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Bridging the near and the far: constraints on first star formation from stellar archaeology

R. Schneider[1,2]

[1] Dipartimento di Fisica, Sapienza Università di Roma, P.le A. Moro 2, 00185 Roma, Italy
[2] INAF/Osservatorio Astronomico di Roma, Via di Frascati 33, 00078 Monteporzio Catone, Rome, Italy, e-mail: raffaella.schneider@uniroma1.it

Abstract. In his book with Steve Stahler, Francesco introduced the section on first stars writing: *"As we extend our investigation to the formation of the first stars, we reach the limits, in both time and space, of current knowledge."* In my contribution, I will present some recent progresses that we have made in understanding the nature of the first stars through stellar archaeology. The observed metallicity distribution function of Galactic halo stars and the relative fraction of carbon-normal and carbon-enhanced metal poor stars allow to constrain the initial mass function of the first stars, the nature of the first supernovae and the physical processes that drive the transition to a more conventional mode of star formation.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population III – Galaxy: halo – Galaxy: abundances

1. Introduction

During the last decades, surveys looking for very metal-poor stars, with [Fe/H] < -2, have explored the stellar halo of our Galaxy. One of the main outcomes of these surveys has been the determination of the Metallicity Distribution Function (MDF), namely the number of stars as a function of their iron abundance, [Fe/H], which is used as a metallicity tracer (Beers & Christlieb 2005; Schörck et al. 2009; Yong et al. 2013).

These extremely metal-poor stars are of key importance to understand the early chemical enrichment processes. In particular, it has been shown that the shape of the low-[Fe/H] tail of the Galactic halo MDF can shed new light on the properties of the first stellar generations, and on the physical processes driving the transition from massive Population III (Pop III) stars to normal Population II (Pop II) stars (Salvadori et al. 2007; de Bennassuti et al. 2014, 2017). In Fig. 1, we show the most recent determinations of the low-Fe tail of the Galactic halo MDF as derived by various groups which exploited different data-sets. By normalizing the MDFs to the same cumulative number of stars at [Fe/H] $= -3$, we compare the results from different surveys. The observed MDF rapidly declines with decreasing [Fe/H], exhibits a sharp cut-off at [Fe/H] $= -4.2$ and a low-Fe tail made by 9 stars that extends down to [Fe/H] $= -7.2$.

Interestingly, 8 out of the 9 Galactic halo stars identified at [Fe/H] < -4.5 show high overabundance of carbon, [C/Fe] > 0.7, and all of them can be likely classified as "CEMP-no" stars. CEMP-no stars do not show s-process elements that are produced by AGB

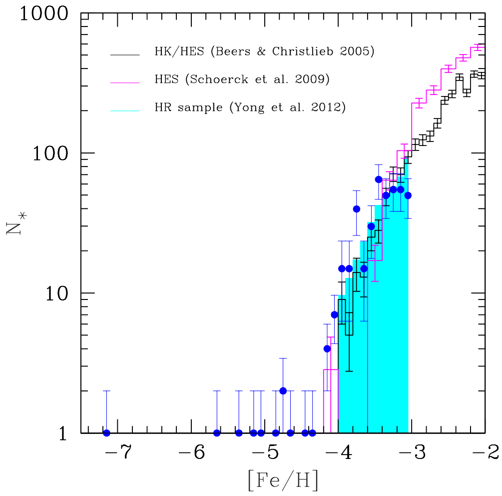

Fig. 1. The Galactic halo MDFs obtained using different data-sets and normalized to the same number of stars at [Fe/H] = −3. Histograms show the result from the HK and HES surveys (black, Beers & Christlieb 2005) the HES survey corrected for observational biases and incompleteness (magenta, Schörck et al. 2009), the homogeneous sample of high-resolution (HR) spectroscopic data from Yong et al. (2013, shaded cyan). The blue points show the uncorrected sample by Yong et al. (2013) to which we added HR data for [Fe/H] < −4 stars from more recent literature. The figure is reproduced from de Bennassuti et al. (2017).

stars, they are not preferentially associated to binary systems, and they most likely appear at low [Fe/H] (Placco et al. 2013; Yong et al. 2013). For these reasons, the chemical abundances measured in their photo-spheres are believed to reflect their formation environment, which was likely polluted by Pop III stars that developed mixing and fallback evolving as "faint SNe" (Umeda & Nomoto 2003; Iwamoto et al. 2005; Marassi et al. 2014) or by primordial spinstars, which experienced mixing and mass-loss because of high rotational velocities (Maeder et al. 2015).

The questions that naturally arise from these observations are:

(i) what is the origin of CEMP-no stars?
(ii) what are the physical processes that shape the low-[Fe/H] tail of the MDF?
(iii) why does the CEMP-no fraction decrease with [Fe/H]?

2. Simulating the birth environment of C-normal and C-enhanced stars at extremely low [Fe/H]

To address the first question, we have explored the formation pathway of SDSS J102915+172927, ([Fe/H] = −4.73, [C/Fe] < 0.93), the most iron-poor C-normal star identified so far (Caffau et al. 2011), and of SMSS J031300.36-670839.3 ([Fe/H] < −7.1, [C/Fe] = 4.9), the most iron-deficient CEMP-no star (Keller et al. 2014). We first identified plausible Pop III SN models by matching the predicted metal yields with the observed surface elemental abundances. We found that SDSS J102915 is best matched by core-collapse SN models with progenitor masses of 20 and 35 $M_\odot$ (Schneider et al. 2012a), while SMSS J031300.36 requires more massive Pop III stars, with 50 and 85 $M_\odot$, that explode as faint SNe, with mixing and fallback (Marassi et al. 2014). For each of these SN models, we have estimated the amount of freshly formed dust produced in the ejecta and the fraction of this that is able to survive the passage of the SN reverse shock, enriching the surrounding interstellar medium. We found that while in ordinary core-collapse SNe the grains are mostly silicates, with condensation fractions in the range $0.2 \leq f_{\rm sil} \leq 0.6$, the carbon-rich ejecta of faint SNe favor the formation of carbon grains, with condensation fractions $0.01 \leq f_{\rm carb} \leq 0.84$. The range of values reflects differences in the SN explosion and reverse shock models, which lead to differences in the condensation and destruction efficiencies (Schneider et al. 2012a; Marassi et al. 2014). For each combination of metal and dust composition, we then explored the thermodynamical evolution of a collapsing gas cloud, assumed to be the parent birth cloud of either SDSS J102915 or SMSS J031300.36. The impact of metals and dust on the thermodynamic evolution of collapsing gas concentrations has been studied by a number of authors, to understand the metallicity range and the physical processes responsible

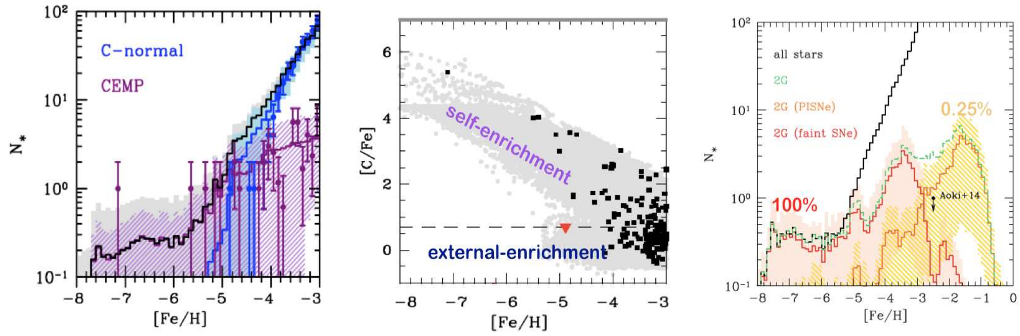

Fig. 2. Comparison between model predictions and observations. The left panel shows observed (points with poissonian errorbars) and simulated (histograms with shaded areas) Galactic halo MDFs, where we differentiate the contribution of C-enhanced (purple histograms/points) and C-normal (blue histograms/points) stars. The middle panel shows the stellar [C/Fe] vs [Fe/H] measured in Galactic halo stars (black squares) and obtained in 50 realizations of our fiducial model (grey dots). The red triangle shows the upper limit for the only C-normal metal-poor star observed at [Fe/H] < -4.5 so far. The line shows the value of [C/Fe]= 0.7, which discriminates between CEMP-no and C-normal stars. The right panel shows the simulated average MDF for all stars (black histogram) and for second generation (2G) stars (dashed green histogram), selecting them as stars formed in environments where metals come mostly ($> 50\%$) from Pop III stars. The red (orange) histogram represents 2G stars with a dominant ($> 50\%$) metal contribution from Pop III faint SNe (PISNe). The figure is adapted from de Bennassuti et al. (2017).

for deviating the evolution from that of metal-free Pop III case. Idealized, one-zone thermodynamic models generally suggest that once the gas metallicity has exceeded some critical value $Z_{\rm cr}$, the thermodynamical behaviour, and thus the characteristic fragmentation mass, changes drastically, either due to metal line cooling ($Z_{\rm cr} \sim 10^{-3.5} Z_{\odot}$) or due to the onset of gas-dust collisional coupling ($Z_{\rm cr} \sim 10^{-6} Z_{\odot}$). Using the model presented in Omukai et al. (2005) and adopted in Schneider et al. (2012b), we found that the collapsing star forming clouds experience a first phase of fragmentation at central densities $n_{\rm H} \sim 10^4 - 10^7$ cm^{-3}, that is either due to CI and HD cooling (for the CEMP-no star SMSS J031300.36) or to OH cooling (for the C-normal star SDSS J102915). The newly formed fragments have masses of $\sim 10-100\,M_{\odot}$ and continue to collapse until, at central densities of $n_{\rm H} \sim 10^{10}-10^{14}$ cm^{-3}, dust cooling is able to activate a second phase of fragmentation where sub-solar mass fragments are able to form. Hence, we find that the formation of both C-rich and C-normal stars, even at lowest [Fe/H] currently observed, can follow a thermal pathway, where either carbon or silicate dust cooling is able to efficiently fragment the gas, giving birth to low-mass stars.

3. Probing high-z star formation with stellar archaeology

The above results have been obtained under the implicit assumption that the most iron-poor stars populating the low-[Fe/H] tail of the MDF are truly second-generation stars, i.e. they have been polluted by metals released by one or a few Pop III SN explosions. To confirm or disprove this assumption, detailed models predicting the formation history of the Milky Way (MW) halo are required. To this aim, we have used an improved version of the semi-analytical code GAlaxy MErger Tree and Evolution (GAMETE), originally developed by Salvadori et al. (2007), and later improved by Salvadori et al. (2008); Salvadori & Ferrara (2009); Salvadori et al. (2014); de Bennassuti et al. (2014, 2017). GAMETE reconstructs the hierarchical merger tree of the MW, following the star formation history and the metal and dust evolution in individual progenitors. A summary of the results is shown in

Fig. 2. We find that the simulated MDF is very sensitive to the adopted Pop III IMF and metal yields. In particular, current observations of the tail of the MDF at [Fe/H] < -4 require faint SN explosions to dominate the metal yields produced by Pop III stars, disfavoring a strong contribution from stars with masses $> 140\,M_\odot$, into the Pair-Instability SN (PISN) progenitor mass range (de Bennassuti et al. 2014). Indeed, the incomplete sampling of the Pop III IMF in inefficiently star-forming mini-haloes ($< 10^{-3} M_\odot$/yr) strongly limits the formation of PISN progenitors, even when a flat Pop III IMF is assumed (de Bennassuti et al. 2017).

The relative contribution of C-normal and C-enhanced stars to the MDF and its dependence on [Fe/H] points to a scenario where the Pop III/II transition is driven by dust-cooling and the first low-mass stars form when the dust-to-gas ratio in their parent clouds exceeds a critical value of $\mathcal{D}_{\rm crit} = 4.410^{-9}$ (Schneider et al. 2012a). The middle panel of Fig. 2 show that the model predicts a decreasing [C/Fe] value for increasing [Fe/H], in good agreement with observations. This trend reflect the properties of the formation sites of the first low-mass Pop II stars, that are minihalos self-enriched by primordial faint SNe. Chemical enrichment then proceeds via ordinary core-collapse SNe, and as a result the [C/Fe] decreases with increasing [Fe/H].

We also find that at [Fe/H]< -4.5, C-normal stars can only form in halos with a dust-to-gas ratio above the critical value, and that have accreted their metals and dust from the surrounding MW environment. When this occurs, normal Pop II SNe in self-enriched haloes have already become the major contributors to the metal enrichment of the external MW environment, leading to [C/Fe] < 0.7.

Finally, the right panel confirms what we anticipated in the previous section: the low-[Fe/H] tail of the MDF is dominated by second generation (2G) stars, defined as stars formed in environments where metals come mostly ($>$ 50%) from Pop III stars. More specifically, we find that 50% of CEMP-no stars with [Fe/H]< -3 are imprinted by Pop III faint SNe, thus providing a a powerful way to constrain the nucleosynthetic products of the first stars. On the contrary, the distribution of 2G stars polluted by PISNe is shifted towards higher [Fe/H] values, because massive PISNe produce larger amount of iron than faint SNe. Unfortunately, at these [Fe/H] the Galactic halo population is dominated by stars formed in environments mostly polluted by normal Pop II SNe. This makes the detection of 2G stars imprinted by PISNe very challenging as they represent 0.25% of the total stellar population, which is fully consistent with current observations (see point in the right panel of Fig. 2). Indeed, among the 500 Galactic halo stars analyzed so far at [Fe/H]< -2, there is only one candidate at [Fe/H]$= -2.4$ that might have been imprinted by a PISN (Aoki et al. 2014).

4. Conclusions

Although primordial stars were formed in the distant past, some of our greatest clues to the process of their formation are likely to come from our local Galactic neighborhood. Future improvements require, on the theoretical side, accurate modeling to interpret observations and, on the observational side, larger statistical samples of metal poor stars with [Fe/H] < -3, that have the potential to constrain the IMF of Pop III stars and the physics of star formation at extremely low metallicities.

5. A few personal memories

The first time I met Francesco was in April 2000, when I moved to Arcetri as a young postdoc. I was coming from the relativistic astrophysics community and the only paper by Francesco I knew at that time was the paper *How small were the first cosmological objects?* by Tegmark et al. (1995) where they computed the minimum mass that a virialized gas cloud must have in order to be able to cool in a Hubble time, using a detailed treatment of the chemistry of molecular hydrogen. This turned out to be a seminal paper in first stars and first galaxies that since then has been my main field of work. The very first time I met him, when I introduced myself, he told me: *"Oh I know you, I was in the selection committee for your* *postdoctoral fellowship and by reading your CV I realized you grew up 200 meters away from my family house in Rome. I had to support your application!"* The simple fact that we were both "Romans" and that we grew up in the same neighborhood immediately established a sort of empathy, fostered by ironic jokes on the differences between Romans and Florentines. For a few years my office was next door to the office he shared with Daniele, and I could enjoy daily interactions with him. Thanks to Francesco, I started my long-lasting collaboration with Kazu Omukai who, at the same time, was a young postdoctoral fellow in Arcetri. Francesco then became the Director of the Observatory and almost at the same time, it was December 2005, I got my first permanent position in Arcetri. This came at the end of a long and strenuous national selection, with more than 200 candidates for about 10 positions. I remember that I was sitting in my car, with my smaller son, waiting for my older son in front of his school. I got this call on my mobile, it was Franco Pacini, that happily announced me that I got the position! You can guess my feelings. I was still recovering from the excitement when, less than a minute later, my phone rang again. It was Francesco, who - as the Director of the Observatory - was happily announcing me that I got the position! I never found the courage to tell him that Franco's verbal incontinence spoiled his role. Beside the many inspiring discussions and funny moments I shared with him, I am really thankful to Francesco for having shown me, through his own personal example, that it is possible to reconcile a strong dedication to work with "the lightness of being", a fundamental prerequisite for a happy life.

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