The First Structures in the Universe: Pop III Objects

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Abstract. We review some of the possible observable effects (reionization, feedback on galaxy formation, supernovae and metal enrichment) of the first collapsed, luminous (Pop III) objects in the universe. We show that supernovae in these objects should be considerably magnified by the intervening cosmological matter distribution; the implications of this process are briefly discussed, anticipating some of the results of Marri & Ferrara (1998).

1. Introduction

As the temperature of the cosmic bath decreases, atoms start to recombine and therefore decouple from CMB radiation at redshift \( z \approx 1100 \). The baryonic Jeans mass after this event is given by (assuming \( \Omega = 1 \))

\[
M_j \approx 6 \times 10^4 \left( \frac{1 + z}{30} \right)^{-3/2} \left( \frac{T}{500 \text{K}} \right)^{3/2} \Omega_b M_\odot,
\]

where \( T \) is the gas temperature and \( \Omega_b \) the baryon density parameter. Masses larger than \( M_j \) are gravitationally unstable and should, in principle, collapse. However, in order for the actual collapse to occur a more severe condition must be satisfied, i.e. that the cooling time of the gas is shorter than the Hubble time at that epoch; in fact radiative losses provide the only way for the gas to lose pressure and to settle down in the potential well of the dark matter halo. Since the virial temperature corresponding to Pop III object masses is typically \( \lesssim 8000 \text{K} \), cooling by hydrogen Ly\( \alpha \) excitation is strongly quenched, and the only viable coolant in a primordial H-He plasma is molecular hydrogen. \( H_2 \) is produced during the recombination phase, but its relic abundance is so small that it contributes only marginally to the cooling. However, its fractional abundance increases during the collapse phase along with the density, finally becoming dominant. Tegmark et al. (1997) have determined the minimum mass necessary for collapse and they find that these first objects in a standard CDM model should form at redshift \( z \approx 30 \) and have total masses \( M \approx 10^6 M_\odot \). During the collapse, if fragmentation occurs, a stellar cluster is likely to be formed with a stellar mass, \( M_\ast \), which depends on the (unknown) details of the star formation process. An educated guess, based both on the experimental data available...
for the Galaxy and on theoretical arguments, suggests that $M_* \approx 10^{2-3}$. The number of massive stars and supernovae produced depends on the postulated IMF; if the latter is not too steep, it is reasonable to expect that the Pop III star cluster will be a source both of ionizing photons and (explosive) energy injection in the surrounding environment. In the next section we provide some estimates of these effects and finally we discuss how these (very) high redshift supernovae might be close to enter the realm of visibility in the next few years, thanks to their relatively strong magnification due to the intervening cosmological matter distribution.

2. Effects of Pop III Objects

2.1. Reionization and Feedback

As Pop III objects start to shine ionizing photons produced by their pristine stellar clusters, they will create an approximately spherical ionized (HII) region in the surrounding IGM. The radius of each sphere is relatively small ($\approx 0.1 - 0.2$ Mpc); this value depends linearly on the (unknown) value the fraction of ionizing photons escaping from the Pop III ISM, here assumed to be $f_{\text{esc}} \sim 0.2$. Therefore, the reionization epoch, defined as the $z$ at which the ionized spheres overlap, is rather delayed with respect to the formation of the Pop III, i.e. $z \approx 10$ (Ciardi & Ferrara 1997). The above calculation requires that the galaxy formation follows closely the underlying hierarchical clustering that aggregates dark matter halos. This, however, needs not to be the case. In fact, in addition to ionizing the intergalactic hydrogen, the emitted radiation in the soft-UV band $11.2 - 13.6$ eV is also able to photodissociate $H_2$ molecules inside collapsing objects, thus temporarily inhibiting the formation of objects smaller than the mass threshold for the ignition of Ly$\alpha$ cooling ($M \approx 10^8 M_\odot$). This process is often referred to as a kind of ”negative feedback”, according to Haiman et al. 1997, who first suggested that such mechanism can be at work. More recently, this negative role of Pop III on subsequent galaxy formation has been revisited by Ciardi, Abel & Ferrara (1998). Without entering the details of their argument, the main point is that it appears that Haiman et al. (1997) have considerably overestimated the photodissociating soft-UV radiation produced by Pop III objects, calculated by the crucial assumption that HII spheres (and consequently the photodissociation spheres) overlap already at high $z$. Instead, as discussed above, overlap occurs only much later, at an epoch at which the role of $H_2$ cooling in the collapsing galaxies has become negligible with respect to atomic cooling, thus strongly reducing, if not even suppressing, the alleged negative feedback.

2.2. Explosions and Metal Enrichment

In the likely situation in which stars more massive than $8 M_\odot$ are born in the Pop III stellar cluster, supernovae will start to explode after a few million years. Even if the stars in the cluster are all coeval (i.e. born from the same initial burst of star formation) supernovae will explode at different times due to their mass spread. For a stellar cluster inside a Pop III with properties as the ones discussed above, we expect, for a Miller-Scalo IMF, about $N = 2 - 20$ supernovae to blow
off. The total mechanical luminosity of such a multi-SN explosion, approximated as a continuous energy injection, is of the order of $\epsilon_0 N/t_{OB} \approx 0.6 - 6 \times 10^{37}$ erg s$^{-1}$, where $\epsilon_0 \approx 10^{51}$ is the energy of a single supernova explosion and $t_{OB} \approx 10^7$ yr is the typical lifetime of a massive star association. The point to be appreciated is that Pop III objects, due to their low mass and binding energy, are very fragile objects and tend to be blown-away (Ciardi & Ferrara 1997) by explosions: a number $N_c \approx M_6^{5/3} (1 + z/30) h^{2/3}$ of supernovae will suffice to disrupt the object, where $M_6 = M/10^6 M_\odot$. Since for our reference stellar cluster $N > N_c$, its residual gas content will be swept away by the expanding multi-SN driven shock and lost to the IGM. As a result, further star formation will be inhibited and the remaining low mass stellar population will continue to evolve passively. The final fate of this object is not yet clear: stars can become unbound due to dynamical instabilities following the blow-away or they can steadily evaporate from the stellar cluster and be lost in the field; the timescale of these processes, though, should be compared with the one for merging. The gas injected in the IGM is enriched by the heavy elements produced by supernova nucleosynthesis processes. Assuming that the mass in heavy elements averaged on a Miller-Scalo IMF is $\approx 3 M_\odot$, we estimate that the metallicity inside a secondary halo corresponding to a blow-away event driven by $N$ supernovae is

$$Z \approx 1.7 \times 10^{-4} N^{2/5} \left( \frac{1 + z}{30} \right)^{18/5} (\Omega_b h^2)^{-2/5},$$

or $Z \approx 0.05 N^{2/5} Z_\odot$ at $z \approx 30$ and $(\Omega_b h^2) = 0.05$. This estimate shows that Pop III objects might be responsible for the origin of polluted regions of relatively high metallicity, although of rather small (sub-kpc) size. Hence, the enrichment of the universe might very well have been very patchy in its early phases.

3. Cosmological Lensing of Pop III SNe

Pop III supernova events as the ones discussed in the previous Section should represent one of the best tracers of star formation at (very) high redshift. The typical luminosity of a Type II SN is of order $10^{42}$ erg s$^{-1}$; the luminosity of a $10^6 M_\odot$ Pop III object, assuming a reasonable mass-to-light ratio, is about 100-1000 times smaller. In addition to what we can learn on the formation of the first objects, Pop III SNe can provide crucial information on cosmological models due to their different predictions concerning the gravitational lensing magnification patterns by the intervening matter in the universe.

To investigate this and other aspects, we have have recently undertaken a project aimed at simulating the magnification properties of SNe located at redshift $z_a$, and lensed by the matter distribution predicted by three different cosmological models: SCDM (Standard Cold Dark Matter: $\Omega_M = 1$), LCDM (Lambda Cold Dark Matter: $\Omega_M = 0.4, \Omega_\Lambda = 0.6$), CHDM (Cold Hot Dark Matter: $\Omega_M = 1, \Omega_\nu = 0.3$); all models have $h = 0.65$ and are COBE normalized. The detailed description of the models, simulations and results are presented in Marri & Ferrara (1998); here we concentrate on some aspects concerning the magnification probabilities of SNe. Technically speaking, the matter distribution in the universe behaves like a thick gravitational lens. Such 3D distribution must
be approximated as a sequence of planes, on which the matter is projected, separated by a given redshift interval (typically $\Delta z = 0.25$). We assume that the lensing matter is all contained in collapsed point-like dark halos (we neglect baryons at this stage) whose number density as a function of mass and redshift is calculated using the Press-Schechter formalism; obviously, this quantity depends on the given cosmological model. Such lenses are then distributed randomly on each plane, i.e. neglecting any possible clustering effect.

Our numerical outputs are a set of magnification maps displaying the magnification, $\mu$ (i.e. the source flux enhancement factor) of a point source located at a given spatial position inside the considered $5' \times 5'$ field of view. There are several unambiguous differences among the three families of cosmological models that we can identify by analysing the magnification maps. SCDM models give intense, but not very numerous caustics ($\mu \approx 30 - 40$) for $z_s \approx 3$; intermediate magnification caustics appear at higher $z_s$ due to lower mass objects that have not yet hierarchically merged into larger ones. LCDM models produce the most intense caustics ($\mu \approx 50$), but most of the map is covered with more diffuse and lower $\mu$ magnification patterns. Finally, CHDM models, which form large structures later than $z = 3$, show very rare intense events and many moderate $\mu$ caustics. We have performed extensive statistical analysis of the magnification maps. Here we present some results for the cumulative source magnification probability, $P(\mu > \mu)$, that is the probability that a source in our field is magnified by more than a value $\mu$. In terms of this distribution, we can define two useful quantities: (i) $\mu_{10}$, or the largest magnification with a probability larger than 10%, and (ii) $P(\mu > 10)$, or the probability of magnification larger than 10 (high magnification probability). Fig. 1 shows the evolution of $\mu_{10}$ (top panel) and $P(\mu > 10)$ (bottom), with the source redshift. First, we note that magnifications higher than $\mu = 2$ are very likely ($> 10\%$) for all the cosmological models considered; this fact strongly enhances the chance of detection of high redshift SNe (Marri & Ferrara 1998). In addition, magnification in SCDM and LCDM models shows appreciable evolution even at redshift larger than 5, whereas CHDM magnifications saturate at that epoch, since little action is going on at higher redshifts in that particular model. Hence, gravitational lensing of very high $z$ sources can prove to be a very sharp tool to discriminate among different cosmological models. By inspecting the bottom panel of Fig. 1, we also see that there is more than 1% chance to obtain magnifications $> 10$ at high redshift for the three models. A caveat to keep in mind is that this value might be somewhat overestimated by our assumption of point-like lenses and underestimated if clustering is present. Future work will include a more realistic schematization of these variables.

4. Important Points

We summarize here the main points of the paper:

- Pop III objects form at $z \approx 30$, provide the first light after CMB and start to reionize the universe. They also partially photodissociate the relic $H_2$, but the negative feedback on galaxy formation, responsible for a temporary halt in the galaxy formation sequence, is probably not taking place, as discussed by Ciardi et al. (1998).
Figure 1. Evolution of the largest magnification with probability larger than 10%, $\mu_{10}$, and of the probability of magnification larger than 10, $P(\mu > 10)$, as a function of the source redshift for the three different cosmological models considered.

- Blow-away of Pop III seems unavoidable if their masses are of the order of $10^6 M_\odot$. Metal enriched gas is cast into the IGM, producing regions of relatively high ($Z > 10^{-2} Z_\odot$) metallicity which, however are distributed with a patchy pattern.

- High redshift SNe in PopIII lensed by the intervening cosmological matter distribution have considerable chance ( $> 1\%$) to get magnified by more than 10 times. Thus, detection chances of these primordial objects are enhanced; at the same time, lensing of high-z objects will likely allow to discriminate among cosmological models.

References

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