

# The abundance of Lyman- $\alpha$ emitting galaxies in hierarchical galaxy formation models

M. Le Delliou<sup>1,2,\*</sup>, C. Lacey<sup>1,3</sup>, C.M. Baugh<sup>3</sup>, B. Guiderdoni<sup>4</sup>, R. Bacon<sup>1</sup>, H. Courtois<sup>1</sup>, T. Sousbie<sup>1</sup>, S.L. Morris<sup>3</sup>.

<sup>1</sup> Centre de Rech. Astron. de Lyon (CRAL), 9 avenue Charles André, 69561 Saint Genis Laval Cedex, France

<sup>2</sup> GAM - UMR 5139 - CNRS/in2p3 CC 85 U. M. II Place Eugène Bataillon 34095 Montpellier Cedex 5

<sup>3</sup> Institute for Comp. Cosmology, U. of Durham Science Laboratories, South Road Durham DH1 3LE., England

<sup>4</sup> Institut d'Astrophysique de Paris, CNRS 98 bis Boulevard Arago 75014 Paris France

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**Abstract.** We present predictions for the abundance of Ly- $\alpha$  emitters in hierarchical structure formation models. We use the GALFORM semi-analytical model to explore the impact on the predicted counts of varying assumptions about the escape fraction of Ly- $\alpha$  photons, the redshift at which the universe reionised and the cosmological density parameter. A model with a fixed escape fraction gives a remarkably good match to the observed counts over a wide redshift interval. We present predictions for the expected counts in a typical observation with the Multi Unit Spectroscopic Explorer instrument proposed for the Very Large Telescope.

**Key words.** high-redshift galaxies – Lyman alpha – galaxy formation – cosmology

## 1. Introduction

Dedicated narrow-band searches for Ly- $\alpha$  emitters have proven to be very efficient at detecting high-redshift galaxies (e.g. Hu & McMahon (1996); Cowie & Hu 98; Rhoads et al. 2000; Ouchi et al. 2003). Objects found by this technique have to be confirmed spectroscopically, to rule out possible low redshift interlopers that may arise due to lines other than Ly- $\alpha$  falling within the targetted wavelength interval. Nevertheless, a significant fraction of the detections appear to be bona-fide Ly- $\alpha$  emitters, and the number of objects accumulated to date by this technique in the redshift interval  $3 < z < 6.6$  is quite impressive. The Ly- $\alpha$  line is also found in a significant fraction of Lyman break galaxies (e.g. Steidel *et al.* (1996)), which are selected on the basis of their continuum emission.

The ubiquity of the Ly- $\alpha$  line is surprising at face value given that it is a resonant line that is quickly destroyed in a dusty gaseous medium, even if a small amount of dust is present. It is suspected that Ly- $\alpha$  emitters exhibit large galactic winds (as is the case with Lyman break galaxies) that result in Ly- $\alpha$  photons being able to avoid any resonant scattering, thus allowing them to escape from the galaxy (Pettini et al. 2001). The Ly- $\alpha$  line shows an asymmetric, P Cygni profile characteristic of such a process. The physics of such a phenomenon remain complicated, however.

The purpose of this letter is to address how Ly- $\alpha$  emitters fit into the hierarchical galaxy formation scenario. Semi-analytical models are a powerful tool that can be used to follow the formation and evolution of galaxies in a universe in which the structure builds up hierarchically (Cole *et al.* (1994); Kauffmann *et al.* (1994); Somerville & Primack (1999); Hatton *et al.* (2003)). The abundance of Ly- $\alpha$  emitters is sensitive to the adopted cosmological model and to astrophysical phenomena, such as the fraction of Ly- $\alpha$  photons escaping from galaxies and the distribution of galactic dust. Semi-analytical models are ideally suited to the exploration of such a parameter space.

The semi-analytical calculations are described in Section 2. In Section 3, we first present a compilation of the available observational data on the abundance of Lyman- $\alpha$  emitters at different redshifts. We then compare these data with the predictions of the semi-analytical models. Finally, we present our conclusions in Section 4.

## 2. The model

We use the semi-analytical model of galaxy formation, GALFORM, to make predictions for the abundance of Ly- $\alpha$  emitters as a function of redshift. The GALFORM model is described in full by Cole *et al.* (2000) and Benson *et al.* (2003); further details of the model used in this Letter are given in Baugh et al. (2004). The follow-

\* Morgan.LeDelliou@gamum2.in2p3.fr

$z$	$\Delta z$	$f_{lim}^*$	$\frac{d^3 N}{dzd\Omega}(f)$	$\Delta \left( \frac{d^3 N}{dzd\Omega} \right)^{**}$	Nb of Objects	Area of Survey <sup>***</sup>	level of correction	$\frac{d^2 N}{d\Omega}(f)$	confirmation methods	refs.
2.42	0.14	20	0.33	0.04	58	1260	-35%	0.046	OII sub	Sti01
3.09	0.066	2	2.3	0.3	12	78	-80%	0.15	/5 from LBG	C1 Ste01
3.13	0.043	2	4.3	1.4	9	49	-70%	0.18	spec on 10	K00
3.43	0.063	1.5	3.60	0.87	17	75	-11%	0.23	spec on 2	C2 H98
3.43	0.063	2	3.5	1.1	10	46	0%	0.22	NBF	C&H98
4.39	0.07	2.6	0.97	0.11	75	1100	-67%	0.68	NBF	R00
4.54	0.064	1.5	4.2	3.0	2		-50%	0.27	spec on 2	H98
4.86	0.06	0.6	0.52	0.09	34	1100	-20%	0.031	spec on 5	S03
4.86	0.06	0.38	2.67	0.27	87	543	0%	0.16	CCS	O03
5	1	2	2.3	1.0	5	2.2	0%	2.3	n/a	C3 D01
5.1	0.005	0.01154	48.29	48.29	1	4.2		0.24	spec on 7	S04
5.1	0.008	0.03651	29.51	14.75	4	4.2		0.95	spec on 7	S04
5.1	0.06	0.1154	4.024	2.323	3	4.2		0.71	spec on 7	S04
5.1	0.27	0.3651	0.8853	0.5111	3	4.2		0.71	spec on 7	S04
5.1	1.74	1.154	0.1368	0.1368	1	4.2		0.24	spec on 7	S04
5.7	0.12	1.5	0.20	0.06	13	550	-28%	0.024	CCS	R&M01
6.56	0.10	0.4	21	21	1	0.46	0%	2.1		H02
6.56	0.10	2.7	< 0.0036		0		n/a			H02
6.56	0.109	1	0.18	0.13	16	814	-78%	0.020	spec on 9 (2 Ly- $\alpha$ )	K03
6.57	0.21	2.5	0.60	0.60	1	8	0%	0.13	n/a	L03

**Table 2.** Data Compilation. The data are divided into unit redshift bins: the following symbols are used to denote data from each redshift interval in the figures ( $\blacksquare$  : [ $<3$ ],  $\blacktriangledown$  : [3;4],  $\blacktriangle$  : [4;5],  $\circ$  : [5.1 S04] (not yet published),  $\bullet$  : [5;6],  $\times$  : [6;7]). All surveys are narrow-band filter (NBF), except D01(long-slit: LS) and L03(multi-slit: MS).

Col.1: redshift; Col.2: error on  $z$ ; Col.3: max. Ly- $\alpha$  flux; Col.4: Ly- $\alpha$  counts; Col.5: counts error estimate; Col.6: number of Ly- $\alpha$  objects retained; Col.7: area of sky surveyed; Col.8: estimates of rejected objects; Col.9: raw counts per area; Col.10: method for computing Col.9; Col.11: comments; Col.12: references (see references below)

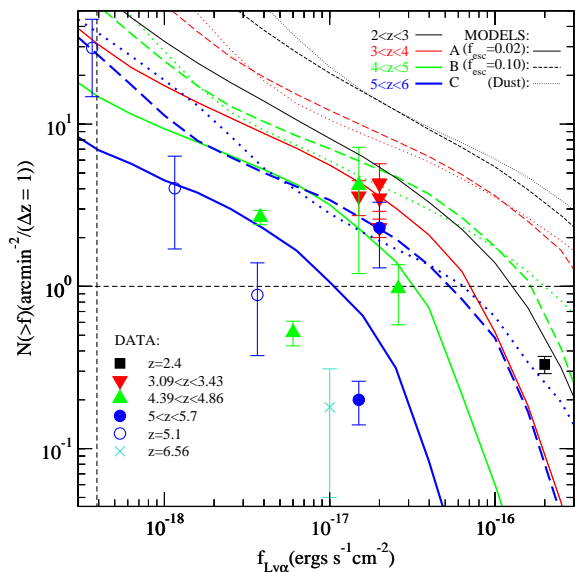
\* in units of  $10^{-17}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  \*\* Poisson error; also non-P error for R00 at 0.39 \*\*\* in arcmin<sup>2</sup>

comments: C1=correction for overdensity, C2=follow up from Cowie & Hu, C3=HST underestimates counts — area to be reduced

• OII sub: OII estimated continuum subtraction – • /5 from LBG: /5 factor from LBG estimation (see C1) – • spec on N: N objects spectroscopy – • CCS: continuum colour selection –

MODEL	$\Omega$	$\Lambda$	$\sigma_8$	$z_{\text{reion.}}$	$f_{\text{esc.}}$	MUSE COUNTS
A	0.3	0.7	0.93	10	0.02	70
B	0.3	0.7	0.93	10	0.1	248
C	0.3	0.7	0.93	10	diffuse	366
D	0.3	0.7	0.93	6	0.02	163
E	0.3	0.7	0.93	20	0.02	77
F	0.2	0.8	1.15	10	0.02	145
G	1	0	0.52	10	0.02	59

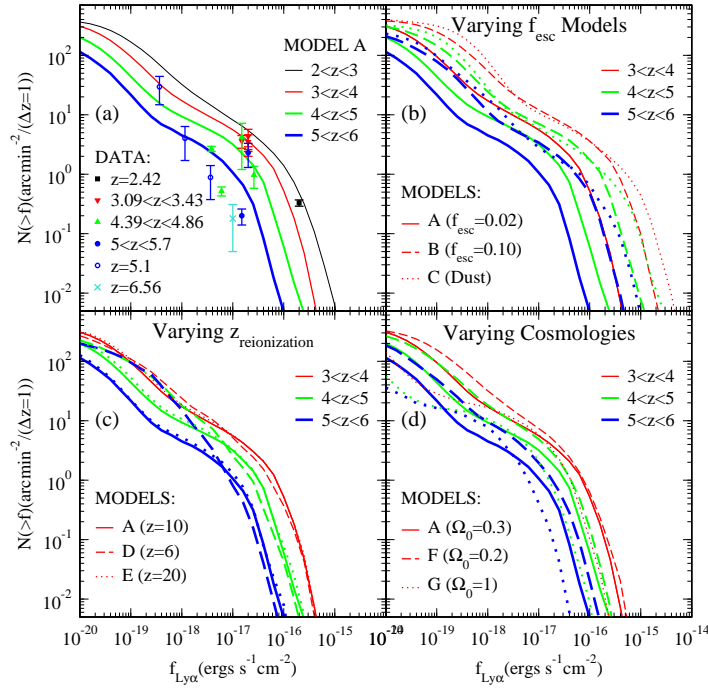
**Table 1.** The semi-analytical models for which the abundance of Ly- $\alpha$  emitters is predicted. The first column gives the model label. The next three columns give the basic cosmological parameters: the density parameter,  $\Omega$ , the cosmological constant,  $\Lambda$ , and the amplitude of density perturbations, as specified by  $\sigma_8$  ( $\sigma_8$  values are taken from Eke *et al.* (1996)). In each case the baryon density is  $\Omega_b = 0.04$  and the Hubble constant expressed is  $H_0 = 70 \text{kms}^{-1} \text{Mpc}^{-1}$ . Column five gives the redshift at which the model universe is assumed to reionise,  $z_{\text{reion.}}$ . Column six gives the fraction of Lyman- $\alpha$  photons that escape from the model galaxies,  $f_{\text{esc.}}$ . In the case of model B,  $f_{\text{esc.}} = 1$ , but diffuse dust can scatter the photons. The final column gives the number counts of Lyman- $\alpha$  emitters for a reference MUSE observation. This is the number of emitters per square arcminute brighter than  $3.9 \times 10^{-19} \text{ergs}^{-1} \text{cm}^{-2}$  in the redshift interval  $2.8 < z < 6.7$ .



**Fig. 1.** The symbols show the data compilation from Table 2, divided into different redshift ranges, as indicated by the lower key. Model predictions are shown by lines, as indicated by the upper key. The thickness of the lines increases with redshift.

ing steps are taken to compute the Ly- $\alpha$  emission from

a model galaxy: (i) The number of Lyman continuum photons is computed from the star formation rate in the



**Fig. 2.** The predicted counts of Ly- $\alpha$  sources, plotted in different redshift intervals, as indicated by the key. (a) Shows the predictions for model A; a subset of these are reproduced in each panel for reference. The data from Fig. 1 are also plotted here using the same symbols as before. The remaining panels show the impact on the predictions of changing different aspects of the model: (b) Varying the escape fraction or applying diffuse dust. (c) Varying the redshift of reionisation. (d) Varying the matter density parameter.

model galaxy and the stellar initial mass function (IMF). In the Baugh *et al.* (2004) model, quiescent star formation in galactic disks produces stars with a Kennicutt (1998) IMF, whereas bursts of star formation triggered by galaxy mergers follow a flat (“top-heavy”) IMF. (ii) The luminosity of the Ly- $\alpha$  line is computed assuming that Ly- $\alpha$  photons originate in HII regions, assuming case B recombination (Stasinska (1990)). (iii) The observed Ly- $\alpha$  line emission depends on how many Ly- $\alpha$  photons escape from the galaxy. We have taken two approaches. In the first, we assume that some fraction,  $f_{\text{esc}}$ , of Ly- $\alpha$  photons escape from the galaxy. Physically, this implies that  $f_{\text{esc}}$  of the Ly- $\alpha$  photons pass through holes in the galactic distribution of dust and gas. In the second approach, we set  $f_{\text{esc}} = 1$  and include the effects absorption by a diffuse dust component, without any resonant scattering. This situation would be expected in high velocity galactic winds.

We explore the impact on the abundance of Ly- $\alpha$  emitters of varying the redshift at which the Universe was reionised,  $z_{\text{reion}}$ , which is still poorly constrained. We examine the consequences of making three choices: (i)  $z_{\text{reion}} = 10$ , (ii)  $z_{\text{reion}} = 20$  and (iii)  $z_{\text{reion}} = 6$ . The first two values are consistent with the optical depth

to last scattering suggested by the WMAP measurement of the correlation between microwave background temperature and polarisation maps (Kogut *et al.* (2003)). The latter value is suggested by the detection of a Gunn Peterson trough in the spectrum of a  $z = 6.28$  quasar by Becker *et al.* (2001). Gas is prevented from cooling in haloes with a circular velocity below  $60\text{kms}^{-1}$  for redshifts  $z < z_{\text{reion}}$ . The models that we consider are listed in Table 1. Models A-E reproduce the luminosity function of the local galaxy population (e.g. Baugh *et al.* (2004)). Finally, we also consider the effect on the Ly- $\alpha$  counts of varying the cosmological density parameter,  $\Omega$  (models F and G). Note that we have not attempted to vary any other parameters of the GALFORM model in these cases to force the model to reproduce the local optical luminosity function.

### 3. The data and model predictions

We have carried out a census of the available number counts of Ly- $\alpha$  emitters in the literature. For convenience, we present this compilation in Table 2. In order to make a meaningful comparison between different data sets, it is important to pay attention to the details of

the construction and execution of each survey. Dawson *et al.* (2001) and Lilly *et al.* (2003) used long slit and multi-slit spectroscopy respectively to select Ly- $\alpha$  emitters. Spectroscopy is the most direct and robust approach to take to compute the abundance of sources. The remaining surveys in Table 2 were carried out using narrow band filters. This approach is susceptible to contamination by low redshift sources emitting at longer wavelengths than Ly- $\alpha$ , e.g. OII or OIII. Thus, the sources detected with narrow band imaging need either to be confirmed spectroscopically or the number counts need to be corrected using an estimate of the likely contamination by other lines. The method used to correct the number of sources detected by the narrow band filter and the size of the correction are listed for each survey where applicable in Table 2. The data are plotted in Fig. 1, with different symbols indicating data from a given unit redshift range. The predictions of our fiducial model, A from Table 1, are shown by the solid lines in Fig. 1. The escape fraction  $f_{\text{esc}}$  was set to give a reasonable match to the observed number counts at  $z \sim 3$ . This simple model, in which the escape fraction is independent of redshift and galaxy properties, does a surprisingly good job of matching the observed counts at different redshifts. In Fig. 2, we present the predicted counts of Ly- $\alpha$  emitters predicted as a function of redshift for the GALFORM models listed in Table 1. The results for model A, our fiducial model, are reproduced for reference in each panel. In Fig. 2(a) we show the effect of varying the escape fraction by a factor of 5. Fig. 2(b) we show that the simple model of assuming a fixed escape fraction produces similar number counts to a model in which the Lyman- $\alpha$  photons are scattered by diffuse dust *without* resonant scattering, as would be expected in a galactic wind in which the interstellar medium is rapidly expanding. Fig. 2(c) shows the impact on the predicted counts of varying the redshift at which the model universe is reionised. Finally, Fig. 2(d) illustrates the impact of changing the density parameter whilst retaining a flat model universe.

#### 4. Discussion and conclusions

The conclusion of this first study to look at the predictions of hierarchical models for the number of Ly- $\alpha$  emitters is that simple models do extremely well at reproducing the observed counts. Assuming that typically just 2 % of the Ly- $\alpha$  photons escape from high- $z$  galaxies, a value chosen to match the counts measured at  $z \sim 3$ , is sufficient to give a good match to the observed counts at faint fluxes over the redshift interval  $2 < z < 6$ .

This study demonstrates the capability of semi-analytical modelling to make predictions that can serve as an input into the design of new instruments. The Multi Unit Spectroscopic Explorer (MUSE) has been proposed to ESO as a second-generation instruments for the *Very Large Telescope*, Bacon *et al.* (2004). MUSE will be able to identify Ly- $\alpha$  emitters over a redshifts interval  $2.8 < z < 6.7$  over a field of view of 1 arcmin<sup>2</sup>. An exposure of 80 hours will reach a  $5 \sigma$  sensitivity of  $3.9 \times 10^{-19}$

erg/s/cm<sup>2</sup>. We predict that MUSE will be able to detect a large number of such objects at this flux limit: around 70-400 per arcmin<sup>2</sup> (see the final column of Table 1). Observations with MUSE will be able to reject some of the models we have considered and therefore remove some of the uncertainties in our modelling of Ly- $\alpha$  emission. Such an observational advance is clearly needed to motivate more complete models of the emission and escape of Ly- $\alpha$  photons by galaxies at high redshift.

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