Pop III objects and their Relationship with Dwarf Galaxies

A. Ferrara 1, B. Ciardi 2
1 Osservatorio Astrofisico di Arcetri, Firenze, Italy
2 Dipartimento di Astronomia, Università di Firenze, Italy

Abstract

In this paper we briefly review some of the most recent developments concerning the formation of the first luminous objects in the universe, to which we refer to as Pop III objects, and their observable effects. In particular, we try to critically discuss the possible connection between them and dwarf spheroidal galaxies. We come to the conclusion that, if the properties of Pop IIIs are correctly predicted by hierarchical cosmological models, their identification with present day dwarf galaxies presents several difficulties.

1 The First Luminous Aggregations in the Universe

Determining how structure formed in the early universe, and how the first luminous objects (hereafter Pop III) form, appears to be one of the most challenging and interesting problems in physical cosmology. Current models of cosmic structure formation based on CDM scenarios predict that the first collapsed, luminous (hereafter Pop III) objects should form at redshift $z \approx 30$ and have a total mass $M \approx 10^6 M_\odot$ or baryonic mass $M_b \approx 10^5 M_\odot$ ([3], [8], [12], [1]). This conclusion is reached by requiring that the cooling time of the gas is shorter than the Hubble time at the formation epoch. In a plasma of primordial composition the only efficient coolant in the temperature range $T \leq 10^4$ K, the typical virial temperature of Pop III dark matter halos, is represented by H$_2$ molecules, whose abundance increases from its initial post-recombination relic fractional value ($f_{H_2} \approx 10^{-6}$) to higher values during the halo collapse phase. It is therefore crucial to determine the cosmic evolution of such species in the early universe to clarify if small structures can continue to collapse according to the postulated hierarchical structure growth or if, lacking a cooling source, the mass build-up sequence comes to a temporary halt.
During the collapse, if fragmentation occurs, a stellar cluster is likely to be formed with a stellar mass, $M_*$, which depends on the (unknown) details of the star formation process. As an order of magnitude estimate, we can calculate the mass of stars formed in a free-fall time using the following simple formula (\[5\]):

$$M_* \approx \frac{\Omega_b f_b}{\tau} M \simeq 300\Omega_{b,5} f_b M_6 \ M_\odot$$

(1)

The baryon density parameter is $\Omega_b = 0.05 \Omega_{b,5}$, of which a fraction $f_b$ is able to cool and become available to form stars. The total mass of the object is $M = 10^6 M_6 \ M_\odot$; finally, $\tau^{-1} = 0.6\%$ is the star formation efficiency, calibrated on the Milky Way. Clearly, large uncertainties affect the three free parameters entering equation (1), and in particular $f_b$. Generally speaking, the first objects should have a baryonic mass of about $10^5 \ M_\odot$ and form about 100-1000 stars during the first episode of star formation. Thus, given these derived properties, a Pop III object might look very similar to a star-forming molecular cloud in the Galaxy, and indeed they are very likely to be the first molecular, self-gravitating objects in the universe.

Some of the formed stars could be more massive than $8 \ M_\odot$. Their number crucially depends on the actual IMF in those conditions, which, needless to say, is almost totally unknown. However, if we assume a standard Salpeter-like IMF with a low-mass cutoff at $0.1 \ M_\odot$, then one such star is produced for each 56 $M_\odot$ of stars formed, or, according to the previous estimate, about 2-20 massive stars. Massive stars are particularly important for two reasons: (i) they produce ionizing photons, and (ii) end their lives exploding as supernovae. In turn, photons with energies above 13.6 eV produce ionized regions that expand in the surrounding IGM, a cosmological analog of galactic HII regions. However, in addition to hydrogen, if the ionizing spectrum is hard enough, similar ionized spheres may occur for helium as well. Pop III are thus certainly initiating the process of reionization of the universe, which was essentially neutral since the recombination epoch at $z \approx 1100$. It is not completely clear, though, if they can bring this process to completion and on which timescale. Also, keeping the universe ionized might require additional ionizing sources - maybe larger galaxies or QSOs. This uncertainty is due to the fact that the radiation emitted by star-forming Pop IIs can photodissociate H$_2$ molecules that are necessary to continue the hierarchical collapse sequence. In this sense, Pop IIs are a population potentially committing self-suicide ! Massive stars also provide mechanical energy input to the parent galaxy ISM via winds, and most importantly, supernova explosions. The effects of such energy injection can be dramatic in low-mass objects (for a detailed discussion see [10]), possibly leading to the complete dispersal of the parent galaxy ISM. In that case the star formation activity is subsequently quenched by the lack of gas and only a stellar remnant made of low-mass stars is left over. Moreover, such pristine supernovae contribute to the pollution of the IGM with heavy elements, which are now detected by absorption line experiments toward QSOs. The first solid particles in the universe, i.e. dust grains, could also be formed in the expanding Pop III SN ejecta: such a possibility has recently become clear after the SN1987A event. Finally, together with reionization, reheating of a fraction of the IGM to temperatures of the order of a million degrees must occur as a result of shocks produced by explosions.

In the following we discuss radiative and mechanical feedback due to Pop III objects in more detail. Some of the presented results will provide us with some ground to speculate about the possible connection between Pop III objects and local dwarf galaxies.

## 2 Radiative Feedback Effects

If massive stars form in Pop III objects, their photons with $h\nu > 13.6$ eV create a cosmological HII region in the surrounding IGM. Its radius, $R_i$, can be estimated by solving the following
standard equation for the evolution of the ionization front:

\[
\frac{dR_i}{dt} - HR_i = \frac{1}{4\pi n_H R_i^2} \left[ S_i(0) - \frac{4}{3}\pi R_i^3 n_H^2 \alpha^{(2)} \right]; \tag{2}
\]

note that ionization equilibrium is implicitly assumed. \(H\) is the Hubble constant, \(S_i(0)\) is the ionizing photon rate, \(n_H = 8 \times 10^{-6} \Omega_b h^2 (1 + z)^3 \text{ cm}^{-3}\) is the IGM hydrogen number density and \(\alpha^{(2)}\) is the hydrogen recombination rate to levels \(\geq 2\). First, we note that since \(R_i \ll c/H\), the cosmological expansion term \(HR_i\) can be safely neglected. In its full form eq. (2) must be solved numerically [2]. However, in some limiting cases \(R_i\) can be evaluated analytically. If steady-state is assumed \((dR_i/dt \simeq 0)\), then \(R_i\) is approximately equal to the Strömgren radius, \(R_S = [3S_i(0)/(4\pi n_H^2 \alpha^{(2)})]^{1/3}\). In general, \(R_s\) represents an upper limit for \(R_i\), since the ionization front completely fills the time-varying Strömgren radius only at very high redshift, \(z \approx 100\). For our reference parameters it is:

\[R_i \leq R_s = 0.05 \left( \Omega_b h^2 \right)^{-2/3} (1 + z)^{-2} S_i^{1/3} \approx 20 \text{ kpc},\tag{3}\]

where \(S_{47} = S_i(0)/(10^{47} \text{ s}^{-1})\). The approximate expression for \(S_i(0)\) is \(\approx 1.2 \times 10^{48} f_b M_6 \text{ s}^{-1}\) when a 20% escape fraction for ionizing photons is assumed ([2]). A detailed comparison ([2]) between \(R_i\) and \(R_s\) shows that \(R_s\) is typically 1.5 times larger than \(R_i\) in this redshift range.

As mentioned above, in addition to a cosmological HII region, photons with \(11.26 \text{ eV} \leq h\nu \leq 13.6 \text{ eV}\), create a photodissociated sphere by exciting the H\(_2\) Lyman-Werner bands (LW) which eventually decay into the continuum (this is the so-called two-step photodissociation process). The main difference between ionization and dissociation sphere evolution consists in the fact that at high \(z\) there is no efficient mechanism to re-form the destroyed H\(_2\), analogous to H recombination. As a consequence, it is impossible to define a photo-dissociation Strömgren radius. Given a point source that radiates \(S_{\text{LW}} = \beta S_i(0)\) photons per second in the LW bands, an estimate of the maximum radius of the H\(_2\) photodissociated sphere, \(R_d\), is the distance at which the photo–dissociation time becomes longer than the Hubble time:

\[R_d \sim 2.5 h^{-1/2} (1 + z)^{-3/4} S_{\text{LW},47}^{1/2} \approx 20 \text{ kpc},\tag{4}\]

where \(S_{\text{LW},47} = S_{\text{LW}}/(10^{47} \text{ s}^{-1})\). Eqs. (4) and (3) show that the photodissociated region is larger than the ionized region; however, even if \(S_{\text{LW}} \ll S_i(0)\) under most conditions \(R_d\) cannot be smaller than \(R_i\) since inside the HII region, H\(_2\) is destroyed by direct photoionization.

At high \((z \approx 20 - 30)\) redshifts the mean separation between Pop III objects is larger compared to the photodissociated sphere radius. In between the dissociated spheres, a ”soft” UV background (SUVB) is established, which is able to photodissociate intergalactic H\(_2\) molecules in a time shorter than the Hubble time only if its intensity exceeds the critical value

\[J_{\text{LW}}^{\text{crit}} = 6.2 \times 10^{-4} J_{21} h(1 + z)^{3/2} \left( \frac{\text{erg}}{\text{s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}} \right),\tag{5}\]

where \(J_{21} = 10^{-21} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}\). The SUVB intensity can then be calculated to a good approximation (for the detailed derivation and discussion see [2]) in the limit of small volume filling factor of the photodissociated spheres; overlapping starts to be important at redshift \(z \approx 20\). The calculation of the above authors includes intergalactic H\(_2\) attenuation, the effects of cosmological expansion and neutral H line absorption. In Fig. 1 the spectrum of the SUVB at \(z = 27\) is shown, for the particular value of the baryon cooling efficiency \(f_b = 0.08\) (this fixes the intensity of the radiation field) and in which the IGM LW attenuation is either included or neglected for comparison sake. As \(J_{\text{LW}}\) depends linearly on \(\beta\), the ratio between the flux just below and above the Lyman limit, the results for different values of \(\beta\) can be
Figure 1: Spectrum of the SUVB, $J_{LW}$, for $z = 27$, $\beta = 1$ and for baryon cooling efficiency $f_b = 0.08$; from the top to the bottom, no shielding (dashed line), H lines opacity (dotted), H$_2$ lines opacity (dotted) and H$_2$ and H lines opacity (solid) is included.

easily obtained by appropriately scaling the plotted curves. Fig. 1 allows to conclude that the intergalactic H$_2$ absorption cannot be neglected as it decreases the SUVB intensity by more than an order of magnitude at energies just below 13.6 eV, while the attenuation is reduced at lower energies by the cosmological expansion. Also, by inspecting Fig. 1 it is possible to compare the relative effects of hydrogen line and H$_2$ LW line absorption on the SUVB attenuation, for a typical choice of the parameters. The H lines are optically thick at their center; this, combined with the effect of the cosmological expansion, produces the typical sawtooth modulation of the spectrum. On the other hand, the radiative decay of the excited H atoms produces Ly$\alpha$ and other Balmer or lower line photons, which are out of the LW energy range and result in an increase of the flux just below the Ly$\alpha$ frequency. From Fig. 1 we see that the molecular line attenuation dominates the hydrogen one over the entire range of frequencies.

These results are particularly important to estimate the relevance of the so-called “negative feedback” effects ([8]). In brief, the SUVB created by pregalactic objects, could penetrate large clouds, and, by suppressing their H$_2$ abundance, prevent the collapse of the gas. However, the low values of the SUVB found at high redshift are well below the threshold required ($J_{LW} = 10^{-24}$ erg s$^{-1}$ Hz$^{-1}$ cm$^{-2}$ sr$^{-1}$) for the negative feedback ([9]), note that there was an error in their original paper) on the subsequent galaxy formation to be effective. A complete discussion on the issue of negative feedback can be found in [2].

3 High-z SNe and the Fate of Pop IIIIs

If stars more massive than $8M_\odot$ are born in the Pop III stellar cluster, supernovae will start to explode after a few million years. As discussed above, for a Salpeter IMF we expect about
$N = 2 - 20$ supernovae to blow off inside a Pop III object. The total mechanical luminosity of such a multi-SN explosion, approximated as a continuous energy injection, is of the order of $\epsilon_0 N / t_{OB} \simeq 0.6 - 6 \times 10^{37} \text{ erg s}^{-1}$ ([5]), where $\epsilon_0 \approx 10^{51} \text{ erg}$ is the energy of a single supernova explosion and $t_{OB} \approx 10^7 \text{ yr}$ 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 ([1]) by explosions: a number $N_c \approx M_5^{2/3} (1 + z)_{30} h^{12/5}$ of supernovae will suffice to disrupt the object. 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 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 Salpeter IMF is $\approx 3 M_\odot$ we estimate that the metallicity of the hot gas inside the IGM swept-up shell corresponding to a blow-away event driven by $N$ supernovae is

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

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 ([7]).

Interesting conclusions can also be drawn from the study of dust in the IGM, and, in particular, in Lyα clouds. In fact, if Pop III SNe act as metal polluters for the IGM, it is very likely that some dust (which is now firmly established to form in SN ejecta) is also injected at the same time. In a recent paper ([6]) we have investigated the possible observational consequences of dust in Lyα forest clouds. We relate the dust content, $\Omega_{d, Ly\alpha}$, to the metal evolution of the absorbers and assume that dust is heated by the ultraviolet background radiation and by the CMB. We find that the dust temperature deviates from the CMB temperature by at most 10% at redshift $z = 0$. The Lyα cloud dust opacity to redshift $\sim 5$ sources around the observed wavelength $\lambda_0 \sim 1 \mu m$ is $\sim 0.13$, and could affect observations of the distant universe in that band. The dust opacity as a function of redshift and wavelength for two different metallicity evolution scenarios is shown in Fig. 2. The expected CMB spectral distortions due to reradiation by high-$z$ dust in Lyα clouds is shown to be $\sim 1.25 - 10$ times smaller than the current COBE upper limit, depending on the metallicity evolution of the clouds.

4 Are dSphs Dead Pop III Remnants?

The final fate, and consequently the nature of the possible local counterparts of Pop III objects, are not yet clear. For example, 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. Nevertheless, it is conceivable that some of these primordial structures might have survived up to the present epoch. Clearly, the most suitable counterpart candidates are dwarf spheroidal galaxies (an extensive review on dSphs is given in [4]), which could be tentatively identified with Pop III objects that underwent blow-away but managed to survive merging into larger structures. This idea has also been proposed recently by [11]. It is tempting, therefore, to explore this hypothesis further by comparing different properties of the two classes of objects. This comparison is schematically shown in Fig. 3, where we consider seven different parameters: total mass, age, size, stellar mass, star formation history, metallicity and merging history; in the following we discuss them in detail and highlight possible problems and positive
Figure 2: Dust opacity as a function of the present observation wavelength. The curves refer to different values of the metallicity evolution parameter $q = 0$ (no evolution, solid lines), $q = 1$ (moderate evolution, dashed) and redshift $z = 5, 10, 20$ from the lowermost to the uppermost curves, respectively. For details see [6].

aspects of such identification. The expected initial gas mass (in units of $10^7 M_\odot$) of Pop III is $0.01 \lesssim M_{g,7} \lesssim 0.1$, where the lower limit is dictated by the cooling timescale condition for formation discussed above and the upper one corresponds to the largest mass that cannot escape blow-away. The last condition is shown in Fig. 4, in the plane $\phi - M_g$ ($\phi$ is the initial total to baryonic mass ratio of the object) along with the regimes in which either blow-out (essentially a wind rather that a complete ejection of the baryons as in the blow-away case, see [10]) or no mass loss is taking place. In addition, in Fig. 4 we have plotted the collapse redshift as a function of mass in a CDM model with spectrum power index $n = 2$; again, we see that above $z = 30$ the cooling time becomes larger than the Hubble time and hence the collapse of small objects is inhibited. If $\phi$ takes the cosmological dark-to-baryonic ratio $\Omega_b^{-1} = 16.6$ (dashed horizontal line in Fig. 4), then the above mass range shift into $0.1 \lesssim M_7 \lesssim 0.6$, where $M_7 = M/10^7 M_\odot$ is the total mass. The typical mass of dSph dark matter halos are instead in the range $1 \lesssim M_7 \lesssim 5$. However, for at least two galaxies (Fornax and Sculptor) the value of $\phi \ll \Omega_b^{-1}$; this could be explained by the fact that these galaxies have been formed in a gas rich environment in which baryonic accretion was relatively easy. These galaxies might have been initially in the blow-out regime, but after an outflow phase in which a fraction of the gas is lost, they entered the regime in which blow-away was unavoidable. We conclude that observed dSphs in principle could be associated with the high mass tail of the Pop III distribution; lower mass objects could be simply faint enough to have escaped detection to date. Pop III objects in the mass range overlapping dSphs form at redshift $z = 10 - 15$, corresponding to a present age of about 10 Gyr. Essentially all the dSphs in the Local Group show the presence of an old stellar population; however, in some of them (the prototypical example being Carina) the analysis of color-magnitude diagrams has convincingly demonstrated that at least one subsequent star
Are dSphs Dead Pop III Remnants?

A Tentative Scorecard

| Pop III | Properties | R | dSphs (LG) | Comments |
|---------|------------|---|------------|----------|
|         | Total Mass |   | "Universal" DM Halo? | dSphs: high M tail? |
| 0.01 < M< 1 | If φ = 1/Ω_b, 0.1 < M < 0.6 | | φ < 1/Ω_b,Fornax, Sculptor | Require low Total/Baryon Formation? Accretion? |
| Objects in interesting M range form | Age | ~ All show presence of old stellar population | Some show intemed. pop | Rejuvenation by accretion? |
| 10 < z < 15 | | | | |
| R ~ 4.5 [M^(1/3) / (1+z)] kpc ~ 200 pc | Size | R_c ~ 200 - 650 pc | Dynamic Exp. after Baway | Require low Total/Baryon |
| M* ~ (f_φ Μ_☉) ~ 600 - 6x10^7 M☉ | Stellar Mass | M* ~ (1-80)x10^7 M☉ | | |
| Single burst before Baway | SF History | Single-Multiple/Bursts | Environment? | |
| Larger objects form later using IGM enriched by smaller ones | Metallicity | [Me/H]= -2.5 / -1.0 | There is enough time between z=30 and z=10? | |
| Only few escape merging | Merging | Clustered around normal gals | Low M tail too faint or disappeared? | |

Figure 3: Comparison among various properties of Pop III objects and dwarf spheroidal (dSph) galaxies.

Figure 4: Regions in the φ – M_g plane in which blow-away, blow-out or mass loss respectively occur in a Pop III object. Also shown is the collapse redshift of the objects in a CDM model with n = 2 as a function of M_g; for redshift higher than z = 30 (dashed line) no collapse is possible. The horizontal line show the cosmological value of φ = Ω_b^{-1}.
formation episode might have taken place. This represents a serious problem for the blown-away Pop III scenario, which could be reconciled only if some rejuvenation by accretion or some other gas input to the system (returned from low mass stars?) is postulated. To alleviate the problem, it has to be noted that this intermittent star formation activity is not explained in detail by any current theoretical model. This particular star formation history might suggest, as for the low observed values of $\phi$, that dSphs might be Pop III that formed/lived in particularly high density environments. Sizes of the two classes of object are compatible, being of the order of tenths of kpc; again, dSphs are found to be slightly larger. Probably the major difficulty for the identification hypothesis is represented by the stellar content, which, as shown in Fig. 3, is about a factor of $\approx 10$ larger for dSphs. Implicitly, this discrepancy has its roots once again in the fact that dSphs are more baryon-rich than canonical Pop IIIs. Finally, the metallicity-mass relation commonly observed in dSphs can be qualitatively explained in the framework of hierarchical structure formation models: in fact, as larger objects form, they use IGM previously metal enriched by smaller ones. The time interval required for the metallicity build-up does not seem to represent a particular problem between redshift 30 and 10, when the oldest generation of stars has to be in place. As mentioned above, some of the Pop IIIIs must be swallowed/merged into larger objects; the fraction of them that has survived such events can be rather small.

Clearly, the comparison carried out in Fig. 3 and in its relative discussion can be seen only as a tentative scorecard and it remains highly speculative. Nevertheless, it is clear that a one-to-one identification between Pop III objects, as theoretical predictions describe them, and dSph galaxies, as we observe them today, appears to be difficult to maintain.

References

[1] Ciardi, B., & Ferrara, A. 1997, ApJ, 483, 5
[2] Ciardi, B., Ferrara, A. & Abel, T. 1998, ApJ, submitted
[3] Couchman, H. M. P. & Rees, M. J. 1986, MNRAS, 221, 53
[4] Ferguson, H, & Binggeli, B. 1994, A&ARv, 6, 67
[5] Ferrara, A. 1998, ApJ, 499, L17
[6] Ferrara, A., Nath, B., Sethi, S. & Shchekinov, Y. 1998, MNRAS, submitted
[7] Gnedin, N. & Ostriker, J. P. 1997, ApJ, 486, 581
[8] Haiman, Z., Rees, M. J., & Loeb, A. 1997, ApJ, 476, 458
[9] Haiman, Z., Rees, M. J., & Loeb, A. 1997, ApJ Erratum, 484, 985
[10] MacLow, M. M. & Ferrara, A. 1998, ApJ, submitted
[11] Miralda-Escudé, J. & Rees, M. J. 1998, ApJ, 497, 21
[12] Tegmark, M., Silk, J., Rees, M.J., Blanchard, A., Abel, T. & Palla, F. 1997, ApJ, 474, 1