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# TRACKING THE REIONISATION HISTORY OF THE UNIVERSE

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## RESUMEN

Se utiliza el modelo AMIGA (Analytical Model of Igm and GAlaxy formation and evolution) para constreñir la historia de reionización del universo. El modelo incluye de manera consistente el enfriamiento molecular y sigue la formación y efectos de retroalimentación de estrellas de Población III (Pop III), y su residuos (agujeros negros y metales), junto con la formación y evolución (incluyendo también efectos de retroalimentación) de las subsiguientes generaciones de galaxias ordinarias. Se analiza la historia de formación de galaxias predicha por el modelo que mejor ajusta los observables actualmente disponibles sobre el universo a alto $z$ ($z$>3). Se muestra que todos estos observables sobre la evolución de las propiedades del universo y la forma de la función de luminosidad (LF) de las LBGs a distintos $z$ imponen restricciones importantes sobre la historia de reionización del universo.

## ABSTRACT

We use a powerful Analytical Model of Igm and GAlaxy formation and evolution (AMIGA) to bracket the reionisation history of the universe. The model includes in a fully consistent way molecular cooling and follows the formation and feedback effects of Population III (Pop III) stars and their remnants (black holes and metals), together with the formation and evolution of the subsequent generations of ordinary galaxies as well as their feedback effects. We analyse the galaxy formation history predicted by the model that better fits the different observables currently available on the high-$z$ universe ($z$>3). We show that all these observables on the evolution of cosmic properties and the shape of the luminosity function (LF) of LBGs at different z's put very severe constraints on the reionisation history of the universe.

*Key Words:* galaxies: evolution — galaxies: formation — intergalactic medium

## 1. INTRODUCTION

Cosmic gas recombined at $z \sim 1100$ when the gas temperature went below the recombination temperature of the hydrogen, however it should have reionised since then as evidenced by the Ly$\alpha$ forest. Recent observations show that the universe reionised at $z_{\rm ion} > 5.5$ (McGreer, Mesinger, & Fan 2011), the fraction of ionised hydrogen $Q_{\rm HII} < 0.9$ at $z$=7 (Morlock et al. 2011), $z_{\rm ion} < 11.8$ (optical depth of CMB photons: Komatsu et al. 2011) and reionisation was not sudden (Bowman & Rogers 2010). Nevertheless, there is little or no information about the time evolution of $Q_{\rm HII}$, which has important implications for high-$z$ Ly$\alpha$ emitters, on the main ionising sources (faint galaxies? / Pop III stars?) or the effects of reionisation on galaxy formation, in particular as feedback on dwarf galaxies.

To shed some light on these aspects we use the Analytical Model of Igm and GAlaxy formation and evolution (AMIGA), developed in the spirit of the popular semi-analytic models of galaxy formation. AMIGA does not rely on the explicit construction of merger trees by means of $N$-body or Monte Carlo simulations, but on the interpolation in grids of halo properties that are progressively built. This strategy is particularly well suited for monitoring in a self-consistent way the coupled evolution of luminous objects (galaxies and AGN) and the intergalactic medium from reliable trivial boundary conditions. The model includes molecular cooling and accounts for the important feedback of primordial, metal-poor stars. In addition, the total number of free parameters is minimised by causally connecting some physical processes usually treated as independent from each other. Thus, the goals of this work are to see whether it is possible to simultaneously fit all data on the high-$z$ universe with AMIGA, have a deeper insight on reionisation and ionising sources and show how our model can serve as a theoretical guide for ALBA observations

## 2. STRATEGY AND RESULTS

To characterise the formation and evolution of the stellar content in AMIGA the following free parameters are initially considered. For primordial (Pop III) stars we have 3 mass fractions, $f_i$

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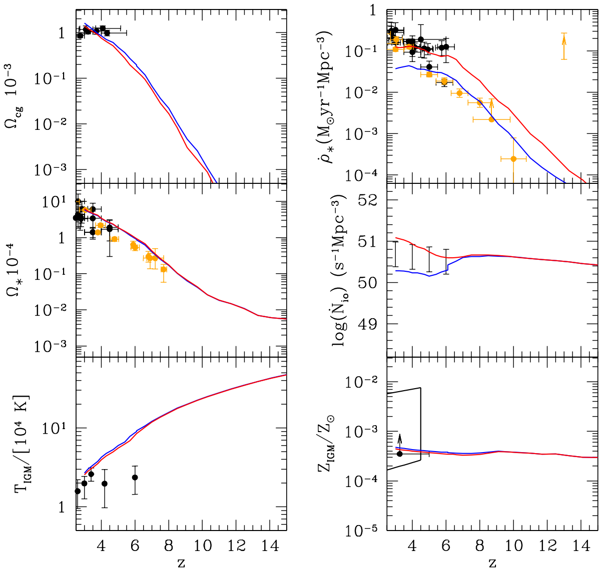

Fig. 1. Cosmic global properties: (left panel, from top to bottom) cold gas mass density, stellar mass density and IGM temperature; (right panel, from top to bottom) star formation rate density, ionisation flux density and IGM metallicity. Predictions for two values of $\alpha$ (blue curve for the lower and red curve for the higher) are displayed.

(for low-mass $M_* < 130\ M_\odot$, intermediate-mass $130\ M_\odot < M_* < 250\ M_\odot$, and massive $M_* > 250\ M_\odot$ stars[2]) which describes the poorly known IMF, the global yield, $Y_{\rm III}$, and the mass fraction locked in black holes, $f_{\rm BH}$. For ordinary (Pop I/II) stars we have the star formation efficiency, $\alpha$, the SN heating efficiency, $\epsilon$, and the escaping fraction of ionising photons, $f_{\rm esc}$. However, $f_i$ are not independent, but related to $Y_{\rm III}$ and $f_{\rm BH}$. By fixing $f_{\rm BH}$=0.05, which gives the right AGN abundance, and $f_{\rm esc}$=0.20, which is an upper value according to observations at intermediate $z$, finally three parameters remain: $Y_{\rm III}$ (controlling the metal enrichment and ionising flux of Pop III stars), $\alpha$, and $\epsilon$.

By assuming that ionisation is governed mainly by Pop III stars (they are initially very abundant and yield 10–20 times more ionising photons than ordinary stars), we adjust $Y_{\rm III}$ to have the universe reionised at $z_{\rm ion} \sim 6$, and $\alpha$ and $\epsilon$ to fit also the cosmic histories of density of SFR and cold gas mass. The consistency of AMIGA should ensure correct predictions for other quantities as it is shown in Figures 1 and 2. However, our model predicts less dwarf galaxies than observed at $z$=8. This is caused by the intense feedback of high-$z$ forming galaxies which sustains a high $T_{\rm IGM}$ (see Figure 1) and prevents the baryonic gas from being trapped by small haloes.

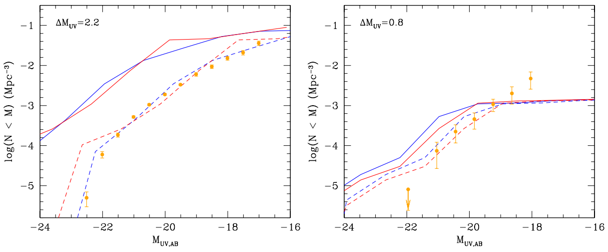

Fig. 2. Predicted dust uncorrected (solid line) rest-frame UV luminosity functions (LF) at $z$=4 (left panel) and $z$=8 (right panel) for two values of $\alpha$ (as in Figure 1. Tentative corrections are shown (dashed line) by shifting the luminosity functions towards dimmer magnitudes. Empirical points are from Bouwens et al. (2007, 2011).

In order to obtain a better prediction for the faint end of the UV LF at $z$=8, we have increased the contribution of massive Pop III stars through $Y_{\rm III}$. In this way, more free e$^-$ are present in the IGM at high $z$, strengthening the cooling processes. We have also tuned $\alpha$ and $\epsilon$ to reionised the universe at $z_{\rm ion} \sim 6$ and fit the cosmic histories of density of SFR and cold gas mass as in the previous case. We obtain results similar to those displayed in Figure 1 but with a lower $T_{\rm IGM}(z)$ and a higher $Z_{\rm IGM}(z)$ curves giving better fits. Also the faint end of the UV LF at $z$=8 is now compatible with observations. A distinct feature of this last model is a double reionisation: a first one at $z \sim 10$ driven by Pop III stars and second one $z \sim 6$ driven by ordinary stars.

We have shown that AMIGA is a powerful tool to study the high-$z$ universe. In combination with observational data coming from large, ground-based telescopes like GTC (as those expected from the ALBA project) will allow a better constraint (and understanding) of the galaxy formation history.

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[2] Stars in the first mass bin have SEDs and evolve as ordinary ones. Stars in the other two bins have Planckian SEDs at very high temperatures and evolve very fast; those in the second bin die ejecting half of their mass as metals and do not leave a black hole, those in the third bin collapse into a black hole.