Towards a panchromatic picture of galaxy evolution during the reionization epoch

Jaime E. Forero-Romero\(^1\), Gustavo Yepes\(^2\), Stefan Gottlöber\(^3\) and Francisco Prada\(^4,5,6\)

\(^1\)Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
\(^2\)Grupo de Astrofísica, Universidad Autónoma de Madrid, Madrid E-28049, Spain
\(^3\)Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
\(^4\)Campus of International Excellence UAM+CSIC, Cantoblanco, E-28049 Madrid, Spain
\(^5\)Instituto de Física Teórica, (UAM/CSIC), Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain
\(^6\)Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía, E-18008 Granada, Spain

Abstract. There are thousands of confirmed detections of star forming galaxies at high redshift \((z > 4)\). These observations rely primarily on the detection of the spectral Lyman Break and the Lymanα emission line. Theoretical modelling of these sources helps to interpret the observations in the framework of the standard cosmological paradigm. We present results from the \textit{High-z MareNostrum Project}, aimed at constructing a panchromatic picture of the high redshift galaxy evolution that will improve our understanding of young star forming galaxies. Our simulation successfully reproduces the observational constraints from Lyman Break Galaxies and Lymanα emitters at \(5 < z < 7\). Based on this model we make predictions on the expected Far Infrared (FIR) emission that should be observed for LAEs. These predictions will help to settle down the question on the dust content of massive high-z galaxies, an issue that will be feasible to probe observationally with the Atacama Large Millimetre Array (ALMA).

1. Introduction

Observationally, there are two main ways to detect high redshift star forming galaxies. The first technique uses broad band measurements in order to detect the drop in flux due to the Lyman Break in the galaxy’s Spectral Energy Distribution (SED). Galaxies detected through this technique receive the name of Lyman Break Galaxies (LBGs). The second technique aims at detecting the Lymanα emission line either by narrow band filtering techniques or by direct spectral measurements. Galaxies detected through this selection technique receive the name of Lymanα Emitters (LAEs). For some of the high-z LBGs there has
also been detected in their rest-frame near-IR which has allowed to provide an estimation of their stellar masses.

In this work we describe our efforts to build a panchromatic picture of high-z galaxies at $5 < z < 7$. Our work is based on the results from a large hydrodynamics simulation that follows the gravitational collapse of dark matter and gas and including radiative processes and the ensuing star formation, together with associated chemical and mechanical feedback from exploding stars. Based on the analysis of the numerical galaxies, we have suggested a model to account for the dust extinction and the radiative transfer of the Lyman $\alpha$ line. We have shown how this model is in fair agreement with the observed properties of LBGs and LAEs (Forero-Romero et al. 2010, 2011). Special attention was made to reproduce the observed fraction of LBGs with a strong Lyman $\alpha$ emission (Forero-Romero et al. 2012). In what follows, we will describe the main features of our model and will conclude by pointing out the expected trends for the FIR emission that will be probed by ALMA in the near future.

2. The Simulation and Galaxy Finding

The High-Z MareNostrum Simulation follows the nonlinear evolution of a cubic region of $50 \, h^{-1}\,$Mpc (comoving) on a side. The dark matter and gas distributions are sampled with $1024^3$ particles for each component. The gas physics includes radiative cooling and photoionisation from an homogeneous UV background switched on at $z = 6$. Star formation and feedback (chemical and dynamical) are included following the Springel and Hernquist (2003) model. We identified all gravitationally bound objects using the Amiga Halo Finder (Knollmann & Knebe 2009). All objects with at least 1000 particles are kept for further analysis. More details can be found in Forero-Romero et al. (2010).

3. Modelling the UV Continuum and the Lyman $\alpha$ line

The stellar SED is constructed from the stellar particles contained in the galaxies detected as described in Section 2. The main assumption under this calculation is that each stellar particle in the simulation can be treated as a burst of star formation with a given mass, age and metallicity. We assume a constant Salpeter IMF.

We implement a phenomenological model to quantify the extinction produced by dust in the stellar SED. The physical model assumes that extinction is divided into two contributions that affect different stellar populations of different ages. Old stellar populations see an effective extinction from an homogeneous Interstellar Medium (ISM), while young stellar populations suffer additional extinction due to the molecular clouds where they are embedded at birth.

The calculation of the escape fraction of Lyman $\alpha$ radiation assumes the same geometry as the UV continuum extinction. We have developed the Monte-Carlo radiative transfer code CLARA to follow the path of Lyman $\alpha$ photons through the ISM in simplified geometrical configurations. Details of the implementation of this model can be found elsewhere (Forero-Romero et al. 2011).
4. Results

- **LBGs, LAEs and Stellar Masses**: Our numerical results for the luminosity functions for LBGs are in good agreement with the observational results. Only a minor disagreement is noticeable at the faint end of the luminosity function, where there seems to be an overabundance of simulated dwarfs with respect to the observations. UV colours as parametrised by the $\beta$ slope as a function of restframe UV magnitudes are also in agreement with results derived from observations. This shows that the dust correction we have applied to the simulated galaxies is reasonable (Forero-Romero et al. 2010). The simulated LF of LAEs shows a good agreement with observations at the bright end, while showing an overabundance at the faint end, which is somewhat more noticeable than in the restframe UV (Forero-Romero et al. 2011). Recently, we have shown that the stellar masses as a function of intrinsic UV luminosity are also in good agreement with the observational estimates, at least for the most massive systems (Forero-Romero et al. 2012b).

- **LBGs as LAEs**: As part of the international observational effort to probe the reionisation epoch using LAEs and LBGs, a new kind of observations were conducted. Galaxies detected primarily as LBGs were then followed up spectroscopically. From these measurements one can determine whether a LBG is also a LAE by requiring the equivalent width to be larger than a fixed threshold value. Using these results we can consider now a new kind of statistics, the fraction of LBGs showing strong Lyman $\alpha$ emission, $X_{\text{Ly} \alpha}$. The results from our simulations, without any further change, fully agree with the observational measurements of this fraction. We have also shown that the Lyman escape fraction is decreasing with galaxy mass (Forero-Romero et al. 2012).

- **FIR Emission** For each galaxy in the simulation we calculate the expected flux measured in the ALMA band at 353 GHz as a function of observed Lyman $\alpha$ luminosity. We find that the brightest LAEs do not have a high FIR luminosity, passing completely undetected by ALMA (Fig. 1). This prediction of our model can be quantitatively understood as follows. Bright galaxies in the FIR have a high star formation rate and dust mass contents. These high dust values and neutral hydrogen associated with the most massive FIR bright galaxies naturally corresponds to very low escape fractions.

5. Conclusions and Outlook

We have constructed a model for high redshift galaxies (LBGs and LAEs) based on the results of the *High-z MareNostrum Simulation*. From the numerical results we are able to estimate the observed restframe UV and Lyman $\alpha$ emission in these galaxies.

We find that our results are broadly consistent with the current observational constraints. The largest discrepancy is an overabundance in the faint end LF
Figure 1. Flux in the ALMA band at 353 GHz as a function of the observed Lyman-α emission. The horizontal line represents the threshold for detection. In our model the brightest Lyman-α galaxies won’t be detected by ALMA.

both for LBGs and LAEs. The agreement between our model and observations for objects brighter than $M_{UV} < -20$ is remarkable.

We also predict the expected flux at 353 GHz as a function of the observed Lyman-α emission. In our model, the brightest LAE galaxies are too faint FIR emitters. Correspondingly, bright IR sources will be detected by ALMA, but they will not be detected as bright LAEs.

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