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Models for High–Redshift Lyα Emitters

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Abstract. We present models for dusty high–redshift Lyα emitting galaxies by combining the Press–Schechter formalism with a treatment of inhomogeneous dust distribution inside galaxies. These models reproduce the surface density of emitters inferred from recent observations, and also agree with previous non–detections. Although a detailed determination of the individual model parameters is precluded by uncertainties, we find that (i) the dust content of primordial galaxies builds up in no more than $\sim 5 \times 10^8$ yr, (ii) the galactic HII regions are inhomogeneous with a cloud covering factor of order unity, and (iii) the overall star formation efficiency is at least $\sim 5\%$. Future observations should be able to detect Lyα galaxies upto redshifts of $z \sim 8$. If the universe is reionized at $z_{\rm r} \lesssim 8$, the corresponding decline in the number of Lyα emitters at $z \gtrsim z_{\rm r}$ could prove to be a useful probe of the reionization epoch.

INTRODUCTION

Until a decade ago, the search for high–redshift Lyα galaxies had enjoyed no compelling successes [1]. With the improved sensitivity on large area telescopes in the last couple of years, these young galaxies are finally being detected [2,3]. Clearly, this population is of great interest to the field of galaxy formation and the early evolution of the universe. Fundamental questions we need to understand are why the 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 Lyα radiation may escape.

In a galactic setting, the emerging luminosity of the Lyα line is strongly modulated by the amount and spatial distribution of stellar dust [4]. Observations have firmly established the strong decrease in Lyα equivalent width with increasing oxygen abundance [5]. Indeed, even a modest amount of dust (observationally traced by oxygen) inside a homogeneous HII region is sufficient to attenuate all of the produced Lyα radiation, because Ly alpha photons are resonantly scattered, and dust absorption significantly increases the effective line optical depths [6]. However, this situation can be alleviated if the medium is inhomogeneous [4]. In a multi–phase medium where dust resides in opaque clumps, the photons do not penetrate the clumps and spend most of their time in the interclump medium, where the opac-

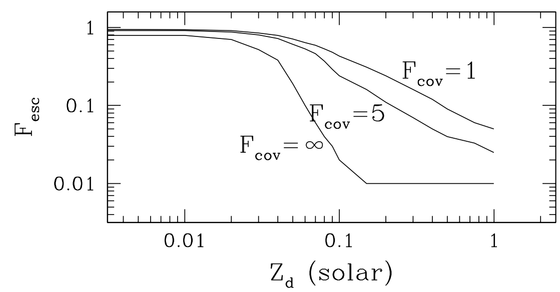

FIGURE 1. *The escape fraction $F_{\rm esc}$ of Lyα photons from an inhomogeneous medium, as a function of dust content. The three curves correspond to three different values of the covering factor of opaque clumps, $F_{\rm cov}$ =1, 5, and ∞.*

ity is very small. The result is that the escape of Lyα radiation is significantly enhanced compared to the case of resonant scattering in a homogeneous medium. Alternatively, large enough velocity gradients can provide a second way of efficient escape of Lyα radiation, as suggested by recent observations of 4 nearby galaxies [7].

In a cosmological context, the formation of dust requires the presence of metals. Since the enrichment of the gas with metals is expected to build up only gradually during the star formation history of the universe [8], at high enough redshifts the enrichment level will be low. The correspondingly small dust content of the earliest galaxies would facilitate the escape of their Lyα radiation. Such an interplay between the dust enrichment of the IGM and the galactic environment could be the mechanism that leads to the observed surface density of high–z Lyα emitters [9].

LYα EMISSION FROM INHOMOGENEOUS CLOUDS

The radiative transfer problem which needs to be solved for the Lyα line is well studied [10]. We have modeled individual galaxies with a range of masses for the ionizing stars, dust content, and inhomogeneity, using a numerical Monte Carlo approach [11]. We assumed a Scalo IMF for the spectral types of the central stars in the HII regions, ranging from O5 to B1, with the stars distributed in a statistically homogeneous manner inside a percolating multi–phase medium. We adopted the formalism of Neufeld [4] for a multi–phase medium, and assumed a typical line width of $\Delta v \sim 8$ km/s. We parameterized the multi–phase medium by opaque clumps embedded in an inter–clump medium of negligible opacity. The clump covering factor $F_{\rm cov}$, i.e. the average number of clumps along a line of sight, fixes the degree of inhomogeneity. The escape fractions $F_{\rm esc}$ were computed on a grid of models with dust contents between $Z_{\rm d} = 10^{-2} - 1$ solar, and covering factors $F_{\rm cov} = 1, 5, \infty$. Figure 1 shows the escape fraction, and demonstrates its sensitivity to the covering factor. The inhomogeneous percolating slabs are much more transparent than the homogeneous ones; the difference around $Z_{\rm d} \sim 10^{-1}$ solar is over an order of magnitude.

COSMOLOGICAL ABUNDANCE OF LYα EMITTERS

In order to model the cosmological abundance of high–redshift Lyα emitters, we assumed that the formation of dark matter halos follows the Press–Schechter [12] theory, and every halo with a virial temperature larger than 10^4 K forms a galaxy that goes through a Lyα emitting phase [13]. A fraction $\epsilon_\star$ of the gas was turned into stars, with a constant star formation rate (SFR) over a period of $t_\star$ years. The SFR was related to the intrinsic Lyα luminosity [14], assuming case B recombination. We adopted the simplest assumption, i.e. that $\epsilon_\star$ and $t_\star$ both have the same constant values in each halo. The amount of dust produced and retained in each galaxy, $Z_{\rm d,ISM}$ then increases linearly for $t_\star$ years, after which it reaches the final value of $Z_{\rm d,ISM}(t_\star) = 0.3$ solar. Similarly, we assume that each galaxy deposits dust into the surrounding IGM at a constant rate for $t_\star$ years, and causes an enrichment of the *surrounding regions* within the intergalactic medium to $Z_{\rm d,IGM}(z)$. We normalize $Z_{\rm d,IGM}$ to the cluster metallicity of ~ 0.3 solar at redshift $z \sim 1$. Note that our $Z_{\rm d,IGM}$ is the average metallicity within the polluted regions, and not the universal average dust fraction of the IGM. Given a cosmology, the five parameters $t_\star$, $F_{\rm cov}$, $\epsilon_\star$, $Z_{\rm d,IGM}(z=1)$, and $Z_{\rm d,ISM}(t_\star)$ uniquely determine the number density of Lyα emitters at any flux and redshift. Figure 2 shows the resulting surface density of emitters, as a function of redshift, in a flat ΛCDM model with a tilted power spectrum $(\Omega_0, \Omega_\Lambda, \Omega_{\rm b}, h, \sigma_{8h^{-1}}, n)$=(0.35, 0.65, 0.04, 0.65, 0.87, 0.96). We also indicate the observed surface density of emitters [2] at the two redshifts $z = 3.4$ and $z = 4.5$.

Figure 2 has several interesting features. It demonstrates that the surface abundance strongly depends on the time over which the dust is produced ($t_{\rm star}$), and on the ambient inhomogeneity of the HII regions that surround the ionizing OB stars ($F_{\rm cov}$). Our models indicate that the dust content builds up in $\lesssim 5 \times 10^8$ yr, the galactic HII regions are inhomogeneous with a cloud covering factor of order unity, and the overall star formation efficiency is at least $\sim 5\%$. These numbers should be predicted by more complete and detailed models of galactic evolution, and will be useful discriminators between such models. The surface density of emitters is also a steep function of the detection threshold, a feature that makes our model consistent both with recent detections [2] and earlier upper limits [1]. Our models predict that the surface density changes relatively slowly with redshift to $z \lesssim 8$, and Lyα galaxies will be detectable, around the present flux threshold, upto redshifts as high as $\sim$8. Recent detections of three new Lyα emitters at $z \sim 5.7$ support this conclusion [15]. However, if the universe is reionized at $z_{\rm reion} \lesssim 8$, then the damping wing of Lyα absorption from the neutral IGM would severely damp the Lyα emission line [16]. This would render Lyα emission from $z \gtrsim z_{\rm reion}$ undetectable, and cause a decline in the number of observed emitters beyond $z_{\rm reion}$. In addition, the neutral IGM would likely imprint a characteristic assymetry on the emission line profiles of emitters located near the reionization epoch. Provided this assymetry is measured, the disappearance of the Lyα emitter population could be useful diagnostic signature of reionization.

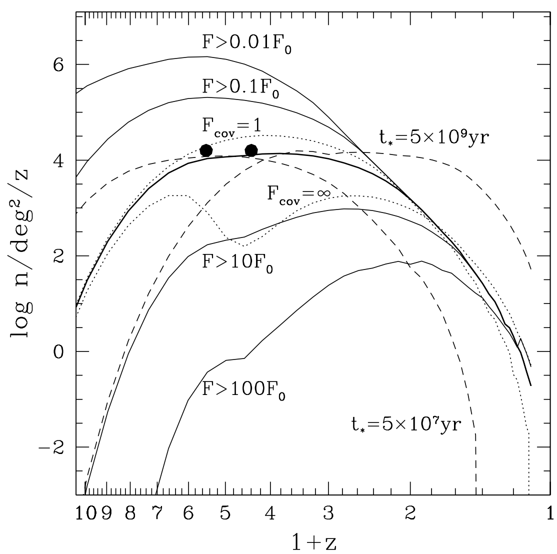

FIGURE 2. *The surface density of Lyα emitters in our standard model (solid lines) with fluxes above different values of the detection threshold. The two data points are taken from [2]. For the fixed threshold* $F_0 = 1.5 \times 10^{-17}$ erg cm^{-1} s^{-1}*, the dashed lines show the surface density when the 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* $F_{\rm cov} = 1$*, or* ∞.

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