The dusty, albeit ultraviolet bright, infancy of galaxies

J. Devriendt, C. Rimes, C. Pichon, R. Teyssier, D. Le Borgne, D. Aubert, E. Audit, S. Colombi, S. Courty, Y. Dubois, et al.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **403,** L84–L88 (2010) doi:10.1111/j.1745-3933.2010.00820.x

The dusty, albeit ultraviolet bright, infancy of galaxies

J. Devriendt,[1,2]⋆ C. Rimes,[2] C. Pichon,[1,3] R. Teyssier,[4,5] D. Le Borgne,[3] D. Aubert,[6] E. Audit,[4] S. Colombi,[3] S. Courty,[2,7] Y. Dubois,[1] S. Prunet,[3] Y. Rasera,[8] A. Slyz[1] and D. Tweed[3]

[1]*Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH*
[2]*Centre de Recherche Astrophysique de Lyon, UMR 5574, 9 Avenue Charles André, F69561 Saint Genis Laval, France*
[3]*Institut d'Astrophysique de Paris, UMR 7095, 98bis Boulevard Arago, F75014 Paris, France*
[4]*Service d'Astrophysique, IRFU, CEA Saclay, Bat 141, F91191 Gif-sur-Yvette, France*
[5]*Institute of Theoretical Physics, University of Zurich, Winterhurerstrasse 190, CH8057 Zurich, Switzerland*
[6]*Observatoire Astronomique, Université de Strasbourg, 11 rue de l'Université, F67000 Strasbourg, France*
[7]*Jeremiah Horrocks Institute for Astrophysics and Supercomputing, University of Central Lancashire, Preston PR1 2HE*
[8]*Laboratoire Univers et Théories, UMR 8102, 5 Place Jules Janssen, 92190 Meudon, France*

Accepted 2010 January 25. Received 2010 January 20; in original form 2009 December 2

ABSTRACT

The largest galaxies acquire their mass early on, when the Universe is still youthful. Cold streams violently feed these young galaxies a vast amount of fresh gas, resulting in very efficient star formation. Using a well resolved hydrodynamical simulation of galaxy formation, we demonstrate that these mammoth galaxies are already in place a couple of billion years after the big bang. Contrary to local star-forming galaxies, where dust re-emits a large part of the stellar ultraviolet (UV) light at infrared and sub-millimetre wavelengths, our self-consistent modelling of dust extinction predicts that a substantial fraction of UV photons should escape from primordial galaxies. Such a model allows us to compute reliably the number of high-redshift objects as a function of luminosity, and yields galaxies whose UV luminosities closely match those measured in the deepest observational surveys available. This agreement is remarkably good considering our admittedly still simple modelling of the interstellar medium physics. The luminosity functions of virtual UV luminous galaxies coincide with the existing data over the whole redshift range from 4 to 7, provided cosmological parameters are set to their currently favoured values. Despite their considerable emission at short wavelengths, we anticipate that the counterparts of the brightest UV galaxies will be detected by future sub-millimetre facilities like ALMA.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: luminosity function, mass function.

1 INTRODUCTION

Over the past decade, the cold dark matter (CDM) model, complemented with dark energy (ΛCDM), has established itself as the theoretical framework of choice to describe the formation of structures in the Universe. Whilst dark matter dominates the dynamics of structure formation on large scales, a host of observational evidence indicates that the situation is reversed on galactic scales (Kassin, de Jong & Weiner 2006). In particular, the inner structure of galactic dark matter haloes must be affected by baryonic processes (Merritt 2006). Whereas it is certainly true that critical aspects of the baryonic physics of galaxy formation are still poorly understood and beyond the reach of direct numerical simulations (Springel et al. 2005), the overwhelming majority of observational constraints unfortunately comes from the electromagnetic emission of these baryons. Therefore, significant progress in our understanding of the theory of galaxy formation and evolution depends on our ability to perform hydrodynamical cosmological simulations. At first, these will necessarily be complemented by appropriate subgrid modelling, presumably based on knowledge gained from hydrodynamical simulations performed on smaller scales (Slyz et al. 2005). Indeed, we are seeking to describe highly non-linear mechanisms that are coupled together, such as radiative gas cooling, star formation and feedback. Such complexity makes it, for instance, very unlikely that even when armed with a satisfying model for supernovae explosions one can describe analytically their interplay with a clumpy, multiphase interstellar medium (ISM) and/or intergalactic medium (IGM).

Perhaps the most significant flaw of all galaxy formation models which rely on the results of pure dark matter simulations is their neglect of the filamentary cold gas flows which feed galaxies (Dekel & Birnboim 2006; Dekel et al. 2009). Gas accreted in this

⋆E-mail: jeg@astro.ox.ac.uk

mode substantially dominates the accretion budget. Indeed, cold flows are the unique mode of gas accretion for galaxies hosted by *all* dark matter haloes with mass less than $5 \times 10^{11}\,M_{\odot}$ (i.e. the vast majority of galaxy size haloes). They are reported in every high-resolution cosmological hydrodynamics simulation of galaxy formation which includes cooling (Keres et al. 2005; Ocvirk, Pichon & Teyssier 2008), regardless of the technique employed to solve the Euler equations. Such an oversight is predicted to have drastic consequences on the ability of these models to match star formation rates and supernova-driven gas outflows. Arguably, the most straightforward observational tracer of the cold flow scenario is the ultraviolet (UV) flux emitted by galaxies, as it mainly originates from newly born stars. However, the matter is rapidly complicated by the presence of dust, which is generated on supernovae time-scales (≈50 Myr) and is very efficient at absorbing UV radiation. The spatial distribution of dust grains relative to stars is therefore a crucial ingredient in any estimate of the UV luminosity function (LF) and it is notoriously difficult to predict (semi-) analytically (Devriendt, Guiderdoni & Sadat 1999; Fontanot et al. 2009). Accordingly, we address this key issue numerically.

2 SETUP AND EXTINCTION MODEL

The evolution of a cubic cosmological volume of $50\,h^{-1}$ Mpc on a side (comoving) containing 1024^3 dark matter particles and a Eulerian root grid of 1024^3 gas cells is followed (Fig. 1). A ΛCDM concordance universe [$\Omega_{\rm m} = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = H_0/(100\,{\rm km\,s^{-1}\,Mpc^{-1}}) = 0.7, \sigma_8 = 0.9, n = 1$, i.e. the *Wilkinson Microwave Anisotropies Probe* (*WMAP*) 1 year best-fitting cosmology (Spergel et al. 2003)] is adopted, resulting in a dark matter particle mass $m_{\rm p} = 1.41 \times 10^7\,M_{\odot}$ and we use an adaptive mesh refinement (AMR) technique (Teyssier 2002) to keep our spatial resolution fixed at around $1\,h^{-1}$ kpc in physical units.

The matter density fields are evolved from $z = 120$ to 4, and we output about 34 snapshots regularly spaced in the expansion factor. In each snapshot, we identify dark matter haloes as well as the subhaloes they contain using the ADAPTAHOP algorithm (Aubert, Pichon & Colombi 2004), and only keep groups with more than 100 particles. We measure the basic physical properties of these groups and subgroups, such as their masses $M_{\rm hop}$ and radii $R_{\rm hop}$. Key physical processes for galaxy formation such as radiative cooling, UV background radiation, star formation and supernovae feedback are also implemented self-consistently in RAMSES (Rasera & Teyssier 2006; Dubois & Teyssier 2008). Gas cools down to a minimum of 10^4 K at a rate which depends on the local metallicity in each grid cell, and turns into stars on a constant time-scale of $t_{\star} = 2$ Gyr. Massive stars produce type II supernovae, releasing an amount of metals and energy into the ISM specified by a Salpeter initial mass function and the physics of a Sedov explosion (Dubois & Teyssier 2008). In some cases, the combined supernovae blow part of the ISM back into the halo's hot phase and further into the IGM. For each time snapshot of the simulation we associate the stars located within each dark matter substructure detected by ADAPTAHOP with a different galaxy. Note that, proceeding this way, we account for *all* the stars created in the simulation. By keeping track of the stellar content of each galaxy, as a function of age and metallicity, and knowing the galaxies' gas content and chemical composition, we then compute the spectral energy distribution of each galaxy, along the lines described in the STARDUST model (Devriendt et al. 1999).

Setting aside the star formation rate and stellar initial mass function, the key issue to derive correct UV fluxes lies in our ability to estimate dust extinction accurately, since dust grains very easily absorb light in this wavelength range. Because a full modelling of the formation and evolution of the dust grain population is beyond the reach of current simulations, we have tried a couple of phenomenological models to assess the impact of extinction on our results. First, as a sanity check, we use the most widespread method in the literature, which assumes a universal shape for the extinction curve (Calzetti, Kinney & Storchi-Bergmann 1994) and then fits its normalization, $E(B - V)$, to obtain the best possible match to the observational LF (Night et al. 2006). This means that a unique 'average' extinction is assigned to every galaxy for which we compute a UV magnitude. We believe this is, at best, a very awkward state of affairs, since it is empirically known that, at least in the local Universe, the value of the extinction is correlated to the UV magnitude, such that brighter galaxies have larger values of $E(B - V)$ (Heckman et al. 2005). However, as pointed out by Night et al. (2006), invoking luminosity-dependent extinction can be seen as a cheat, as it is equivalent to hiding the discrepancy between simulated and observed LFs in the extinction law. As a more ambitious alternative, we therefore measure the distribution of gas and metals on the line of sight towards each of the star particles in our simulated galaxies, which allows us to calculate the optical depth as a function of wavelength for each of these lines of sight (see Fig. 2).

More specifically, we use the empirical calibration of Guiderdoni & Rocca-Volmerange (1987), in which the optical depth scales with metallicity and in proportion to the column density of gas. The optical depth, τ, is therefore given by

$$\tau(\lambda) = \left(\frac{A_{\lambda}}{A_{\rm V}}\right)_{Z_{\odot}} \left(\frac{Z_{\rm g}}{Z_{\odot}}\right)^{s} \left(\frac{N_{\rm H}}{2.1 \times 10^{21}\ {\rm cm}^{-2}}\right), \qquad (1)$$

where λ is the wavelength and $(A_{\lambda}/A_{\rm V})_{Z_{\odot}}$ is the extinction curve for solar metallicity, which we take to be that of the Milky Way (Cardelli et al. 1989). We adopt a scaling with metallicity of $s = 1.6$ for $\lambda \geq 2000$ Å and $s = 1.35$ for $\lambda \leq 2000$ Å. Note that such a scaling implies that gas rich galaxies with metallicities of the order of $Z_{\odot}/10$ have extinction curves close to these of the Magellanic clouds. Finally, we calculate the extinction for subsamples of galaxies in logarithmic bins of stellar mass (100 objects per bin). The resulting distributions are then used to draw random extinctions for galaxies with similar stellar masses. The total number of galaxies varies between 43 000 and 86 000 between $z = 7$ and 4. The main caveats of this second approach are (i) the assumption that dust properties depend only on these two quantities (at least for absorption of UV light) and (ii) the ability of our simulation to estimate them properly. It was shown that the former assumption seems to be a fair description of internal extinction in local galaxies (Guiderdoni & Rocca-Volmerange 1987), and we argue that provided galaxies are not much more compact than our spatial resolution ($\sim 1\,h^{-1}$ kpc), values for gas column densities and metallicities should be fairly accurate on these scales.

3 THE UV LF OF HIGH-z GALAXIES

Observationally, the largest samples of UV emitting galaxies at $z > 3$ are selected according to a colour-colour criterion that maps the Lyman-break feature in their spectral energy distributions [hence their name 'Lyman-break Galaxies' (Steidel et al. 1999)]. This now well-established technique allows the detection of large numbers of galaxies per field of view using relatively little observing time, and does not strongly bias the selection process (Ilbert et al. 2005; Bouwens et al. 2006; Bunker et al. 2006). Such data sets provide us with the best sample of high-z galaxies against which to perform

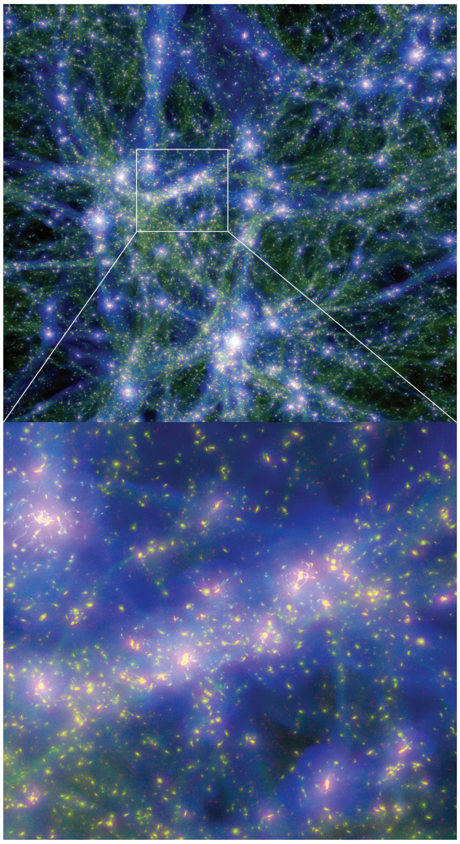

Figure 1. A global composite multiscale view of the Mare Nostrum simulation described in the text. The blue colour traces the gas temperature, green represents the gas density and red shows the dark matter density. The box size is 50 h^{-1} comoving Mpc on a side for the top panel and 10 h^{-1} comoving Mpc for the bottom one. Galaxies appear as pinkish yellow small-scale disc-like structures.

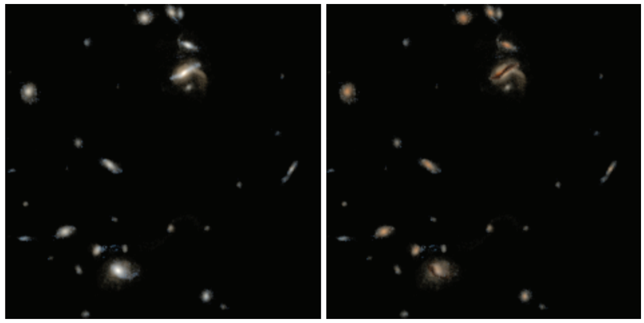

Figure 2. A typical field of view of 1 comoving Mpc on a side in the Mare Nostrum simulation shown in composite rest-frame true colours (*R*, *B* and *V* filters). Colours of the stellar population are shown in the left-hand panel without dust extinction, and with extinction in the right-hand panel. Note the presence of dust lanes in the two largest galaxies, testimony of the highly non-homogeneous distribution of dust and stars in the ISM.

a meaningful statistical comparison. The most robust and simple statistics to consider for such a comparison is the LF of galaxies. This is the main focus of this Letter.

Like the observations, which are limited by the resolving power of the telescope/instrument combination with which they are obtained, the LFs measured in numerical simulations suffer from finite box size and resolution effects, so their domain of validity is restricted to a certain range of magnitudes. In the simulation presented here (Fig. 1), dark matter haloes smaller than $\approx 10^9\,\mathrm{M}_\odot$ in mass are barely resolved in terms of the hydrodynamics of their gas content, so galaxies hosted by smaller haloes are absent, which introduces a non-physical cut-off at the faint end of the LF (Fig. 3). As spectral energy distributions of galaxies are computed as the weighted sum of single stellar populations, we avoid being dominated by the Poisson noise by restricting our results to galaxies containing at least 10 star particles. At the bright end, objects become rarer and rarer, until we reach the point where we run out of bright galaxies. This effect is somewhat amplified by our finite simulated volume, which is small compared to the size of the current observable Universe: at some point, the statistical error on the LF becomes of the order of the measurement itself. Vertical and horizontal dashed lines in Fig. 3 mark these numerical limitations, respectively, clearly delineating the region where our LFs can be trusted. Note that, although approximate, these are conservative boundaries. A truly accurate determination would require running several simulations encompassing larger volumes and featuring a higher mass resolution. Finally, despite our resolution, still short of being able to provide a fully self-consistent model for reionization by about an order of magnitude in mass (Whalen, Abel & Norman 2004; Greif et al. 2008), the UV background radiation has little effect on the galaxies discussed here (Gnedin 2000) since the minimal circular velocity of their host dark matter halo is larger than 25 km s^{-1} (Okamoto, Gao & Theuns 2008).

The two dust models described in Section 2 produce LFs that match the observed one quite well within the whole range of magnitudes it covers, as observational error bars plotted in Fig. 3 only roughly estimate cosmic variance errors (Bouwens et al. 2008). We discuss our results in terms of the most commonly used analytical parametrization of the galaxy LF, i.e. the Schechter function, examples of which are plotted in Fig. 3. This description relies on three parameters, $\Phi_\star$, $M_\star$ and α, i.e. the normalization, characteristic magnitude and faint-end slope of the LF, respectively. The preferred Schechter fit for our LF at $z = 4$ (i.e. the green curve in the bottom-right panel of Fig. 3) yields a faint-end slope of 1.6 and a characteristic magnitude of 20.9, compared to 1.73+/0.05 and 20.98+/0.1 for the data, respectively (Bouwens et al. 2007). Our normalization of 0.003 Mpc^{-3} appears a bit high with respect to that measured in the data (0.0013+/0.0002 Mpc^{-3}). However, this is the parameter of the Schechter function which is the most sensitive to a change in cosmological model. In other words, the error we make when we rescale our LFs from the (*WMAP*) 1 year (Spergel et al. 2003) to the *WMAP* 5 year parameters [green curves in Fig. 3, $\Omega_\mathrm{m} = 0.26$, $\Omega_\Lambda = 0.74$, $h = H_0/(100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}) = 0.72$, $\sigma_8 = 0.8$, $n = 0.96$; Dunkley et al. 2009] mostly affects $\Phi_\star$, so that the factor of about 2 difference is not statistically discrepant. To be more precise, in order to recast the results of our simulation for a different set of cosmological parameters, we have used the Press & Schechter (1974) formalism to calculate the dark matter halo mass function at a given z in both cosmologies. Assuming an occupation number of one galaxy per dark matter halo, we then divide our LFs by the ratio of the dark matter halo mass functions. Given the mass resolution of our simulation, we expect this correction to be quite accurate at higher redshift (above $z = 6$) and to slowly degrade as more massive haloes begin to form and start hosting a larger number of galaxies on average. This explains, at least partially, the larger discrepancy (at the $\sim 2\sigma$ level once cosmic variance is taken into account) between model and observed LFs at intermediate and low luminosities for $z < 6$. Note that these considerations do not apply to the brightest objects, which are much more scarce and have a

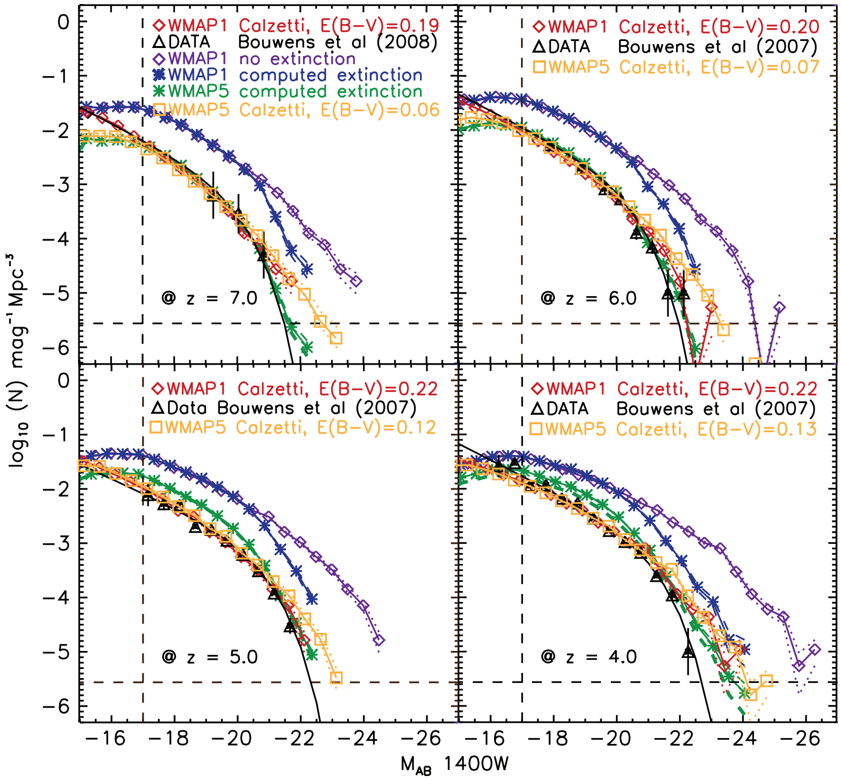

Figure 3. Redshift evolution of the UV (1400 Å) rest-frame galaxy LF measured in the Mare Nostrum simulation. Vertical dashed lines indicate mass resolution and horizontal dashed lines volume resolution. Purple diamonds indicate non-extinguished *WMAP*-1 cosmology LFs, blue stars LFs extinguished with a dust content scaled using the measured abundance of metals and gas in the simulation. Green stars represent LFs extinguished as the blue star ones but rescaled to the currently favoured *WMAP*-5 cosmology. Red diamond LFs stand for galaxies uniformly extinguished with a (Calzetti et al. 1994) law in a *WMAP*-1 universe whereas yellow squares are obtained using the same law but rescaled to the *WMAP*-5 cosmology first. Black triangles and solid lines mark data gathered by Bouwens and collaborators (Bouwens et al. 2007, 2008).

much higher probability of being unique in their host dark matter halo. As a result, the correction remains valid for these objects even for $z < 6$, as can be seen in Fig. 3.

In a nutshell, we find that our simulated LFs at $z \sim 4$ are in respectable agreement with the available UV data and robustly predict a faint-end slope with a value $\alpha \approx -1.6$ compatible with the findings of Steidel and collaborators (Adelberger et al. 2003; Reddy et al. 2008) ($\alpha \approx -1.6$) but not with the slope found in the Subaru data (Ouchi et al. 2004) ($\alpha \approx -2.2$). Our LFs also show quite an important amount of evolution, as measured by $M_\star$, which varies from 19.8 at $z = 7$ to 20.9 at $z = 4$. This strong evolution is a direct consequence of the rapid decrease of the cosmic star formation rate density from $z = 4$ to 7 in our simulation and is, to a large extent, unaffected by resolution effects (Rasera & Teyssier 2006). At $z > 6$, recent analyses of the *Hubble Space Telescope* Ultra Deep Field and the Great Observatories Origins Deep Survey data (Bouwens et al. 2007, 2008) suggest a slightly steeper faint-end slope of $\alpha \approx -1.74$, again in good agreement with our simulation as we find that the faint-end slope of our LF does steepen slowly with redshift. This is of key importance since ionizing photons from low-luminosity galaxies could possibly suffice to carry out the reionization of the Universe, provided these latter are numerous enough. Reversing the argument and marching down in redshift, this raises the question of what mechanism is responsible for such a flattening of the faint-end slope of the UV LF, which extends down to the local Universe, since a shallow slope ($\alpha \approx -1.22$) is observed locally for $z < 0.1$ in the *GALEX* far-UV data (Wyder et al. 2005). Supernova feedback could potentially drive powerful galactic outflows and quench star formation, but smoothed particle hydrodynamics simulations that explicitly include winds efficient enough to drive gas out of low-mass haloes systematically measure a steeper faint-end slope than we do ($\alpha \approx -2.0$) (Night et al. 2006). Finally, at the bright end of the LF, our two dust extinction models yield different results. The self-consistent extinction model has a more pronounced cut-off, which better matches the shape of a Schechter function. This feature stems from an intrinsically stronger dust attenuation that occurs in the most UV bright galaxies. We therefore predict that these very same UV beacons also are the most luminous infrared (IR) sources in the sky. The forthcoming generation of sub-millimetre facilities, and in particular ALMA, will either validate or disprove this prediction.

4 CONCLUSIONS AND DISCUSSION

We have derived UV LFs of simulated high-z galaxies using the largest hydrodynamical cosmological simulation performed so far. Including a self-consistent post-treatment of the extinction in our galaxies based on the abundance of gas and metals measured in the simulation, we have compared these synthetic LFs to the observed ones. We have studied how sensitive these LFs are to both cosmological parameters and dust absorption, using the most commonly used extinction model in the community (Calzetti et al. 1994) as a reference. Our self-consistent treatment of dust absorption enables us to match the observed UV LFs. This match quantitatively compares to the fit obtained with the simple model where all the galaxies are dimmed in the same way, provided that we set the cosmological parameters (in particular the normalization of the power spectrum and its rolling index) to their best-fitting *WMAP* 5 year values (Dunkley et al. 2009). However, contrarily to the Calzetti extinction model, such an agreement is achieved without the introduction of an extra free parameter, i.e. the average extinction of the galaxy population as a function of redshift can be retrieved from the simulation itself. Moreover, this self-consistent model receives support from (i) the extrapolation of low-z observations which show that extinction depends on UV luminosity (Heckman et al. 2005) and (ii) the mounting evidence for an extremely low metallicity in faint $z \sim 7$ galaxies (Bouwens et al. 2010), which both favour a non-uniform degree of extinction throughout the magnitude range spanned by the LF.

Although current observational surveys still probe small volumes of the high-redshift universe, and are therefore prone to suffer from cosmic variance at the bright end of the LF, they seem to go deep enough to yield reliable estimates of its faint-end slope in the UV, up to $z \sim 7$. At fixed cosmological parameters, the key to matching UV luminosities with any model of galaxy formation is the amount of dust extinction present in galaxies. However, the absorbed UV light is reprocessed by dust, and astronomers should be able to detect the far-IR counterparts of low-luminosity primordial galaxies, provided extinction strongly affects galaxies across their entire luminosity range. Future wider surveys together with the advent of IR and deep millimetre observations from the JWST and ALMA, respectively, should therefore give us a robust handle on where energy from star formation is really coming out at these redshifts. These measurements will, in turn, confirm or invalidate our improved treatment of dust attenuation. Indeed, we predict that this attenuation should strongly correlate with UV luminosity, with low-luminosity galaxies almost dust free at $z \sim 7$, and massive galaxies extinguished by 1.5–2 mag. Hence, only the tip of the iceberg of primordial galaxy formation should be visible at rest-frame IR wavelengths if our model is correct: the bulk of the galaxy population will mostly be UV bright with a few isolated monsters shining across the entire wavelength range. However, it should be noted that high-z obscured quasars could complicate efforts to secure a confirmation of this prediction.

ACKNOWLEDGMENTS

This work was supported by ANR grant number 05441478 awarded to the Horizon Project. CP acknowledges support from a Leverhulme visiting professorship at the University of Oxford. The simulation was run on the Mare Nostrum machine at the BSC and we thank the staff for their competent support and warm hospitality.

REFERENCES

Adelberger K., Steidel C., Shapley A., Pettini M., 2003, ApJ, 584, 45
Aubert D., Pichon C., Colombi S., 2004, MNRAS, 352, 376
Bouwens R. et al., 2006, ApJ, 653, 53
Bouwens R. et al., 2007, ApJ, 670, 928
Bouwens R. et al., 2008, ApJ, 686, 230
Bouwens R. et al., 2010, ApJ, 708, L69
Bunker A. et al., 2006, New Astron. Rev., 50, 94
Calzetti D., Kinney A., Storchi-Bergmann T., 1994, ApJ, 429, 582
Cardelli J., Clayton G., Geoffrey C., Mathis J., 1989, ApJ, 345, 245
Dekel A., Birnboim Y., 2006, MNRAS, 368, 2
Dekel A. et. al., 2009, Nat, 457, 451
Devriendt J., Guiderdoni B., Sadat R., 1999, A&A, 350, 381
Dubois Y., Teyssier R., 2008, A&A, 477, 79
Dunkley J. et al., 2009, ApJ, 180, 306
Fontanot F. et al., 2009, MNRAS, 392, 553
Gnedin N., 2000, ApJ, 542, 535
Guiderdoni B., Rocca-Volmerange B., 1987, A&A, 186, 121
Greif T., Johnson J., Klessen R., Bromm V., 2008, MNRAS, 387, 1021
Heckman T. et al., 2005, ApJ, 619, L35
Ilbert O. et al., 2005, A&A, 439, 863
Kassin S., de Jong R., Weiner B., 2006, ApJ, 643, 804
Keres D., Katz N., Weinberg D., Davé R., 2005, MNRAS, 363, 2
Merritt D., 2006, ApJ, 648, 976
Night C. et al., 2006, MNRAS, 366, 705
Ocvirk P., Pichon C., Teyssier R., 2008, MNRAS, 390, 1326
Okamoto T., Gao L., Theuns T., 2008, MNRAS, 390, 920
Ouchi M. et al., 2004, ApJ, 611, 660
Press W., Schechter P., 1974, ApJ, 187, 425
Rasera Y., Teyssier R., 2006, A&A, 445, 1
Reddy N. et al., 2008, ApJS, 175, 48
Slyz A., Devriendt J., Bryan G., Silk J., 2005, MNRAS, 356, 737
Spergel D. et al., 2003, ApJS, 148, 175
Springel V. et al., 2005, Nat, 435, 629
Steidel C. et al., 1999, ApJ, 519, 1
Teyssier R., 2002, A&A, 385, 337
Whalen D., Abel T., Norman M., 2004, ApJ, 610, 14
Wyder T. et al., 2005, ApJ, 619, L15

This paper has been typeset from a TEX/LATEX file prepared by the author.