Mem. S.A.It. Suppl. Vol. 5, 307

Memorie della
Supplementi

The Cosmic Dawn: from first stars to the the observable universe

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Abstract. The first stars that are able to form in the Universe represent the first sources of light, heat and metals. For these reasons they play a fundamental role in cosmic evolution, affecting the properties of subsequent generations of stars as well as the physics on the intergalactic medium. We will discuss the main physical properties of the first stars, their impact on the overall evolution of the Universe and the relevant observational consequences.

Key words. Cosmology: theory – Galaxies: evolution – Stars: formation

In the last decade with the advent of 10m class telescopes and of sensitive IR instruments the epoch of galaxy formation became observationally accessible. Thousands of high-redshift galaxies have been discovered, covering the full redshift range up to $z \approx 6$, when the Universe was less than a Gyr old. These observations confirmed theoretical expectations that galaxy formation is a gradual process and that big galaxies build up by merging of smaller galaxies. At the same time, a cosmological standard model has been established which predicts that this process should have started at much earlier times than probed by the highest redshift galaxies observed so far. This theoretical prediction has been taken much more seriously since spring 2003, when the *Wilkinson Microwave Anisotropy Probe* (WMAP) satellite team announced its discovery that the Cosmic Microwave Background (CMB) fluctuations are polarized on the largest scales, indicating that hydrogen reionization occurred as early as $z \approx 20 - 30$. The exciting period of the Cosmic Dawn, when the Universe undergoes its transition from a state where it is filled by a featureless gas of neutral hydrogen and helium (the so-called Dark Ages) to the transparent Universe full of stars and galaxies which we observe nearby, is yet to be explored. This period hosts a number of important processes: the birth of the first stars, supernovae and black holes; the first ultraviolet/ionising photons emitted by stars and/or black holes start the process of cosmic reionization; a large number of radiative, mechanical and chemical feedback processes shape the formation and evolution of galaxies later on. Many of these processes have only recently started to be seriously investigated. So far, we can only give very crude and uncertain answers to fundamental questions such as: when and where did the first stars form? What were their masses and properties? To what extent did they affect cosmic reionization and metal enrichment? Do intermediate-mass black holes originate from

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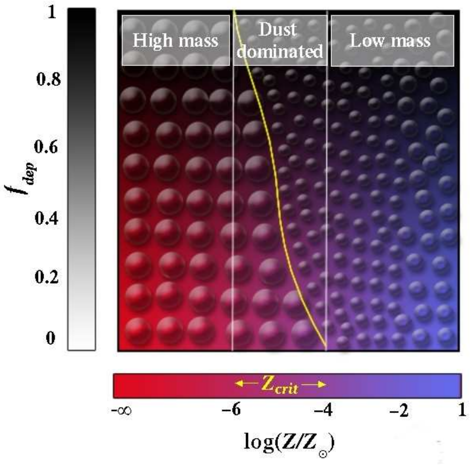

Fig. 1. Critical metallicity regimes in the metallicity (Z) - dust depletion factor ($f_{\rm dep}$), plane. See text for explanations.

the collapse of such stars? Addressing these questions successfully is key to understanding the transition from the Dark Ages to the present-day Universe.

1. The first stars

Recent theoretical studies consistently predict that the first, so-called Population III (Pop III), stars had characteristic masses of 100-600 $M_\odot$, i.e. about 100 times more massive than those observed today. The basis for this claim is that (i) the fragmentation scale of metal-free clouds is typically 10^3 $M_\odot$ (Abel et al. 2002; Bromm et al. 2002); (ii) because of the absence of dust grains the radiative feedback from the forming star is not strong enough to halt futher gas accretion (Omukai & Palla 2003); (iii) since the accretion rate is as large as $10^{-2}-10^{-3}$ $M_\odot{\rm yr}^{-1}$, the star grows up to $\gg 100 M_\odot$ within its lifetime (Stahler et al. 1986; Omukai & Nishi 1998; Ripamonti et al. 2002).

The detection of these very early cosmic star formation records represents the central goal of future instrumental facilities. Already today, however, a number of indirect evidences which include the amplitude and anisotropy of the Near-Infrared Background (NIRB) (Salvaterra & Ferrara 2003; Magliocchetti et al. 2003) and the failure to find any zero-metallicity star in our Galaxy halo (Bond 1981; Beers 1999) strongly support the theoretical scenario above.

On the other hand, observations in the present-day universe show that Population I (Pop I) stars form according to a Salpeter initial mass function (IMF) with a characteristic mass of $\sim 1 M_\odot$, below which the IMF becomes flatter (Larson 2003).

It has been shown that one of the key elements that control the transition from a top-heavy to a more conventional 'Salpeter-like' IMF is represented by the metallicity of the star-forming gas (Bromm et al. 2001; Schneider et al. 2002; Schneider et al. 2003). The fragmentation properties of the collapsing clouds change as the mean metallicity of the gas increases above a critical threshold, $Z_{\rm cr}$. Clouds with $Z < Z_{\rm cr}$ fragments only to massive (> 100 $M_\odot$) cores, whereas in clouds with $Z > Z_{\rm cr}$ lower mass fragments can be formed. Omukai (2000), Schneider et al. (2002) and Schneider et al. (2003) have thoroughly investigated the thermal evolution of star forming gas clouds with different initial compositions, implementing a complex network of chemical reactions which includes more than 40 species and 400 reactions. According to these detailed studies, the transition between the two fragmentation modes takes place in the metallicity range 10^{-6} – 10^{-4} $Z_\odot$. Low-mass cores are formed by fragmentation induced by dust cooling, which becomes efficient at high densities ($n \gtrsim 10^{11}{\rm cm}^{-3}$). Consequently, the critical threshold is essentially set by the amount of dust grains rather than by the average metallicity. The general picture emerged from these studies is summarized schematically in Fig. 1. The x-axis represents values of the mean metallicity of the star-forming gas and the y-axis indicates the fraction of metals depleted onto dust grains, $f_{\rm dep} = M_{\rm gr}/M_{\rm Z}$ (where $M_{\rm gr}$ and $M_{\rm Z}$ are the mass in dust grains and in metals, respectively). The circles of different size indicate the characteristic mass-scale resulting from fragmentation. For a gas of primordial composition, the only efficient coolant is molecular hydrogen. Cooling due to molecular line emission becomes inefficient at densities $n > 10^3$ cm^{-3}, and the fragment mass of order 10^3 $M_\odot$ is imprinted at this epoch. Clouds with mean metallicity $Z \leq 10^{-6}$ $Z_\odot$ follow exactly the same evolution as the metal-free gas: regardless of the amount of metals depleted onto dust grains, the gas fragments into high-mass cores. For $10^{-6} < Z_{\rm cr}/Z_\odot < 10^{-4}$ the presence of dust becomes important and the fragmentation mode depends strongly on the value of $f_{\rm dep}$ as well as the initial density fluctuation. Indeed, if a sufficient fraction of metals is depleted onto dust grains, the collapsing clumps with initial large fluctuations can experience a new phase of fragmentation at high densities which is driven by thermal emission from dust grains. In this case, fragmentation into low-mass cores occurs at the opacity limit, with characteristic masses of $0.01-0.1$ $M_\odot$ that depend on the metallicity only very weakly. Finally, for $Z \geq 10^{-4}$ $Z_\odot$ the amount of metals in the gas phase is high enough to enhance the cooling efficiency of the gas and fragmentation proceeds down to the opacity limit where characteristic mass-scales are $0.01 - 0.1$ $M_\odot$. Note that these represent the minimum possible values as fragmentation may proceed less efficiently or the cores may grow in mass also by accretion.

2. The Chemical Feedback

We always refer to Pop III stars as stellar objects in the mass range 100-600 $M_\odot$ forming out of the collapse of $Z < Z_{\rm cr}$ gas clouds and to PopII/I stars as to stars forming from the collapse of $Z > Z_{\rm cr}$ gas clouds according to a Salpeter IMF. Still, very little is known about the shape of the IMF in primordial star forming regions. However, at least a fraction of the first stars must have masses in the range $140 - 260$ $M_\odot$ to avoid the so-called *star formation conundrum* (Schneider et al. 2002). Stellar evolution studies have shown that stars with mass below 140 $M_\odot$ (but larger than 50 $M_\odot$) and above 260 $M_\odot$ cannot avoid complete collapse to black holes and are unable to eject their metals (Heger & Woosley 2002). Conversely, metal-free stars with mass in the range $140 - 260$ $M_\odot$ are completely disrupted in pair-instability supernova explosions (PISN) and eject about half of their initial mass in heavy elements. The ashes of these first supernova explosions pollute with metals the gas out of which subsequent generations of low-mass PopII/I stars form, driving a transition from a top-heavy IMF to a 'Salpeter-like' IMF.

Thus, the cosmic relevance of Pop III stars depends on the efficiency of metal enrichment from the first stellar explosions, the so-called *chemical feedback*, which is strictly linked to the number of Pop III stars that explode as PISN, the metal ejection efficiency, diffusion and mixing in the IGM. If a large fraction of first stars is nucleosynthetically sterile and ends up with the formation of very massive black holes (VMBHs), then the chemical feedback is less efficient and the transition from PopIII star formation epoch to PopII/I star formation epoch (or, equivalently from a top-heavy IMF to a 'Salpeter-like' IMF) can be delayed. This scenario seems to be required to account for the amplitude and anisotropy excess observed in the NIRB, (Salvaterra & Ferrara 2003).

It is very likely that the transition occurred rather smoothly because the process of metal enrichment is highly inhomogeneous (Madau et al. 2001; Scannapieco et al. 2002). Even at moderate redshifts, $z \approx 3$, the clustering properties of CIV and SiIV QSO absorption systems are consistent with a metal filling factor of 10%, showing that metal enrichment is incomplete and inhomogeneous (Schaye 2003).

As a consequence, the use of the critical metallicity as a global criterion is somewhat misleading because chemical feedback is a *local process*, with regions close to star formation sites rapidly becoming metal-polluted and overshooting $Z_{\rm cr}$, and others remaining essentially metal-free. Thus, PopIII and PopII/I star formation modes could have been coeval and detectable signatures from PopIII stars could continue well after the volume-averaged metallicity has become larger than critical (Scannapieco et al. 2003).

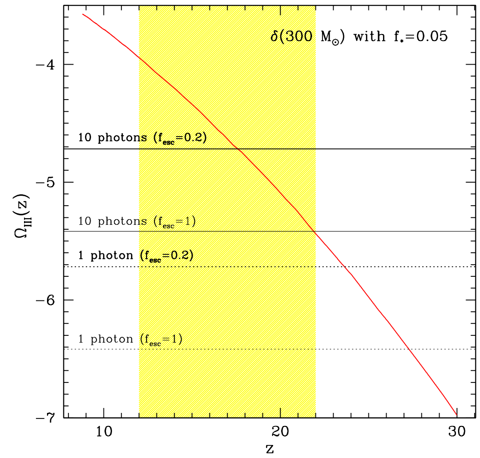

Fig. 2. Density evolution of Pop III stars as a function of redshift obtained by fitting the NIRB data assuming that (i) PopIII stars form with an efficiency of 5% and (ii) their IMF is a delta function peaked at 300 $M_{\odot}$. This quantity is compared with the density of baryons in Pop III stars of 300 $M_{\odot}$ required to ionize the Universe for different values of photon/baryon ratio and $f_{\rm esc}$. The shaded area indicates the *WMAP* constraints.

3. Detectable Consequences

3.1. Reionization

Zero-metallicity stars are efficient sources of ionizing photons (Tumlinson & Shull 2000; Schaerer 2002), particularly if they have masses $M \geq 100 M_{\odot}$. Renewed interest on the importance of PopIII stars in the process of cosmic reionization has been recently induced by the high optical depth to Thomson scattering ($\tau_e = 0.17 \pm 0.04$) measured by the *WMAP* satellite (Kogut et al. 2003; Spergel 2003). Assuming that reionization occurred instantaneously, these values imply reionization redshifts in the range 13 - 19, much earlier than previously thought.

Although the WMAP τ_e value can be reproduced by models assuming metal free, but not very massive, stars only (Ciardi et al. 2003), several scenarios have been proposed in which PopIII stars are involved (Cen 2003; Haiman & Holder 2003; Wyithe & Loeb 2003; Ricotti & Ostriker 2004). For a model to succeed, the PopIII star formation phase should be sufficiently long, namely chemical feedback should not be too severe. This requires a PopIII IMF biased towards the formation of nucleosynthetically sterile stars. These stars contribute to the ionizing photon budget but do not generate chemical or mechanical feedbacks associated with PISN.

Salvaterra & Ferrara (2003) have shown that PopIII stars with mass of 100 – 1000 $M_{\odot}$ can account for the observed NIRB excess[1] if the bulk of their formation stops around $z \sim 9$. Within this scenario, it is straightforward to estimate the impact of PopIII stars on the reionization process. In Fig. 2 we report the density evolution of PopIII stars density required to match the NIRB total intensity (Salvaterra & Ferrara 2003) and fluctuations (Magliocchetti et al. 2003). If we assume that 10 photons/baryon are required to keep the universe ionized and an escape fraction of ionizing photons from galaxies $f_{\rm esc} = 0.2$, we find a reionization redshift ~ 18, in agreement with *WMAP* data. Moreover, the IGM will remain ionized down to $z \sim 9$. This redshift marks the transition from a star formation epoch dominated by regions with $Z < Z_{\rm cr}$ to an epoch in which star formation occurs predominantly in regions with $Z > Z_{\rm cr}$. Below this redshift, the ionizing power of metal-free stars drops and the universe can partially or totally recombine.

[1] The redshift width of the transition depends on the uncertainty in the optical background determination.

3.2. Extremely metal-poor halo stars

According to the critical metallicity scenario, stars with a metallicity below $Z_{\rm cr}$ should not be observed in the local neighbourhood as only massive, short-living stars are formed under those conditions. Indeed, no star is found in the Galaxy with $Z < Z_{\rm cr}$. A puzzling case is the recently discovered HE0107-5240, a 0.8 $M_{\odot}$ star with [Fe/H]=−5.3, but [C/Fe]=4.0 and [N/Fe]=2.3 (Christlieb et al. 2002). *Does the existence of this star suggest that PopIII also contained low-mass and long-lived objects?* To answer this question, we should be able to infer the metallicity of the gas cloud out of which HE0107-5240 formed from the abundance of the elements observed on its surface.

The origin of C and N can be twofold: (i) either these elements were already present in the parent gas cloud or (ii) their origin is due to a post-formation mechanism (Siess et al. 2002) such as mass transfer from a companion star, self-enrichment from the star itself (Fujimoto et al. 2000) or accretion due to repeated passage through the Galactic disk, (Yoshii 1981).

In the first scenario, the star parent cloud would have had a metallicity $Z = 10^{-2}Z_{\odot}$, significantly higher than $Z_{\rm cr}$. This explains the low-mass of the star. Moreover, Umeda & Nomoto (2003) have shown that the metal yields released by zero-metallicity stars with masses in the range $\sim 25 - 130\ M_{\odot}$ exploding as subluminous Type-II SNe can provide a good fit to HE0107-5240 abundance pattern.

In the second scenario, only the elements heavier than Mg, which can not be synthetized in the interior of such a low-mass star, were already present before its formation. The composition of these elements can be equally well reproduced by the predicted elemental yields of either a $20 - 25\ M_{\odot}$ star that exploded as a Type-II SN (Christlieb et al. 2002) or of a $200 - 220\ M_{\odot}$ star that exploded as a PISN (Schneider et al. 2003). Thus, HE0107-5240 may have formed from a pre-enriched gas cloud with $10^{-5.5} \lesssim Z/Z_{\odot} \lesssim 10^{-5.1}$. These values fall within the proposed range for $Z_{\rm cr}$. Indeed, more than 20 % of the metals released by a 220 $M_{\odot}$ PISN are able to condense in dust grains (Schneider et al. 2003; Schneider et al. 2004) and a star of 0.8 $M_{\odot}$ like HE0107-5240 can be a remnant of the dust-dominated fragmentation mode (see Fig. 1).

4. Final Remarks

In this paper, we have discussed the evidences for the existence of a critical metallicity affecting the mass properties of forming stars and its impact on the cosmic star formation history through the so-called chemical feedback. We can summarize the main results as follows: (i) the metallicity has a major impact on the process of star formation, both in the fragmentation phase of the parent cloud and in the accretion phase onto the protostellar core (ii) the critical metallicity $Z_{\rm cr} = 10^{-5\pm1}Z_{\odot}$ marks a transition between a high-mass ($Z \leq Z_{\rm cr}$) to a low-mass ($Z \geq Z_{\rm cr}$) star formation mode. Within the critical range $10^{-6}Z_{\odot} < Z < 10^{-4}Z_{\odot}$, the resulting stellar mass depends on dust depletion factors (dust-dominated fragmentation mode) and can be as high as a few 100 $M_{\odot}$ or as small as 1 $M_{\odot}$ (iii) chemical feedback is fundamentally local, with regions close to star formation sites rapidly becoming metal-polluted and overshooting $Z_{\rm cr}$, and others remaining essentially metal-free.

Thus, the use of the critical metallicity as a global principle is somewhat misleading: PopIII and PopII/I star formation modes could have been coeval and detectable signatures from PopIII stars could continue well after the volume-averaged metallicity has become larger than critical.

Acknowledgements. This work has been achieved through fruitful collaborations and discussions with Andrea Ferrara, Kazuyuki Omukai and Ruben Salvaterra.

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