Mem. S.A.It. Vol. 85, 467

**Memorie** della

# Local Cosmology

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**Abstract.** Our current understanding of the formation of the *first* stars, *first* galaxies, and *first* long-lived low-mass stars, will be briefly reviewed in this theoretical introduction to the Symposium "Local Group, Local Cosmology". I will underline the links between the most solid theoretical findings and the key observations of metal-poor stars and galaxies, further clarifying the purpose of the Symposium. Some of the open questions that might be addressed by exploiting the synergy between theoretical predictions and Local Group observations will be analyzed, and then discussed in more details by our invited and targeted speakers that are contributing to the present volume.

**Key words.** Stars: abundances – Stars: Population III – Stars: carbon-enhanced stars – Galaxy: abundances

## 1. Introduction

Unveiling the nature of the first cosmic objects represents one of the key challenges of modern Cosmology. Yet, despite the huge theoretical efforts in this very active research field, many fundamental questions related to the formation and evolution of the first stars and galaxies remain unsolved. This is primary due to the lack of *direct* observational probes from these extremely remote epochs.

Luckily, ancient metal-poor stars and galaxies dwelling in the Local Group, can be directly observed. The properties of these living fossils that formed more than 10 billion year ago, have been found to provide fundamental insights on the nature of the first cosmic sources. Thus "Local Cosmology" represents a complementary approach to overcome the current limitations of space and ground-based telescopes, and to *indirectly* study the properties of these undetectable distant sources.

## 2. The first stars

Cosmological simulations of the first stars in the standard ΛCDM framework (e.g. Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2006, 2008) have converged upon showing that primordial gas clouds form at $z \approx 20-30$ in the first $T_{vir} < 10^4$ K "minihaloes", which can cool down their gas via molecular hydrogen, $H_2$, only. The gravitational fragmentation of the gas clouds is found to be halted at a characteristic thermodynamic state that *solely* depends on the micro-physics of $H_2$ molecules, and that sets the mass of the proto-stellar gas clouds at $M_J \approx 500 M_\odot$ (Bromm et al. 2009, and references therein).

In other words, the initial stage of the primordial star-formation process has been firmly established.

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However, the subsequent gas accretion phases onto the proto-star and the resulting final stellar products, are substantially affected by different physical processes (e.g. radiative feedback, turbulence, stellar rotation, magnetic-field) that cannot be yet resolved and/or simultaneously captured. It follows that hydro-dynamical simulations designed to study the formation of the first stars, but accounting for different physical processes, yield contrasting results (e.g Hosokawa et al. 2011; Greif et al. 2011; Turk et al. 2012; Hirano et al. 2014).

In conclusion, the final mass of the first stellar generations is still largely debated and their Initial Mass Function (IMF) is unknown. Nevertheless, most of the numerical results seem to suggest that the first (Pop III) stars were likely more massive than today forming stars (Pop II), with a characteristic stellar mass $M_{ch} > 10 M_{\odot}$.

## 3. The first low-mass stars

The massive nature of Pop III stars implies that these objects were short lived, and hence they rapidly disappeared. These predictions are supported by the persistent deficiency of zero metallicity stars in the available stellar sample.

The most metal deficient star ever, indeed, has total metallicity $Z = 10^{-4.5} Z_{\odot}$ (Caffau et al. 2011). Different groups have studied the physical mechanisms driving the transition from such a massive star-formation mode to a more normal one. Their findings show that metals *and* dust grains are the key cooling agents triggering this process. In presence of dust the first low-mass stars can form when the metallicity of the star-forming clouds is as low as $Z_{cr} = 10^{-5\pm1} Z_{\odot}$ (e.g. Schneider et al. 2002, 2006; Omukai et al. 2005, 2010; Clark et al. 2008; Hocuk & Spaans 2010; Dopcke et al. 2011), while when metals are the only available coolant $Z_{cr} = 10^{-3.5} Z_{\odot}$ (e.g. Bromm et al. 2002, 2003; Santoro & Shull 2006).

Both these results imply that among today lived ancient metal-poor stars there must be second-generation objects, which formed out from an inter-stellar medium (ISM) only enriched by the first stars. Chemical abundance studies of second-generation stars may provide direct measurements of the elements released by this extinguished stellar generation.

## 4. The first galaxies

Cosmological simulations of the first cosmic sources jointly predict that low-mass, $M \approx 10^6 - 10^7 M_{\odot}$, $H_2$-cooling minihaloes were the first sites for primordial star-formation. As soon as massive first stars formed, however, copious amounts of UV photons were produced, and they started to photo-ionized and photo-heated the surrounding medium, and to photo-dissociated $H_2$ molecules (e.g. see Ciardi & Ferrara 2005, for a review on feedback processes). Thus, the star-formation in minihaloes was possibly quenched on very short timescales. Following reionization furthermore, gas accretion was suppressed in more massive dwarf galaxies (e.g. Gnedin 2000; Okamoto et al. 2010; Noh & McQuinn 2014). The strenght of these radiative feedback effects crucially depends on different physical processes, such as the flux of ionizing and photo-dissociating photons (Lyman Werner, 11.2 – 13.6 eV), the clustering of the haloes, and their gas density and metallicity (e.g. Bromm & Yoshida 2011). So, what is the minimum mass of haloes that can efficiently form stars and turn into luminous galaxies, and how it evolves during the cosmic time is still highly debates (e.g. Sobacchi in this volume).

## 5. Key observational probes

Ancient metal-poor stars *and* dwarf galaxies can be used to test theoretical predictions and to further characterize the first cosmic sources and their feedback effects. In this Section, I will discuss the implications and open questions arising from observations of Galactic halo *very metal-poor stars*, and nearby and more distant *very metal-poor galaxies*, i.e. the Milky Way dwarf spheroidal satellites (dSphs), and Damped Ly$\alpha$ Absorption systems (DLAs).

### 5.1. Very metal-poor stars

Ancient very metal-poor stars, [Fe/H]$\leq -2$, have been observed in both the stellar halo (e.g Beers & Christlieb 2005) and nearby dSphs (e.g Tolstoy, Tosi & Hill 2009). Comparisons between their observed properties and merger tree models for the early formation of the Milky Way have provided important constraints on the primordial IMF and $Z_{cr}$ value (e.g. Tumlinson 2006; Salvadori et al. 2007; Komiya et al. 2009). The recent discovery of the most metal-deficient star ever requires $Z_{cr} < 10^{-4} Z_{\odot}$ (i.e. Salvadori & Ferrara 2012b), thus implying that the formation of the first low-mass stars must rely on dust. However, the "ordinary" chemical abundance pattern of this star is consistent with that derived for more metal-rich halo stars, and suggests that this object must have formed from a well mixed ISM (Caffau et al. 2012). This result poses the questions on what and where are second-generation stars, and reinforces the puzzle on the origin of "Carbon-enhanced" stars, whose frequency and C-excess increases at decreasing iron-abundances (e.g. T. Beers in this volume).

### 5.2. Very metal-poor dSphs

Local Group dwarf spheroidal galaxies (dSph) are perfect laboratories to study the strength of feedback processes, which are more effective in low-mass systems. In particular the least luminous, least massive, and least metal-rich ultra-faint dwarf galaxies (UFs, e.g. Kirby et al. 2008) represent key objects to understand radiative feedback processes and early cosmic star formation (Salvadori 2012). These extreme systems have been proposed to be the oldest galaxies in the Local group, i.e. the living fossils of the first $H_2$-cooling minihaloes, which withstood radiative feedback processes and managed to form stars during the epochs of reionization, $z > 6$ (e.g. Salvadori & Ferrara 2009; Munoz et al. 2009; Bovill & Ricotti 2009, and his contribution in this volume). These theoretical expectations have been confirmed by pioneering studies of star-formation histories (SFHs) in UFs, which revealed the unique presence of stellar populations > 12.5 Gyr old (Dall'Ora et al. 2012; Okamoto et al. 2012; Brown et al. 2012, and his contribution in this volume). This implies that the SFHs of ultra-faint dwarf galaxies can be used to put constraints on the minimum halo mass of luminous galaxies, and its evolution.

### 5.3. Very metal-poor DLAs

Damped Ly$\alpha$ Absorption systems (DLAs) are dense reservoirs of neutral hydrogen gas, detected in the spectra of distant quasars (e.g. Wolfe et al. 2005). The most metal-poor among these absorbers show intriguing chemical properties, which can be linked with the early cosmic times. First, one of these very metal-poor DLAs likely exhibits a Carbon-excess (Cooke et al. 2011b; Carswell et al. 2012), which might reflect the imprint by either primordial supernovae (Kobayashi et al. 2011) or low-metallicity AGB stars (Salvadori & Ferrara 2012a). Second, all the other $\approx 22$ DLAs with [Fe/H]$< -2$ show *gas* chemical abundance ratios that are in agreement with those measured in Galactic halo *stars*, and that are constant over a wide range of redshifts, $z \approx 2-5$ (Cooke et al. 2011a; Becker et al. 2012, and Pettini in this volume). These findings suggest that these systems might be the gas-rich and star-less counterpart of UFs, i.e. the descendant of low-mass $H_2$-cooling minihaloes that "succumbed" to radiative feedback and passively evolved since their formation epoch (Salvadori & Ferrara 2012a). If confirmed, this idea would imply that very metal-poor DLAs can provide complementay constraints on the evolution of the minimum halo mass for star formation.

## 6. Concluding remarks

Observations of metal-poor stars and galaxies are providing exciting results, which can be connected among each other and linked with the properties of the first cosmic sources by global model for galaxy formation. This is a golden era for "Local Cosmology", which might deliver important discoveries by exploiting the synergy between theory and observations, and between different research fields.

Begin to develop this collaborative interaction has been the main aim of our Symposium.

*Acknowledgements.* I am grateful to Matteo Monelli, who dragged me into this new adventure, sharing with me laughs, fears, and his amazing talent to keep cool in all circumstances. I acknowledge the Netherlands Organization for Scientific Research (NWO) for financial support through a VENI grant 639.041.233.

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