question, the aim here is to set up a general cosmological model, based on the Press–Schechter formalism, where the absolute star formation rate and the physical state of the system are varied while the observational consequences are explored.

2. Ly$\alpha$ Emission from HII Regions

It is well known that even a modest amount of dust inside an HII region is sufficient to attenuate all of the produced Ly$\alpha$ radiation, because the line optical depth is of the order of $10^4$. However, this situation can be alleviated if the dust content is negligible, or, more interestingly, if the medium is inhomogeneous (Neufeld 1991). The latter author has argued that in a multi–phase medium the escape of Ly$\alpha$ radiation is significantly enhanced compared to the standard case of resonant scattering in a homogeneous medium.

The radiative transfer problem which needs to be solved for the Ly$\alpha$ line is well studied and has been investigated extensively (e.g. Adams 1972; Hummer & Kunasz 1980;
Neufeld 1990). Our aim here is to model an individual galaxy with a range of masses for the ionizing stars, dust content, and inhomogeneity. A numerical Monte Carlo approach is therefore adopted whose general implementation can be found in Spaans (1996; and references therein). In these computations, a Scalo IMF is assumed for the spectral types of the central stars in the HII regions, ranging from O5 to B1. The stars are distributed in a statistically homogeneous manner inside a percolating multi-phase medium. A typical line width $\Delta V$ of 8 km/s has been used. Care was taken to sample the line profile sufficiently far into the wings, more than $10^2(N_{20}\Delta V_5)^{1/3}$ km s$^{-1}$ for a homogeneous medium with a hydrogen column density $N_{20}$ in units of $10^{20}$ cm$^{-2}$ and a velocity dispersion $\Delta V_5$ in units of $10^5$ cm s$^{-1}$ (Harrington 1973). For an inhomogeneous medium the formalism of Neufeld (1991) for a multi-phase medium is adopted.

Analogously to the Neufeld investigation, we parameterize the multi-phase medium by opaque clumps embedded in an inter-clump medium of negligible opacity. The clump covering factor $F_{\text{cov}}$, i.e. the average number of clumps along a line of sight, then fixes the degree of inhomogeneity. For the work presented here, the escape fractions $F_{\text{esc}} = \exp(-\tau_*)$ were computed on a grid of models with various dust contents, $Z_d = 10^{-2} - 1$ solar (Draine & Lee 1984), and covering factors, $F_{\text{cov}} = 1, 5, \infty$. The results of the numerical computations for these three covering factors are shown in Figure 1. As this figure shows, the covering factor has a significant effect on the escape fraction. In particular, the inhomogeneous percolating slabs are much more transparent than the homogeneous ones; the difference around $Z_d \sim 10^{-1}$ solar is over an order of magnitude. The reason for the large difference is that photons incident upon highly opaque clumps will be reflected back into the interclump medium. The photons do not penetrate the opaque clumps and spend most of their time in the interclump medium, where the opacity is very small, facilitating their escape through repeated reflections off the clumps (Neufeld 1991).

In order to check the accuracy of our computations, we performed similar calculations for the slab geometry adopted by Neufeld (1991). We were able to obtain good agreement with the analytical solutions for these geometries. In particular, the result for the effective optical depth $\tau_* \approx (\Delta V/\Delta V_*)^{1/2}$ with

$$\Delta V_* = 680 F_{\text{cov}}^{-2} Z_d^{1/2} x(H^0),$$

was reproduced with high accuracy for the neutral hydrogen abundance $x$. For computational convenience, the numerical calculations were terminated once the escape fraction reached $10^{-2}$, although the results presented below do not depend on this choice. In all of the calculations below, we assume the medium to be homogeneous until its metallicity exceeds 3% solar, and allow for inhomogeneities once this level of enrichment is reached.
3. Cosmological Abundance of Lyα Emitters

In order to model the cosmological abundance of high-redshift Lyα emitters as a function of redshift, we assume that the formation of dark matter halos follows the Press–Schechter (1974) theory. Hence, the net rate of change in the comoving number density of halos with mass $M_{\text{halo}}$ is given by the derivative $\frac{d}{dz}(dn_c/dM)$, where $dn_c/dM$ is the Press–Schechter mass function (comoving number density per unit mass). This rate includes a negative contribution from the disappearance of small halos in merger events; the net $\frac{d}{dz}(dn_c/dM)$ becomes negative when mergers dominate, i.e. for masses below a characteristic mass scale $M_s(z)$ at any given redshift $z$. We make the simplifying assumption that no halos form with masses below $M_{\text{halo}} < M_s(z)$, and therefore set $\frac{d}{dz}(dn_c/dM) = 0$ for halos below this mass.

Next, we assume that every halo forms a galaxy that goes through a Lyα emitting phase. Indeed, after a halo collapses and virializes, its gas can fragment into stars, provided it can cool efficiently below its initial virial temperature. Because of the lack of a significant amount of H$_2$ molecules at high redshifts (Haiman, Rees & Loeb 1997), the leading cooling mechanism is expected to be collisional excitation of atomic hydrogen. The corresponding requirement for halos to cool efficiently is that their mass is at least $M_{\text{min}} \sim 10^8 M_\odot [(1+z)/11]^{-3/2}$ (Haiman & Loeb 1998). We therefore assume that in halos that exceed this mass, a fraction $\epsilon_*$ of the gas turns into stars, with a constant rate of star formation over a period of $t_*$ years. The result of this process is a dwarf galaxy with a stellar mass of $M_{\text{star}} = \epsilon_*(\Omega_b/\Omega_0)M_{\text{halo}}$. The values of $\epsilon_*$ and $t_*$ could depend on several further parameters, such as the formation redshift, halo mass, or the initial angular momentum of the gas. There could be further complications, such as a time-dependent star formation rate. A treatment of these important issues is beyond the scope of this paper, and for simplicity we adopt the simplest assumption, i.e. that $\epsilon_*$ and $t_*$ both have the same constant values in each halo.

Finally, an important effect we must include is an external feedback from photo-ionization by the UV background, which heats the gas before it is able to cool and condense inside the dark matter potential wells. This feedback is an inevitable consequence of the background UV flux that builds up after the re-ionization epoch, when the cosmological HII regions have overlapped and the universe is transparent to the ionizing flux from each individual source. Several authors have discussed the consequences of this feedback from first principles (Babul & Rees 1992; Efstathiou 1992; Quinn, Katz & Efstathiou 1996; Thoul & Weinberg 1996; Navarro & Steinmetz 1997), and concluded that the collapse of gas is inhibited in halos with circular velocities below $v_{\text{circ}} = 30 - 80$ km s$^{-1}$. The apparent lack of high-redshift quasar candidates in the Hubble Deep Field (HDF) also requires the
existence of some type of feedback of a similar magnitude. To be consistent with the HDF data, Haiman, Madau & Loeb (1998) have found that either the formation, or the fueling of black holes was prevented in halos with $v_{\text{circ}} < 75$ km s$^{-1}$. Accordingly, we impose a minimum circular velocity $v_{\text{circ}} = 75$ km s$^{-1}$ for the halos of luminous galaxies that form after the re-ionization epoch, here taken to be $z_{\text{reion}} = 10$ (cf. Haiman & Loeb 1997). This constraint results in a minimum halo mass of $M_{\text{min}} \sim 10^{10} M_\odot [(1 + z)/11]^{-3/2}$, two orders of magnitude larger than the minimum mass obtained from the cooling argument above.

We note that recently discovered high-redshift galaxies (Steidel et al. 1998) have revealed Ly$\alpha$ emission only in a fraction of all the sources. This may be consistent with the small duty–cycle of the Ly$\alpha$ emitting phase considered here; alternatively, $t_\star$ could be increased somewhat if only a fraction $f$ of all halos would undergo a Ly$\alpha$ emitting phase. In order to keep the predicted number density constant, $t_\star$ would then need to be increased approximately to $\sim t_\star/f$. The Press–Schechter halo formation rate also depends on the cosmology and power spectrum. For our “standard model” we have adopted the concordance model of Ostriker & Steinhardt (1995), i.e. a flat $\Lambda$CDM model with a slightly tilted power spectrum $(\Omega_0, \Omega_\Lambda, \Omega_\text{b}, h, \sigma_{8h^{-1}}, n) = (0.35, 0.65, 0.04, 0.65, 0.87, 0.96)$. Convenient expressions for the differential volume element, luminosity distance, and time–redshift relation in this model are given in terms of elliptic integrals by Eisenstein (1997); a useful fitting formula for the growth function is given by Carroll et al. (1992). In addition to this $\Lambda$ cosmology, below we consider an open model with the same parameters, except the power spectrum normalization is then changed to $\sigma_{8h^{-1}} = 1.15$.

4. Model Description

In order to compare our models directly with observations, we need to compute the surface density of Ly$\alpha$ emitters on the sky above a given observational threshold flux. As discussed above, each of our model galaxies undergoes continuous star formation for $t_\star$ years. During this time–interval, we relate the local star formation rate (SFR) to an intrinsic Ly$\alpha$ luminosity, assuming case B recombination, and using Kennicutt’s (1983) relation between the SFR and Ly$\alpha$ luminosity, resulting in $L_{\alpha,\text{int}} = (\dot{M}/M_\odot \text{ yr}^{-1}) 10^{42}$ erg s$^{-1}$. Here $\dot{M} \equiv \Omega_\text{b}/\Omega_0 \dot{M}_{\text{halo}} t_\star$ is the adopted star formation rate. We assume that each model galaxy produces stellar dust during the same time–interval, and that some fraction $x_g$ of this dust stays within the galaxy and enriches its interstellar medium, while the remaining fraction $1 - x_g$ is blown out of the galaxy by supernovae, stellar winds, or as a result of mergers between galaxies (Gnedin 1998). Galaxies that form subsequently will be assembled from an intergalactic gas that is pre-enriched with this ejected dust.
It is difficult to estimate from first principles either the fraction $x_g$, or the size of the region around each galaxy polluted by the blown–out dust (although see recent 3–D numerical simulations by MacLow & Ferrara 1998). Instead, here we adopt a phenomenological approach, and introduce two additional parameters that characterize the overall dust content of galaxies. The first parameter, $Z_{d,\text{ISM}}(t)$ is the mass fraction of dust (in solar units) in the interstellar medium of each galaxy, due only to the self–enrichment from the retained dust fraction $x_g$. Consistent with our assumption of a constant star formation rate, we assume that the amount of retained dust increases linearly with time for $t_\star$ years, until it reaches the final value of $Z_{d,\text{ISM}}(t_\star)$. Similarly, we assume that each galaxy deposits dust into the surrounding IGM at a constant rate for $t_\star$ years, and introduce a second parameter, $Z_{d,\text{IGM}}(z)$, denoting the resulting redshift–dependent average dust content of the polluted regions within the intergalactic medium. Note that the ejected dust may not be fully mixed into the IGM, and the universal average dust fraction of the IGM could be lower than $Z_{d,\text{IGM}}$. Here we avoid this issue by defining $Z_{d,\text{IGM}}(z)$ to denote the average dust content only within the pockets of intergalactic gas from which subsequent galaxies form. Observationally, the metallicity of gas in galaxy clusters upto redshift $z = 1$ is approximately 1/3 solar, which we take as the representative value for $Z_{d,\text{IGM}}(z = 1)$.

Figure 2 shows the evolution of $Z_{d,\text{IGM}}(z)$ in our models, obtained by summing over the dust output of all Press–Schechter halos, and assuming three different values of $t_\star$. Note that the longer the dust–producing phase in each individual galaxy, the steeper the buildup to the average $Z_{d,\text{IGM}}(z = 1)$ has to be, resulting in a lower dust content at higher redshifts.

In summary, a galaxy that forms at redshift $z_f$ has, at a later redshift $z$, a total dust content of $Z_{d,\text{IGM}}(z) + Z_{d,\text{ISM}}(\Delta t)$, where $\Delta t$ is the time elapsed from $z_f$ to $z$. Both types of dust contribute to reduce the intrinsic Ly$\alpha$ luminosity $L_{\alpha,\text{int}}$ implied by the star–formation rate. This reduction is expressed by the escape fraction as discussed in Section 2 above. Apart from the underlying cosmology, our model therefore has five adjustable parameters, $t_\star$, $F_{\text{cov}}$, $\epsilon_\star$, $Z_{d,\text{IGM}}(z = 1)$, and $Z_{d,\text{ISM}}(t_\star)$, that uniquely determine the number density of Ly$\alpha$ emitters at any flux and redshift. More precisely, at redshift $z$, the comoving number density $n_c(z, F_\alpha)$ of emitters with observed line flux between $F_\alpha$ and $F_\alpha + dF_\alpha$ is given by a sum over halos of different formation redshifts and ages that exist at redshift $z$,

$$n_c(z, F_\alpha) = \int_z^\infty dz'dM_{\text{halo}}/dF_\alpha (z, z', F_\alpha) \left. \frac{d^2n_c}{dMd\alpha} \right|_{M_{\text{halo}}(z,z',F_\alpha),z'},$$

where the factor $dM_{\text{halo}}/dF_\alpha$ converts the number density per unit mass interval to number density per unit line flux interval. The line intensity $F_\alpha$ is given by $F_\alpha = F_{\text{esc}}(z, z')L_{\alpha,\text{int}}(M_{\text{halo}}, \epsilon_\star, t_\star)/4\pi d_L(z)^2$, where $d_L(z)$ is the standard cosmological luminosity distance.
5. Results and Discussion

We first define a “standard model” by the set of parameter values $t_* = 5 \times 10^8$ yrs, $F_{\text{cov}} = 5$, $\epsilon_* = 10\%$, and $Z_{d,\text{IGM}}(z = 1) = Z_{d,\text{ISM}}(t_*) = 0.3 \, Z_\odot$. The first three of these values are broadly consistent with the star formation rates, covering factors, and stellar mass fractions estimated in low–redshift galaxies; the latter two are chosen based on the metallicity of gas in galaxy clusters and within the interstellar medium of low–redshift galaxies (c.f. Mushotzky & Loewenstein 1997; Lada, Evans, & Falgarone 1997; Ho, Filippenko, & Sargent 1997; Hammer et al. 1997; Young et al. 1996). In Table 1 we summarize the parameters of our standard model, as well the ranges we have considered for each parameter.

In Figure 3 we show the resulting surface density of Ly$\alpha$ emitters in our standard model, with fluxes above different values of the detection threshold. We have chosen the quoted $5\sigma$ detection limit of the recent narrow–band survey of Hu et al. (1998), $F_0 = 1.5 \times 10^{-17}$ erg cm$^{-1}$ s$^{-1}$, as a fiducial threshold value. We also indicate the results from this survey for the surface density of emitters at the two redshifts $z = 3.4$ and $z = 4.5$. As the figure shows, the model is in good agreement with these two available data points. Although the agreement is encouraging, it is important to examine the sensitivity of this result to changes in the model parameters. In Figure 3, we demonstrate the effect of changing the star formation rate by changing $t_*$, while leaving $\epsilon_*$ fixed. This corresponds to changing the SFR but not the total stellar mass. The dashed lines show that when $t_*$ is decreased by a factor of 10, then both starlight and dust is produced earlier, i.e. sooner after the formation of each galaxy. This causes the abundance of emitters to peak at higher redshifts, but this makes the agreement with the data points only slightly worse. On the other hand, when $t_*$ is increased by a factor of 10, the abundance of emitters peaks at lower redshifts, and the discrepancy with the data points becomes significant: the model now

| Parameter | Standard Model | Range Considered |
|-----------|----------------|-----------------|
| $t_*$     | $5 \times 10^8$ yrs | $5 \times 10^7\text{--}9$ yrs |
| $F_{\text{cov}}$ | 5 | 1 -- $\infty$ |
| $\epsilon_*$ | 10\% | 2 -- 20\% |
| $Z_{d,\text{IGM}}(z = 1)$ | 0.3 $Z_\odot$ | 0.1 -- 1 $Z_\odot$ |
| $Z_{d,\text{ISM}}(t_*)$ | 0.3 $Z_\odot$ | 0.1 -- 1 $Z_\odot$ |
underpredicts the abundance by more then an order of magnitude at $z = 4.5$. Finally, we show in Figure 3 the effect of changing the clump covering factor $F_{\text{cov}}$. The dotted lines show that when the medium is assumed to be inhomogeneous with $F_{\text{cov}} = 1$, the model still fits the abundance at $z = 4.5$, but overpredicts it by a factor of $\sim 2$ at $z = 3.4$. On the other hand, for a homogeneous medium ($F_{\text{cov}} = \infty$), the escape fraction drops dramatically (cf. Fig. 1), resulting in a substantial decrease in the surface density of emitters, again leading to a significant (two orders of magnitude) discrepancy with the Hu et al. data at $z = 3.4$.

It is interesting to note that the surface density of emitters is a steep function of the detection threshold. In particular, Figure 3 reveals that, depending on the values of the other parameters, raising the flux threshold by an order of magnitude can decrease the predicted number of emitters by 2–3 orders of magnitude in the relevant redshift range, $z = 2–5$. This is an important feature of the present models, when we consider the existing data together with the lack of detections of Ly$\alpha$ emitters in previous surveys. In particular, based on a lack of detections, Thompson, Djorgovski & Trauger (1995) have deduced a limit on the comoving volume density of emitters that is a steep function of the detection threshold. The surface density found by Hu et al. (1998) is barely consistent with this limit at the faint end of the threshold ($L_{\text{Ly}\alpha} \sim 10^{42}$ erg s$^{-1}$). Consistency with the Thompson, Djorgovski & Trauger (1995) limits then requires that the model predicts a decline in the surface density with increasing flux threshold, and that this decline is at least as steep as the inverse square of the threshold. As Figure 3 shows, our models indeed have this sharply declining feature in the redshift range $2.78 < z < 4.89$ of Thompson, Djorgovski & Trauger (1995), and can therefore simultaneously explain the new detections without violating the existing upper limits on the abundance of emitters.

Finally, in Figure 4, we demonstrate the effects of changing the cosmology, the star formation efficiency $\epsilon_{\star}$, or the intergalactic and galactic dust contents $Z_{\text{d,IGM}}$ and $Z_{\text{d,ISM}}$. In general, lowering the amount of dust raises the escape fraction, and the Ly$\alpha$ line luminosity, and therefore increases the number of emitters above a fixed threshold, and vice versa. However, we find our results to be less sensitive to these changes than those in the star formation rate or in the clump covering factor, shown in Figure 3. In particular, when either $Z_{\text{d,IGM}}$ (dashed lines) or $Z_{\text{d,ISM}}$ (dotted lines) is varied between 0.1 and 1 $Z_{\odot}$, the corresponding range in the surface density of emitters is only about an order of magnitude at $z \sim 4$, and even less at higher and lower redshifts. On the other hand, the results are more sensitive to changes in the star formation efficiency (solid lines). For the range $0.02 \leq \epsilon_{\star} \leq 0.2$, the abundance varies by almost two orders of magnitude. Note that a low star formation efficiency results in an underestimate of the abundance that can not be compensated by changes in the other parameters (cf. Fig. 3). Finally, the long–dashed line in Fig. 4 shows the effect of changing the cosmology to an open CDM model. As the figure
shows, around redshifts $z = 3 - 5$, the two cosmological models give almost identical results (although they differ at lower redshifts). We conclude that the parameters that are best constrained by the data are $t_*$, $F_{\text{cov}}$, and $\epsilon_*$. 

6. Conclusions

We have studied the abundance of high-redshift Ly$\alpha$ emitters by combining the Press–Schechter theory, describing the cosmological formation of halos, with a simple prescription for an inhomogeneous dust distribution and its dependence on the star formation process. We find that these simple models can explain reasonably well the recent observations and earlier non-detections of high-redshift Ly$\alpha$ emitters. We find that it is possible to place significant constraints on the inhomogeneity of the spatial distribution of dust, parameterized by the clump covering factor $F_{\text{cov}}$, the star formation rate, parameterized by the duration of the Ly$\alpha$ emitting phase $t_*$, and the overall star formation efficiency, $\epsilon_*$. Our results show that in order to reproduce the surface density observed by Hu et al. (1998), $F_{\text{cov}}$ must be of order unity, $t_*$ must not exceed $\sim 5 \times 10^8$ yr, and the star formation efficiency must be at least $\sim 5\%$. These numbers should be predicted by more complete and detailed models of galactic evolution, and will be useful discriminators between such models.

Our models also predict that more Ly$\alpha$ galaxies will be detectable, around the present flux threshold, up to redshifts as high as $\sim 8$, indicating that for a simple Press–Schechter cosmological model there can be significant Ly$\alpha$ activity in the early phases of galaxy evolution. This is especially interesting in the light of recent discoveries of Ly$\alpha$ galaxy candidates at redshifts $z > 5$. Three spectroscopically confirmed objects have been reported by Hu et al. (1998) at a redshift of 5.64, Weymann et al. (1998) at a redshift of 5.60, and Dey et al. (1998) at a redshift of 5.34. Clearly, the search for Ly$\alpha$ emitters is beginning to enjoy considerable successes and these primeval objects may turn out to hold important clues both for galaxy evolution, as well as ISM physics.

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Fig. 1.— The escape fraction $F_{\text{esc}}$ of Lyα photons from an inhomogeneous medium, as a function of dust content. The three curves correspond to three different values of the covering factor of opaque clumps, $F_{\text{cov}} = 1, 5, \text{ and } \infty$. 
Fig. 2.— The derived evolution of the IGM dust content, $Z_{d,IGM}$ in our models. The three curves correspond to three different values of $t_\star$. Since $\epsilon_\star$ is kept fixed, the assumed star formation rate in each individual galaxy scales as $1/t_\star$. 
Fig. 3.— The surface density of Lyα emitters in our standard model (solid lines) with fluxes above different values of the detection threshold. The two data points are taken from Hu et al. (1998). For the fixed threshold $F_0 = 1.5 \times 10^{-17}$ erg cm$^{-1}$ s$^{-1}$, the dashed lines show how the surface density changes if the assumed star–formation rate is increased or decreased by a factor of 10. Similarly, the dotted lines show the surface density when the covering factor is changed to $F_{cov} = 1$, or $\infty$. 
Fig. 4.— Same as Fig. 3, but now the solid lines show how the surface density changes with the star formation efficiency, $\epsilon_*$; the dashed and dotted lines show the effect of changing the assumed IGM or ISM dust contents in the interval $0.1 - 1 Z_\odot$; and the long-dashed lines show the effect of changing the cosmology.