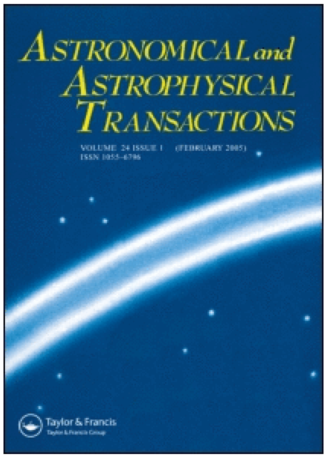

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 June 2001
To cite this Article: Ciardi, B. (2001) 'Inhomogeneous reionization regulated by radiative and stellar feedbacks', Astronomical & Astrophysical Transactions, 20:1, 177 - 182
To link to this article: DOI: 10.1080/10556790108208210
URL: http://dx.doi.org/10.1080/10556790108208210

Astronomical and Astrophysical Transactions, 2001,
Vol. 20, pp. 177–182
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INHOMOGENEOUS REIONIZATION REGULATED BY RADIATIVE AND STELLAR FEEDBACKS

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(Received November 13, 2000)

I present the results of a study of the IGM reionization due to an inhomogeneous distribution of stellar sources, which takes into account a self-consistent treatment of both radiative (i.e. ionizing and H_2-photodissociating photons) and stellar (i.e. SN explosions) feedbacks regulated by massive stars. This allows one to describe the topology of the ionized and dissociated regions in various cosmic epochs and derive the time evolution of the H and H_2 filling factor, the star formation rate and final fate of objects.

KEY WORDS Galaxies: formation, intergalactic medium, cosmology: theory

1 INTRODUCTION

The application of the Gunn-Peterson test to QSO absorption spectra suggests that the IGM is completely reionized by $z \simeq 6$. Several authors have claimed that the known population of quasars and galaxies provides $\simeq 10$ times fewer ionizing photons than necessary to keep the observed IGM ionization level and that additional sources of ionizing photons are required at high redshift. A possible candidate is a population of primeval galaxies. In the standard cosmological hierarchical scenario for structure formation, the objects which form first are predicted to have masses corresponding to virial temperatures $T_{\rm vir} < T_{\rm H} = 10^4$ K (*Pop III objects*). Primordial H_2 forms with a fractional abundance of $f_{\rm H_2} \simeq 2 \times 10^{-6}$, which is usually lower than that required for the formation of Pop III objects, but during the collapse phase, the molecular hydrogen content can reach high enough values to trigger star formation. This criterion is met only by larger haloes implying that for each virialization redshift there will exist some critical mass, $M_{\rm crit}$, such that protogalaxies with a total mass $M > M_{\rm crit}$ will be able to cool in a Hubble time and efficiently form stars and those with $M < M_{\rm crit}$ will fail (Tegmark *et al.*, 1997; Nishi and Susa, 1999; Susa and Kitayama, 2000). On the other hand, objects with virial temperatures (or masses) above that required for the hydrogen Lyα line cooling to be efficient, T_H (M_H), do not rely on H_2 cooling to ignite internal star formation. As the first stars form, their photons in the energy range 11.26–13.6 eV are able to penetrate the gas and photodissociate H_2 molecules both in the IGM and in the nearest collapsing structures, if they can propagate that far from their source. Thus, the existence of a UV flux below the Lyman limit due to primordial objects, capable of dissociating the H_2, could strongly influence subsequent small structure formation, inhibiting the collapse of objects with masses smaller than the characteristic one above which the object is self-shielded against H_2 dissociation, M_{sh}. Both Haiman, Rees and Loeb (1997) and Ciardi *et al.* (2000a), have argued that Pop III objects could depress the H_2 abundance in neighboring collapsing clouds, due to their UV photodissociating radiation, thus inhibiting subsequent formation of small mass structures, although Ciardi *et al.* (2000a) have shown that the 'soft-UV background' (SUVB) produced by Pop IIIs is well below the threshold required for negative feedback to be effective earlier than $z \simeq 20$. In principle, the collapse of larger mass objects can also be influenced by an ionizing background, as gas in haloes with a circular velocity lower than the sound speed of ionized gas may be prevented from collapsing due to pressure support in the gravitational potential, but several authors (Thoul and Weinberg, 1996; Susa and Kitayama, 2000) have shown that the collapse is only delayed by this process. I will refer to this complex network of processes as 'radiative feedback'.

The other feedback mechanism is related to massive stars and for this reason I will call it 'stellar feedback'. Once star formation begins in the central regions of collapsed objects it may strongly influence their evolution via the effects of mass and energy deposition due to massive stars through winds and supernova explosions. These processes may induce two essentially different phenomena. Low mass objects ($M < M_{\rm by}$) are characterized by shallow potential wells in which the baryons are only loosely bound and a relatively small energy injection may be sufficient to expel the entire gas content back into the IGM, i.e. a *blowaway*, thus quenching star formation. Larger objects, may instead be able to at least partially retain their baryons, although a substantial fraction of the latter are lost in an outflow, i.e. a *blowout* (Ciardi and Ferrara, 1997; Mac Low and Ferrara, 1999; Ferrara and Tolstoy, 2000). However, even in this case the outflow induces a decrease of the star formation rate due to the global heating and loss of the galactic ISM. Recently some authors (Omukai and Nishi, 1999; Glover and Brand, 2000; Nishi and Tashiro, 2000) have pointed out that the ionizing radiation of the first stars formed in Pop IIIs can also produce an abrupt interruption of the star formation by dissociating the internal H_2 content. The effect of this feedback is very similar to blowaway, as both processes are regulated by massive stars.

Figure 1 illustrates all possible evolutionary tracks and final fates of primordial objects, together with the mass scales determined by the various physical processes and feedbacks described above. Starting from virialized dark matter halo, the condition that its gas content is able to cool in a Hubble time ($M > M_{\rm crit}$) produces the first branching, and objects failing to satisfy it will not collapse and form only a negligible amount of stars (*dark objects*). Protogalaxies with masses in the range $M_{\rm crit} < M < M_H$ are then subject to the effect of radiative feedback, which could

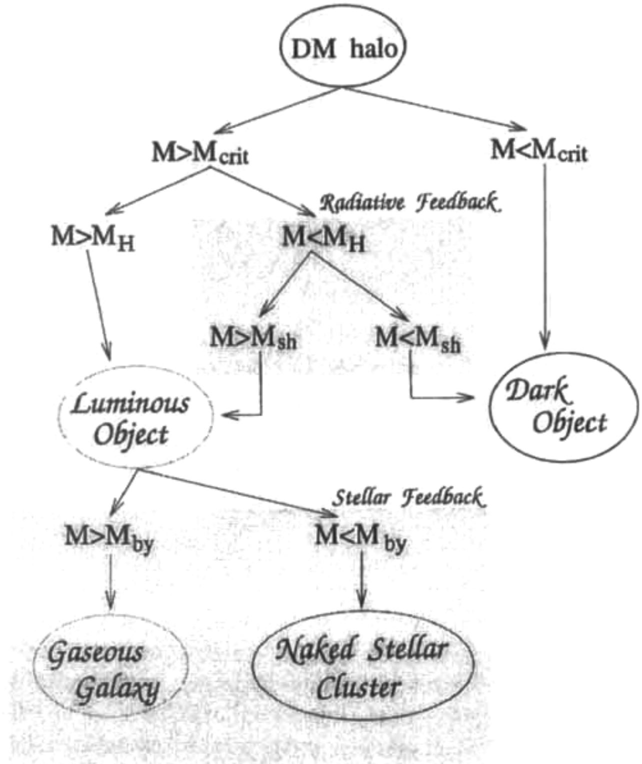

Figure 1

either impede the collapse of those of them with mass $M < M_{\rm sh}$, thus contributing to the class of dark objects, or allow the collapse of the remaining ones ($M > M_{\rm sh}$) to join those with $M > M_{\rm H}$ in the class of *luminous objects.* This is the class of objects that convert a considerable fraction of their baryons into stars. Stellar feedback causes the final bifurcation by inducing a blowaway of the baryons contained in luminous objects with mass $M < M_{\rm by}$; this separates the class into two subclasses, namely 'normal' galaxies (*gaseous galaxies*) and tiny stellar aggregates with negligible traces (if any) of gas (*naked stellar clusters*).

2 IGM REIONIZATION HISTORY AND SFR

In Ciardi *et al.* (2000a) we simulated dark matter structure formation within a periodic cube of comoving length $L = 2.55h^{-1}$ Mpc for a SCDM model ($\Omega_0 = 1$, $h = 0.5$ and $\sigma_8 = 0.6$). From the halo distribution given by the simulation and the prescription for galaxy formation described in the above Section, we are able to assign to each dark matter halo a corresponding luminous or dark object. Each

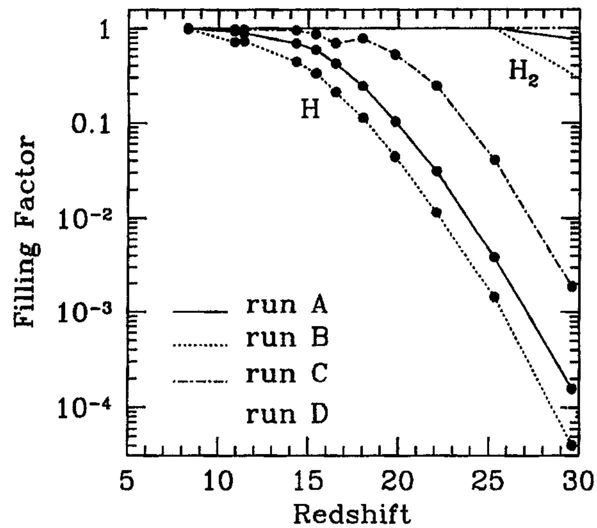

Figure 2

luminous object will then create in the surrounding medium regions of ionized atomic hydrogen and dissociated molecular hydrogen, whose size depend on the object ionizing and dissociating photon production (Ciardi *et al.*, 2000b). As the combination of the numerical simulation and the feedback network described above provides the spatial distribution of luminous objects, this allows us to describe the topology of the ionized and dissociated regions and to derive the evolution of the corresponding filling factors. As the cosmological model is fixed by the N-body simulations, the main parameters involved in the calculation are the fraction of virialized baryons that are able to cool and become available to form stars, f_b, the star formation efficiency, $f_\star$, and the photon escape fraction, f_{esc}. Four runs have been performed with different values for these parameters: A ($f_b = 0.08$, $f_\star = 0.15$ and $f_{esc} = 0.2$), B ($f_b = 0.08$, $f_\star = 0.05$ and $f_{esc} = 0.2$), C ($f_b = 1.00$, $f_\star = 0.15$ and $f_{esc} = 0.2$) and D ($f_b = 0.08$, $f_\star = 0.15$ and $f_{esc} = 0.1$).

In Figure 2 I show the dissociated molecular hydrogen (upper set of lines) and ionized atomic hydrogen (bottom set) filling factor as a function of redshift for the different runs. The intergalactic relic molecular hydrogen is found to be completely dissociated at very high redshift ($z \simeq 25$) independently of the parameters of the simulation. This descends from the fact that dissociation spheres are relatively large and overlap at early times. Ionization spheres are instead always smaller than dissociation ones and complete reionization occurs considerably later. Except for run C, when reionization occurs by $z \simeq 15$, primordial galaxies are able to reionize the IGM at a redshift $z \simeq 10$. In principle, a higher photon injection in the IGM could result both in an increase (as larger HII regions are produced) or a decrease (as the number of sources is reduced by the effect of radiative feedback) of the filling factor. Along the sequence run B, D, A, C the number of ionizing photons injected

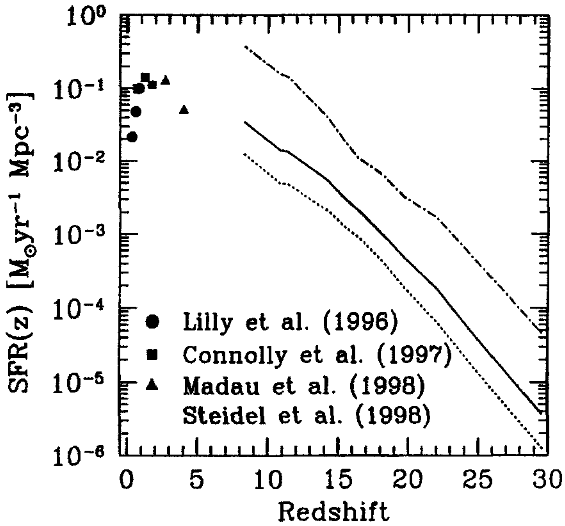

Figure 3

into the IGM is progressively increased. Then Figure 2 allows us to conclude that the former effect is dominant.

Additionally, it is possible to calculate the SFR per comoving volume and to compare it with the values derived by the most recent studies. The results are shown in Figure 3. Obviously, the higher the $f_b \times f_\star$ product, the higher the SFR obtained. Actually, although run A and D have the same value for the above parameters, in run D more luminous objects are formed (as the SUVB is lower more objects avoid negative feedback) and this results in a slightly higher SFR. From Figure 3 we see that runs B and C can be taken respectively as a lower and an upper limit to the SFR derived with our model, thus constraining the product $f_b \times f_\star$. Runs A and D produce a trend consistent with the observations, suggesting a plausible value range for the product $f_b \times f_\star$ around ≈ 0.01.

Although great progress has been made in the study of IGM reionization, we will have an even deeper understanding of the process once a fast method for a better treatment of the propagation of ionization fronts in the early universe is implemented in cosmological simulations. In Ciardi *et al.* (2001) we are working in this direction, developing a Monte Carlo method for the treatment of the radiative transfer of ionizing photons in an inhomogeneous density distribution.

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