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The End of the Dark Ages

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Abstract. The appearence of the first luminous sources marked the end of the Dark Ages, an epoch bracketed at high redshift by the recombination era and, closer to us, by cosmic reionization. The properties of the objects populating such epoch is still largely unknown and so their effects and role in shaping and regulating cosmic structure formation. The current ideas in the field, along with the most recent results are briefly summarized in this paper.

Key words. First Stars – Cosmic Reionization – Intergalactic Medium – Primordial Galaxies

1. Introduction

As the temperature of the cosmic bath decreases, atoms start to recombine and therefore decouple from CMB radiation at redshift ≈ 1100. Current models of cosmic structure formation based on CDM scenarios predict that the first objects in principle able to make stars should form at redshift $z \approx 30$ and have a total mass $M \approx 10^6 M_\odot$ or baryonic mass $M_b \approx 10^5 M_\odot$ (usually referred to as *minihalos*. This conclusion is reached by requiring that the cooling time, t_c, of the gas is shorter than the Hubble time, t_H, at the formation epoch. Since the virial temperature corresponding to the masses of these objects is typically $\lesssim 8000$ K, cooling by hydrogen Lyα excitation is strongly quenched, and the only viable coolant in a primordial H-He plasma is molecular hydrogen. On the other hand, objects with virial temperatures (or masses) above that required for the hydrogen Lyα line cooling to be efficient, do not rely on H_2 cooling to ignite internal star formation. Thus, the the fate of a virialized lump depends crucially on its ability to rapidly increase its H_2 content during the collapse phase. This condition is met only by larger halos implying that for each virialization redshift there will exist some critical mass, M_{crit}, such that protogalaxies with total mass $M > M_{crit}$ will be able to form stars and those with $M < M_{crit}$ will fail.

2. A few key questions

To understand the end of the Dark Ages, and particularly reionization, it is then necessary to pose a number of key questions: *(i)* Where did the first stars form ? *(ii)* What were their properties and their Initial Mass Function (IMF) ? *(iii)* What fraction of their ionizing power could escape in the intergalactic medium (IGM) ? I will dis-

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cuss these questions in detail before assessing the implications for cosmic reionization and the end of the Dark Ages.

2.1. Where did the first stars form ?

There are number of reasons to think that the first stars *did not* formed in minihalos but in the larger Lyα cooling halos with $T_{vir} \gtrsim 10^4$ K. The first argument comes from the so-called radiative feedback. As stars form inside the first collapsed objects, their UV photons start to photodissociate H_2 molecules in the neighbor objects. We have seen that H_2 is a crucial species for the cooling to occur, and the lack of it might prevent the collapse of small protogalaxies. This process is known as *radiative feedback*. The minimum flux required at each redshift to drive the radiative feedback has been obtained by Ciardi *et al.* (2000). The authors conclude that the halo mass range For which star formation is inhibited by radiative feedback is $10^6 - 10^8 M_\odot$, depending on redshift. In order for the feedback to be effective, UV fluxes of the order of $10^{-24} - 10^{-23}$erg s^{-1} cm^{-2} Hz^{-1} sr^{-1} are required (note that this values is only 0.1-1% of the UV background at $z \approx 3$). These fluxes are typically produced by a Pop III with baryonic mass $10^5 M_{b,5} M_\odot$ at distances closer than $\simeq 21 - 7 \times M_{b,5}^{1/2}$ kpc for the two above flux values, respectively. This suggests that at high z radiative feedback is driven primarily by the direct irradiation from neighbor objects in regions of intense clustering. As a result most star formation is likely to be suppresses in minihalos.

An additional argument concerns the star formation efficiency in minihalos vs. larger halos, given by Madau, Ferrara & Rees (2001). The fraction of the baryonic content of a halo that can actually cool and reach the center is determined by the balance between the cooling and the dynamical timescales of the systems. For $4.3 < \log T_{vir} < 5.7$ rapid cooling by atomic hydrogen and ionized helium can occur at these epochs on timescales much shorter than the free–fall time, Therefore, for masses in the range $10^8\, h^{-1} \lesssim M \lesssim 10^{10}\, h^{-1}\, M_\odot$, infalling gas never comes to hydrostatic equilibrium, but collapses to the center at the free–fall rate. For minihalos instead, the gas can be pressure–supported and form a quasi–static hot atmosphere. If we denote with $r_{\rm cool}$ the radius where the cooling time is equal to the free–fall time, a parameter f_b can now be defined as the ratio between the gas mass within $r_{\rm cool}$ and the total baryonic mass within the virial radius, $\Omega_b M$. It is found that f_b drops precipitously below unity for $T_{vir} < 10^4$ K, *i.e.* for minihalos; for these systems the supply of cold gas is regulated by the longer cooling timescale everywhere but for a small amount of gas in the very central region of the halo. When weighted with the steep mass function, it is the gas at the peak of the cooling curve – i.e. gas in larger systems with masses comparable to the masses of present–day dwarf galaxyes ($\approx 10^{8-9} M_\odot$) that may be more readily available to be transformed into stars.

2.2. What were the properties of the first stars ?

Star formation in the early universe is usually assumed to be understood more easily because several complicating effects can be neglected to a first approximation: among these are magnetic fields, dust grains and metal enrichment. Yet little consensus has been reached among various groups. It is clear that gravitational collapse induces fragmentation of the first pregalactic objects with initial baryonic mass $\approx 10^5 M_\odot$ into smaller clumps of typical mass of about $10^{2-3} M_\odot$, which corresponds to the Jeans mass set by molecular hydrogen cooling. The occurrence of such fragmentation has been shown to require the following conditions $\alpha \equiv$(thermal/gravitational)$<$ 0.3 and $\beta \equiv$(rotational/ gravitational)$<$ 0.3 on the relevant energy parameters of the collapsing clouds, at least for the quasi-

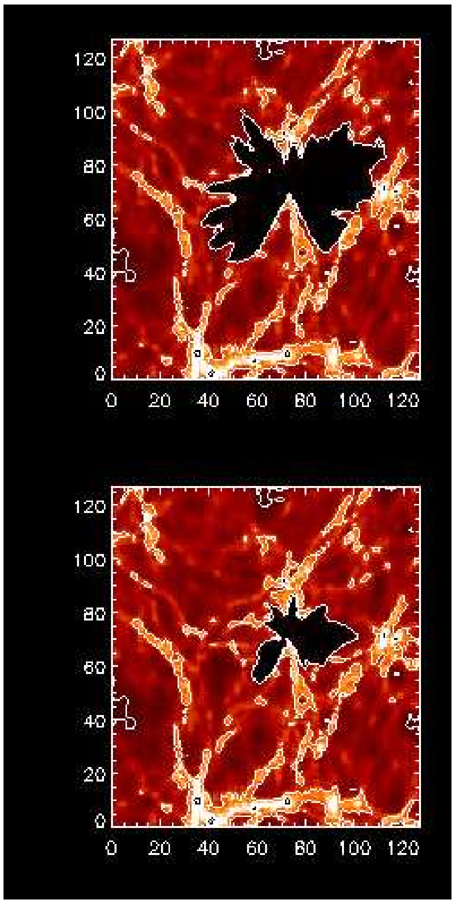

Fig. 1. Slices through the simulation box containing a metal free stellar source of total mass $M = 2 \times 10^8 M_\odot$ at $z \approx 12$ in a Λ+CDM cosmological density field showing a comparison between the final stages ($t = 100$ Myr) of the I-front evolution for a Larson (upper panel) and a Salpeter (bottom) IMF

isothermal case ($\gamma = 1.1$) derived from 1D simulations. Subsequent evolution, in some cases studied with the inclusion of cooling lines radiative transfer, shows that a quasi-hydrostatic central core is formed whose specific mass is somewhat dependent on the details of the problem, but typically in the range $10^{-3} - 1 M_\odot$. However, the precise value of the mass might be irrelevant as the accretion rate of the infalling gas is found to be rather high, around $10^{-2} M_\odot$ yr^{-1}, which implies that, in the absence of any effect quenching accretion, a large fraction of the initial object can become part of the protostar. Pushing this conclusion a bit further, one might predict a top heavy IMF for this first generation of sources.

Indeed these theroretical expectations seem to be supported by the interpretation of observational data for the metal poor halo stars in the Galaxy, which might be considered as relics of eraly cosmic episodes of star formation. Hernandez & Ferrara (2001) compared results for the Milky Way metallicity distribution of such stars as predicted by a ΛCDM cosmological model with observations. They used the sample of Ryan & Norris (1991) of low metallicity halo stars in the local disk. They include a magnitude limited sample, (their NLTT sample) which is complete down to $0.6 M_\odot$ and $V = 13.0$, the same limit used to sample the IMF. The latter was parametrized according to the suggestion by Larson (i.e. a Larson IMF)

$$dN/dlog\, m \propto (1 + m/m_\star)^{-1.35}. \qquad (1)$$

In the above equation $m_\star$ is a characteristic mass scale, of order $0.35 M_\odot$ for a present day solar neighbourhood IMF. This scale mass can be increased to explore the consequences of a top heavy IMF applying to stars of metallicities much lower than solar. Surprisingly, the cosmological predictions fall somewhat above the observational measurements, implying that the assumption of a constant $m_s = 0.35 M_\odot$ is not valid. Reconciling theory with observations requires an increasing trend with redshift for this value. For $z > 9$, the values of the characteristic mass appear to stabilize around the value $m_\star = 10 - 15 M_\odot$, indicative of a (moderately) top heavy IMF at these early epochs, although the increase of the error bars makes determining trends in this redshift range harder. In any case it is safe to conclude that there are clear evidences for a more top-heavy IMF in the past. A similar conclusion has also been drawn from the analysis of the near IR background excess

(Salvaterra & Ferrara 2002, Magliocchetti, Salvaterra & Ferrara 2003).

The effects of a top-heavy IMF on the ionization of the surrounding gas and intergalactic medium are spectacular. Fig. 1 shows a comparison between the final stages (100 Myr after the source turn on) of the I-front evolution for a Larson (upper panel) and a Salpeter (bottom) IMF. The source stellar mass and other properties of the simulations are the same as those discussed above. For a Salpeter IMF, the volume of the ionized region is smaller by a factor 8, although the shape is very similar to the one for a Larson IMF case at an earlier stage, roughly corresponding to 10 Myr. This was expected from the differences between the two adopted SEDs. In fact, the total number of ionizing photons per stellar mass formed integrated over the entire source lifetime and spectral extent is 5×10^{61} (10^{61}) for the Larson (Salpeter) IMF. Thus, the IMF might play an important role for the reionization of the universe; in addition, zero-metallicity stars have larger ionizing power as already stressed previously and recently addressed by other authors.

Table 1. Parameters of the simulations: Initial Mass Function, IMF; photon escape fraction, f_{esc}.

RUN	*IMF*	f_{esc}
S5	Salpeter	5%
S20	Salpeter	20%
L20	Larson	20%

2.3. *What is the escape fraction of UV photons ?*

Although very important, little is know about the fraction of ionizing photons produced by stars in galaxies that are able to escape to infinity, f_{esc}, which remains a very elusive quantity. Theoretically, Dove, Shull & Ferrara (2000) have estimated the fraction of ionizing photons emitted by OB associations that escapes the H I disk of a disk galaxy into the halo and intergalactic medium (IGM) by solving the time-dependent radiation transfer problem of stellar radiation through evolving superbubbles within a smoothly varying H I distribution. They find that the shells of the expanding superbubbles quickly trap or attenuate the ionizing flux, so that most of the escaping radiation escapes shortly after the formation of the superbubble. Superbubbles of large associations can blow out of the H I disk and form dynamic chimneys, which allow the ionizing radiation to escape the H I disk directly. However, blowout occurs when the ionizing photon luminosity has dropped well below the association's maximum luminosity. For a coeval star-formation history, the total fraction of Lyman Continuum photons that escape both sides of the disk in the solar vicinity is $f_{esc} \approx 0.15 \pm 0.05$; for a Gaussian star formation history, $f_{esc} \approx 0.06 \pm 0.03$. Observationally probably the best constraint comes from the interpretation of the redshift evolution of the UV background. Star formation rates of a few tens of solar masses are commonly derived from observations of LBGs. This result may suggest a galaxy-dominated UV background. In fact, Bianchi, Cristiani & Kim (2001) have recently shown that estimates of the local and high-z meta-galactic ionizing flux are consistent with a galaxy-dominated background if $f_{esc} \approx 10\%$. If in addition this result is coupled with the outcome of proximity-effect measurements, a relatively strong upper limit $f_{esc} < 20\%$ can be set. Further support to a low escape fraction comes from recent data obtained by Fernandez-Soto *et al.* (2003) who set a 3σ (statistical) upper limit $f_{esc} \lesssim 4\%$ for galaxies in the redshift range $1.9 < z < 3.5$.

3. Reionization after WMAP

In spite of the many poorly understood details concerning the key questions above,

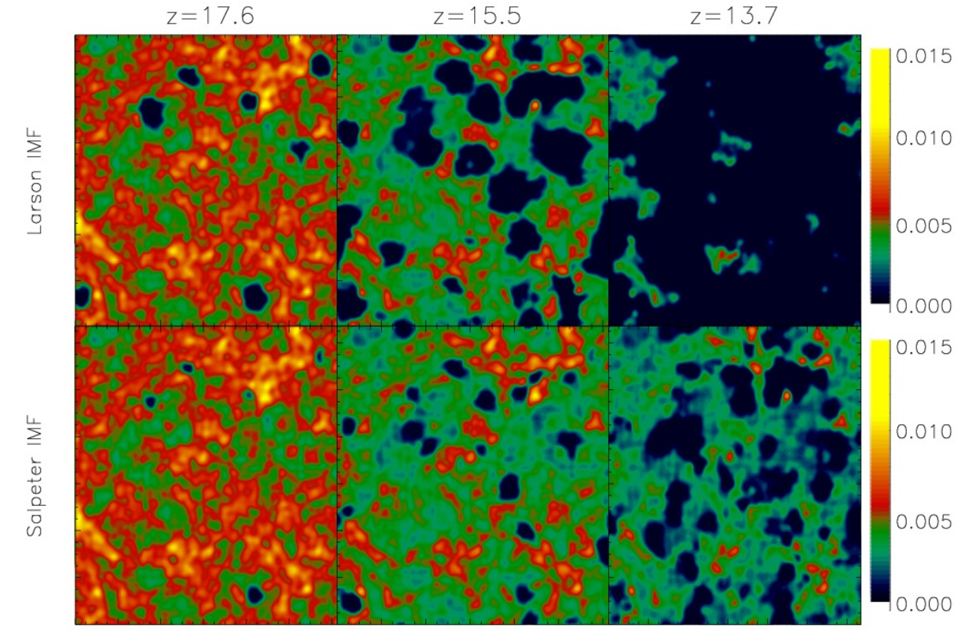

Fig. 2. Slices through the simulation boxes. The six panels show the neutral hydrogen number density for the L20 (upper panels) and the S20 (lower panels) runs, at redshifts, from left to right, $z = 17.6, 15.5$ and 13.7. The box has a comoving length of $L = 20h^{-1}$ Mpc.

concerning the physics of star formation, and the approximations inherent in the various numerical treatments of radiative transfer (for a recent review see Maselli, Ferrara & Ciardi 2003), a number of independent studies have converged on a relatively late ($z_r \lesssim 8$ to 10) epoch for complete reionization of the IGM within current "concordance" (i.e. flat, Λ-dominated) cosmological models.

This conclusion appears challenged by results from the *WMAP* satellite (Kogut et al. 2003; Spergel et al. 2003). This experiment has detected an excess in the CMB TE cross-power spectrum on large angular scales ($\ell < 7$) indicating an optical depth to the CMB last scattering surface of $\tau_e = 0.16$. The uncertainty quoted for this number depends on the analysis technique employed. Fitting the TE cross power spectrum to ΛCDM models in which all parameters except τ_e take their best fit values based on the TT power spectrum, Kogut et al. (2003) obtain a 68% confidence range, $0.13 < \tau_e < 0.21$. τ_e values in these ranges require a substantial fraction of the universe to be ionized before redshift 10. Apparently, reionization occurred earlier than expected. Is this discrepancy real? The discrepancy is not dependent on the particular cosmological parameters adopted, since *WMAP* has confirmed the previous concordance model. Hence the "oversight" must be of astrophysical nature. Several effects might have produced rapid early evolution: a contribution from low-mass minihalos; unexpectedly high star formation efficiency; unexpectedly high ionizing photon production; an unexpectedly large probability for ionizing photons to escape into the IGM; a possible population of early "miniquasars".

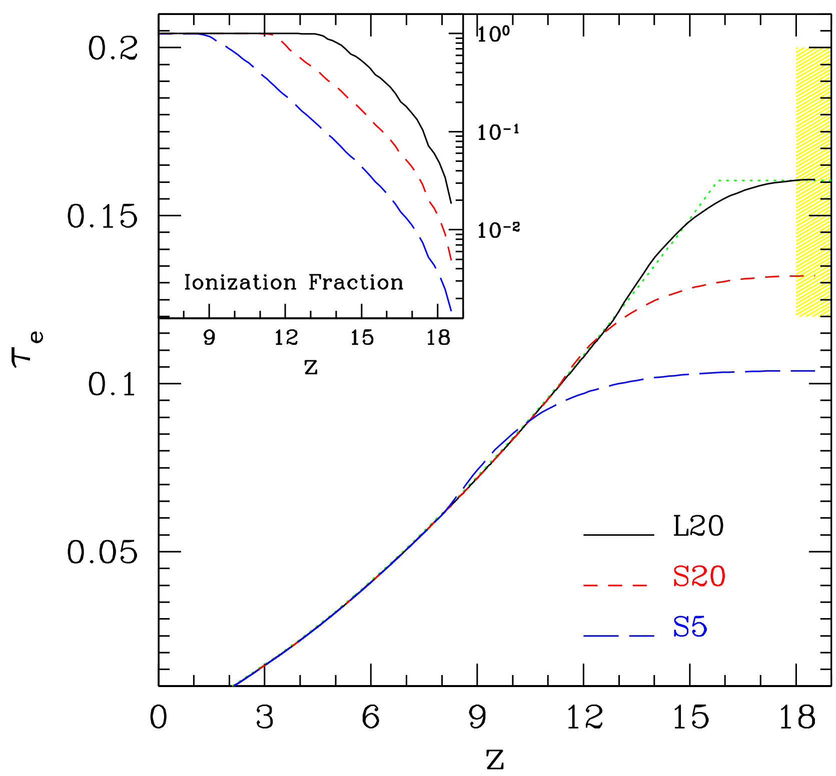

Fig. 3. Redshift evolution of the electron optical depth, τ_e, for the S5 (long-dashed line), S20 (short-dashed) and L20 (solid) runs. The dotted line refers to sudden reionization at $z = 16$. The shaded region indicates the optical depth $\tau_e = 0.16 \pm 0.04$ (68% CL) implied by the Kogut et al. (2003) "model independent" analysis. In the inset the redshift evolution of the volume-averaged ionization fraction, x_v, is shown for the three runs.

However, Ciardi, Ferrara & White (2003, CFW) point out that efficient production and escape of ionizing photons is sufficient to account for the data within conventional galaxy formation models. The data do not *require* very massive stars or miniquasars, although the high efficiencies needed may point to near-zero metallicities or to a moderatly top-heavy stellar Initial Mass Function (IMF) at early times.

The main parameters of the cosmological reionization simulations presented in CFW use the GADGET code coupled with the CRASH radiative transfer code (Maselli, Ferrara & Ciardi 2003). The simulations are based on a ΛCDM "concordance" cosmology with Ω_m=0.3, Ω_Λ=0.7, h =0.7, Ω_b=0.04, n=1 and σ_8=0.9.

We start from a visual inspection of simulated maps. Fig. 1 shows the redshift evolution of the HI number density for the L20 (upper panels) and the S20 (lower) runs (illustrative maps for the S5 runs can be found in CSW). Highly ionized regions (dark areas) are produced by the young galaxies in the box and are well resolved in the maps. They initially occupy a small fraction of the volume, and are typically larger in the L20 run because of the higher ionizing power of the sources. Their shape, particularly for larger ones, appears distorted by nearby high density peaks. (To a good approximation these correspond to peaks in the HI distribution.) The ionization front slows when it encounter such overdensities because of their higher recombination rate. By redshift $z = 15.5$ several bubbles are close to overlap in the L20 run (see upper-right corner of the central panel) whereas in the S20 run the filling factor is still small. Finally, by $z = 13.7$ the overlapping fronts have cleared out most of the volume in L20 with tiny HI islands surviving thanks to their high density; reionization in the S20 run, on the other hand, is far from complete.

Finally, we have calculated the evolution of τ_e (Fig. 3) corresponding to the above reionization histories as follows. Prior to complete reionization, $n_e(z)$ is obtained from the simulations; after the reionization epoch, we simply assume complete H and HeI ionization throughout the box. We also assume HeII reionization at $z = 3$. The three runs yield the values $\tau_e = 0.104$ (S5), $\tau_e = 0.132$ (S20) and $\tau_e = 0.161$ (L20). A value $\tau_e = 0.16$ is also obtained if one assumes instantaneous reionization at $z_r \approx 16$ (dotted line), i.e. three redshift units higher than the actual epoch of complete reionization in the model. At $z = 16$ the ionization fraction is $x_v \approx 0.3$ in L20.

In conclusion, recent *WMAP* measurements are easily reproduced by a model in which reionization is caused by the first stars in galaxies with total masses of a few $\times 10^9 M_\odot$. This requires some combination of a maximal (20%) photon escape fraction, a moderately top-heavy IMF $m_\star = 5M_\odot$, and a high stellar production rate for ionizing photons, similar, perhaps, to that typically inferred for metal-free stars. It is hence possible to reproduce the experimental data without invoking exotica such as very massive stars, early "miniquasars", or minihalos.

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