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First stars and reionization: Spinstars

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Soon after the Big Bang, the appearance of the first stellar generations (hereafter, first stars) drastically changed the course of the history of the Universe by enriching the primordial gas with elements heavier than helium (referred to as metals) through both stellar winds and supernova explosions. High-resolution hydrodynamical simulations of the formation of the first stars suggest these objects to have formed in dark matter mini-halos, and to have played a key role in the formation of the first galaxies. Today these stars are (most likely) long dead, and even though next generation facilities will push the observational frontier to extremely high redshifts, with the aim of discovering the first galaxies, the first stars will still lie beyond reach. Thus, the only way to constrain our theoretical understanding of the formation of the first stars is to search for their imprints left in the oldest, still surviving, stars in our own backyard: the Milky Way and its satellites. Which imprints are we looking for, and where can we find them? We address these questions in the present review.

1 Galactic archaeology: the high-redshift Universe right here in our backyard

The appearance of the first stars marks the first step towards the rich chemical complexity of our present Universe, which ultimately led to our own existence. Moreover, the first stars should have had an impact on the formation of the first galaxies, both in terms of metal injection and energetic feedback (Bromm & Yoshida 2011; Karlsson et al. 2012). Indeed, the deepest space and ground-based observations find metal-enriched galaxies already ~ 800 Myr after Big Bang, thus suggesting that these stellar populations had to be preceded by the metal-free first stars. Furthermore, observations of the near infrared cosmic background (both the spectral energy distribution and the angular fluctuations) show an excess that cannot be accounted by the normal population of galaxies, but point to the contribution of the first stars (and their associated black holes – see Cappelluti et al. 2013; Kashlinsky et al. 2005; Ferrara 2012 and references therein). Theoretical predictions for the luminosities, color and spectra of the first stars are now needed to simulate the capability of the next generation of very large telescopes to observe them (e.g. Joggerst & Whalen 2011). These predictions, however, are strongly dependent on the properties of the first stars, such as their mass spectrum and stellar yields.

To simulate the formation of the first stars is technically very challenging, as one starts from large-scale cosmological simulations that are then zoomed into the highest density peaks, requiring enormous high-resolution hydrodynamical simulations. A big step forward has been achieved by the most recent simulations, which can now resolve scales as small as 0.05 solar radii (e.g. Stacy et al. 2012; Greif et al. 2012). These sophisticated simulations include several processes taking place during the collapse of a rotating proto-cloud, followed by the formation of an accretion disk, which can then fragment due to instabilities. Hence, radiation transfer, dust grains, magnetic fields, accretion disks and ionization fronts must be taken into account (see Ferrara 2012). One of the aims of these simulations is to predict the mass spectrum of the first stars. Here the caveats and uncertainties are still large, involving details on the quenching of the accretion disk by the ionizing flux of the forming star AND on the role of magnetic fields in the fragmentation and turbulence inside accretion disks.

Although the resulting mass spectrum of the first stars is still very uncertain, current simulations suggest the first stars had masses in the range of 10–40 solar masses (see also Hosokawa et al. 2012). This is very different from the large masses suggested by pioneer simulations of Abel et al. (2002) or Bromm et al. (1999). The new simulations also predict two other properties of these first objects: a) sufficient angular momentum is found to yield rapidly rotating stars near to break-up speed (e.g. Stacy et al. 2011); and b) several objects tend to form in binary or triplet systems. Galactic archaeology is most probably the only way of probing the nature of the first stars (Bromm & Yoshida 2011; Tumlinson 2010), thus providing invaluable constraints to the above-mentioned simulations.

Indeed, the old low-mass stars (with masses below 0.8 of the solar mass) we observe today, have lifetimes comparable to the age of the Universe, and in their atmospheres, the elemental abundances of the gas at the time of their birth are mostly preserved. These stars thus represent a fossil record of the unique nucleosynthesis in the first stars, providing invaluable constraints on their masses, and stellar

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yields – the very basic input for modeling subsequent stellar generations, leading to the abundance distribution prevailing at present time. However, to be able to interpret the observed abundances, one must rely on stellar yields, which in turn critically depend on rotation, mass-loss and most probably binarity (see recent reviews by Maeder & Meynet 2012 and Langer 2012). Clearly, stellar evolution models including all these physical processes are still uncertain, and the way to go forward is to make a coordinated analysis of abundance data, stellar models and chemical-evolution models. This is the path we have pursued in the last years, and which have led to the interesting results summarized in this review.

But where do we find the oldest stars? High-resolution N-body cosmological simulations coupled to simple models of chemical evolution show that surviving stars from the epoch of the first galaxies remain in the MW today and should bear the nucleosynthetic imprint of the first stars (e.g. Tumlinson 2010). However, different simulations give different answers to where to find the oldest stars in a galaxy such as the MW (White & Springel 2000; Diemand et al. 2005; Brook et al. 2007; Tumlinson 2010), going from the bulge to the outskirts of our Galaxy.

Most of the current observational efforts in finding the chemical imprints left by the first stars have focused on the most metal-poor (and probably oldest) stars, both in the MW halo and in the recently discovered ultra-faint dwarf galaxies (see Frebel 2011 and references therein). A low metallicity in its own is no guarantee that the star is old, although this assumption seems to work in extreme low metallicity regimes. The correspondence between age and metallicity is strongly dependent on the star formation history of the particular studied component. Fortunately, different star formation histories lead to different chemical patterns and stellar populations properties. Studies based on the chemical and kinematic properties of stars in the different MW components have shown that not only the halo, but also the bulge and thick disk are potential hosts of some of the oldest stars in our Galaxy (Zoccali et al. 2003; Fuhrmann 2008).

In some rare cases it was possible to estimate an age, although with still non-negligible uncertainties, confirming the above suggestions. Namely, in a couple of very-metal poor halo stars in which it was possible to measure long-lived radioactive elements such as Th and U (e.g., Cayrel et al. 2001); in a couple of nearby thick disk sub-giants for which isochrone-ages are less uncertain (Bernkopf & Fuhrmann 2006; Sandage et al. 2003); in the bulge, where the oldest globular cluster of the MW is located (Barbuy et al. 2009). Although the oldest stars of the MW are not confined to the very metal-poor halo stars (hereafter VMP stars), the latter have already been proven to be a rich source of information on the nature of the first stars, as we now describe in the next section.

2 News from the very metal-poor Universe: halo and dwarf spheroids

The strategy adopted so far has been to look for the most metal-poor stars in the Milky Way and its satellites, presumably formed from a gas enriched only by a few first supernovae.

The VMP Universe revealed some striking surprises, requiring a revision of some of our most commonly accepted ideas. Some of them are summarized below:

- Around 20 % of the VMP stars show unexpected large C and N enhancements with respect to solar abundance. In the case of the two most metal-poor stars known to date, the overabundances of these elements can reach 100 to 10 000 times the ratios found in the Sun (Frebel et al. 2005, 2008; Christlieb et al. 2002). These stars are called "carbon enhanced metal-poor stars" (CEMPs).
- The CEMPs can also be classified according to the presence or absence of slow (s-) and/or rapid (r-) neutron capture process elements. The peculiar abundances of those showing over-abundances of s-process elements are usually interpreted as being due to accretion from an asymptotic giant branch (AGB) companion (e.g., Masseron et al. 2010). However, those without s-process element enhancements (CEMP-no; Beers & Christlieb 2005) challenge the above explanation. Some of the CEMP-no stars also show carbon isotopic ratios different from the ones for which the AGB mass-transfer explanation holds.
- More surprises have been found in normal VMP stars (to distinguish from the CEMP discussed above). Fairly large samples of normal halo stars, with [Fe/H] < -2.5, revealed unexpected deviations in the trends of some abundance ratios (such as [Zn-Co-Cr/Fe]) with metallicity, as well as a striking homogeneity in the abundance of alpha (e.g., O, Mg, Ca, Si) and iron-peak elements with respect to iron (Cayrel et al. 2004; Frebel 2011). However, the same stars show a large scatter in C, N, O, and in r- and s-process elements. In addition, Spite et al. (2005) found these stars to have essentially solar N/O ratios already at such low metallicities. This is unexpected from standard models of stellar and chemical evolution, as massive stars, the only ones able to enrich the ISM at such low metallicities , are not producers of primary nitrogen. The complete lack of scatter in some elements and the large intrinsic scatter in others holds potential clues to the origin of these elements, as well as to the early galaxy assembly.
- Until very recently, all known stars with [Fe/H] < -4 were strongly carbon-enhanced. As a consequence, despite of being the most metal-poor stars, their total mass fraction of metals is around $Z = 1.5{\times}10^{-5}$, similarly to other less iron-poor stars. This was taken as a suggestion that low-mass stars did not form until the primitive Universe reached a critical metallicity value, which some theoretical models estimated as being around

$Z = 1.5\times10^{-6}$ (Frebel et al. 2007). This limit has now been ruled out by Caffau et al. (2011), who discovered a normal star with [Fe/H] $= -5$, thus implying a total metallicity $Z = 6.9\times10^{-7}$.
- Very massive stars are expected to explode as pair-creation SNe, which would leave a clear signature, namely, an odd-even abundance pattern. However, such a signature has not yet been observed among VMPs. What could be the reason for that? One hypothesis is that the first very massive stars would have lost part of their masses before exploding, hence dying as normal SNe. The puzzling point is that at such low metallicities, standard stellar evolution models predict mass loss to be negligible. An alternative is that these stars imply such a huge initial enrichment, that their imprints would be left in stars of larger metallicities (Karlsson et al. 2008). However this has not been confirmed. Another possible explanation is offered by more recent simulations which, now predict the first stellar generations to have masses more typical of core-collapse supernovae ($\sim$ 10–40 $M_\odot$).
- One of the expectations was that the ^{7}Li abundance in VMP stars would fall in the so-called Spite plateau, which has been interpreted as the primordial ^{7}Li abundance (Spite & Spite 1982). Unexpectedly, two problems were found (Aoki et al. 2009): a) the observed Spite Plateau value is 2–3 times lower the value predicted by standard Big Bang nucleosynthesis models adopting the baryon density obtained by WMAP, and b) there seems to be a decrease in the ^{7}Li abundance with decreasing metallicity in extremely metal-poor stars. In the specific case of HE13271726 (the most metal-poor star known to date) as well in the Caffau et al (2011) star discussed above, ^{7}Li is strongly depleted. Given the low mass of these old stars, internal processes able to deplete this element are not enough to explain such low values. The latter observations are still not explained (Norris 2011).

3 The important role of rotation on the evolution of the first stellar generations

The first stars were, most probably, very different from present-day massive stars, as they were metal-free. The lack (or only traces) of metals leads to faster surface rotation velocities, as metal-poor stars are more compact than metal rich ones. Stars formed from a gas whose global metallicity is below 1/2000 that of the Sun could attain rotational velocities of 500–800 km s^{-1} (depending on the stellar mass).

Two important effects arise in spinstars:
- Rotation triggers mixing processes inside the star which lead to the production of important quantities of primary ^{14}N, ^{13}C, and ^{22}Ne (Maeder & Meynet 2012, and references therein). The production of primary ^{22}Ne has an important impact on the s-process nucleosynthesis in spinstars compared to non-rotating stars, increasing by orders of magnitude the s-process yields of heavy elements (Pignatari et al. 2008; Frischknecht et al. 2012);
- The strong mixing caused by rotation enriches the stellar surface, thus increasing the opacity of the outer layer, and producing line driven winds. In addition, fast rotation can also lead to mechanical mass loss. Both mechanisms are able to trigger non-negligible mass loss already at very low metallicities (a result not achieved by standard models without rotation).

As a consequence these stars could have left an imprint when enriching the primordial interstellar medium. Moreover, rotation have other important impact in the evolution of massive stars, such as changing their evolution and final fate; pushing the evolutionary tracks to larger temperatures and luminosities; could be related to long duration GRBs; and can also lower the mass limit for the onset of pair instability supernovae from $\sim$ 140 $M_\odot$ to around 65 $M_\odot$ (see Maeder & Meynet 2012; Yoon et al. 2012, and references therein).

In the next sections we show how some of the anomalies discussed in Sect. 2 can be naturally accounted for if the first stellar generations were fast rotators. Interestingly, the latter conclusion came directly from Galactic archaeology, many years before the hydrodynamic simulations of the first stars would point to the same direction. This illustrates the complementarity of the two approaches.

4 Four signatures of the existence of spinstars in the early Universe?

Chiappini et al. (2005) studied the implications of the results of Spite et al. (2005), described above, on our understanding of nitrogen enrichment in the MW. We suggested that the only way to account for the new data was to assume that stars at low metallicities (i.e., below $Z = 10^{-5}$) rotate sufficiently fast to enable massive stars to contribute much larger amounts of nitrogen (a trend already suggested in the work of Meynet & Maeder 2002, and by observations in Maeder et al. 1999). It was predicted that massive stars born with metallicities below $Z = 10^{-5}$ should produce between a factor of 10 and a few times 10^2, more nitrogen than the values given by Meynet & Maeder (2002), for $Z = 10^{-5}$ (their lowest metallicity models at the time), and initial rotation velocities of 300 km s^{-1}. Standard stellar evolution models (without rotation) predicted even smaller amounts of primary nitrogen in massive stars, making the problem worse. Whether the above suggestion was physically plausible remained to be assessed by stellar evolution models computed for lower metallicities, which took rotation and mass loss into account.

At the same time, and completely independently, the stellar evolution group in Geneva was computing new stellar models for metallicities $Z < 10^{-5}$. These models were computed under the assumption that the ratio of the initial rotation velocity to the critical velocity of stars is roughly

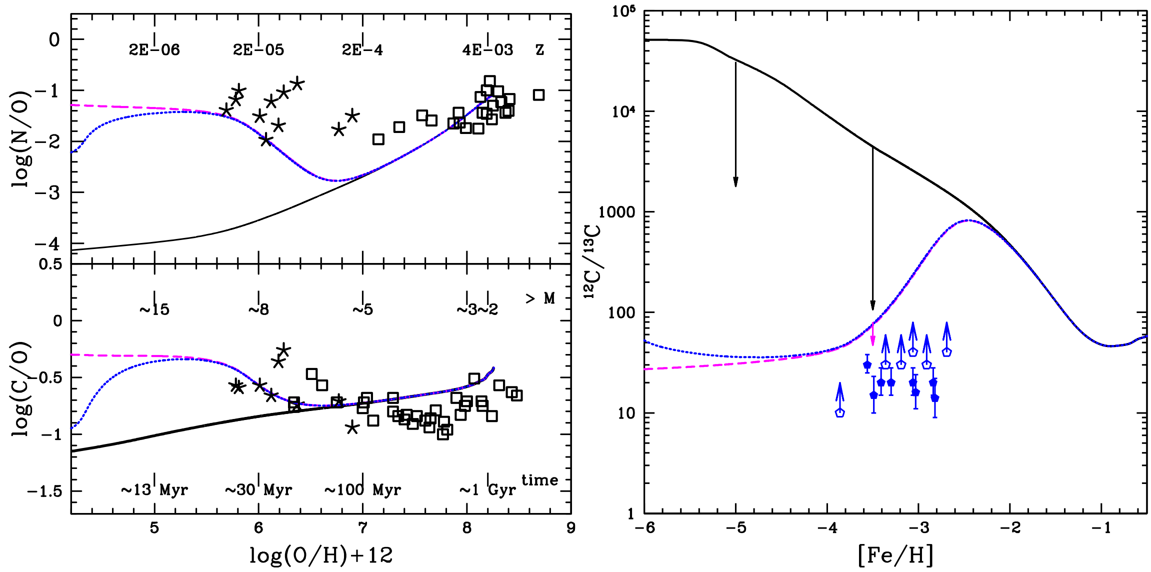


Fig. 1 *Left panel*: evolution of the N/O and C/O ratios in the halo of the MW. Solid (black) curve: the chemical evolution predictions obtained with the stellar yields of slow rotating (300 km s^{-1}) stellar models. Dashed (magenta) line includes the contribution of fast rotating stars at very low metallicities. Dotted (blue) lines show what is obtained upon the inclusion of population III ($Z = 0$) stars. Fast rotation enhances nitrogen in the early phases of the Galactic enrichment by 3 orders of magnitude (figure taken from Ekström et al. 2008a). *Right panel*: predicted evolution of the ^{12}C/^{13} ratio (curves are labelled as in left panel). Arrows indicate the final ^{12}C/^{13}C observed in giants after the first dredge-up. In this framework, the low ^{12}C/^{13}C ratios can be attributed to the contribution to ^{13}C by fast rotating massive stars, before AGB stars had time to enrich the early ISM. Figure taken from Chiappini et al. (2008).

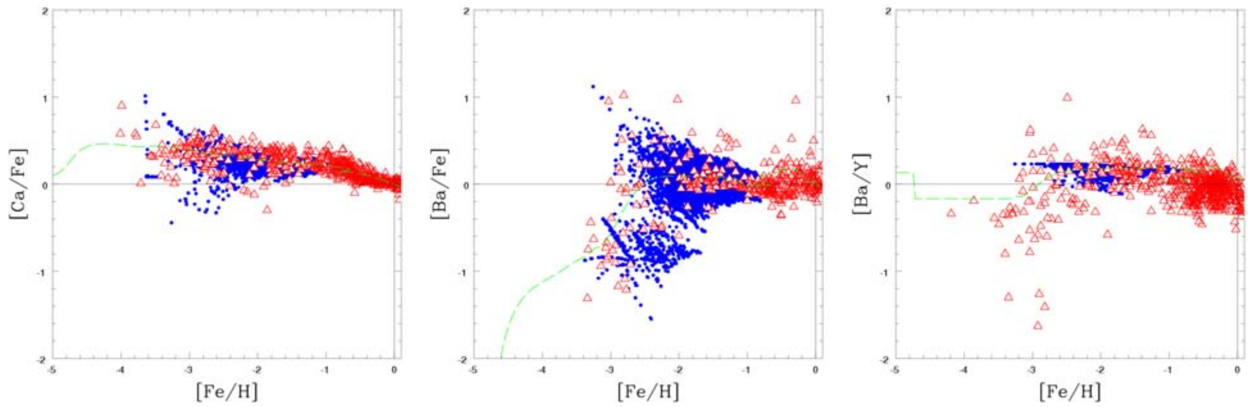


Fig. 2 Observed (red triangles) scatter in [Ba/Fe], (*middle panel*) and lack of scatter in [Ca/Fe (*left panel*), in VMP stars. The *right panel* shows the observed scatter in the [Ba/Y] ratio. The blue dots are the model predictions by Cescutti (2008). Notice that despite the good agreement of the model with the observations in the two first panels, the same model disagrees with the observed scatter in the ratio of the two s-process elements, Ba and Y, observed in the most metal poor halo stars. Figure adapted from Cescutti (2008).

constant with metallicity (Hirschi 2007). This naturally leads to faster rotation at lower metallicity, as metal-poor stars are more compact than metal rich ones. Their calculations for $Z = 10^{-8}$ and rotational velocities of 500–800 km/s led to larger nitrogen yields, close to the predictions of Chiappini et al. (2005). In Chiappini et al. (2006a,b) we computed new chemical evolution models for the MW considering these new stellar yields. We concluded that the existence of fast rotating massive stars (coined by us spinstars) in the very early Universe was (and still is) the only explanation for the large nitrogen abundances observed in normal VMP halo stars. Although the most notable chemical output of spinstars (markedly different from non-rotating standard models) is the large production of primary nitrogen, other elements, such as carbon, are also affected. We also found that the same chemical evolution models accounting for the nitrogen observations would predict an increase in the C/O ratio of halo stars towards low metallicities (Fig. 1, bottom-left panel), exactly as indicated by the observations. Alternative explanations for the C/O upturn at low metallicities invoke a top heavy-IMF (biased to massive stars, e.g., Akerman et al. 2004) but do not explain the large N/O ratios observed in the same stars.

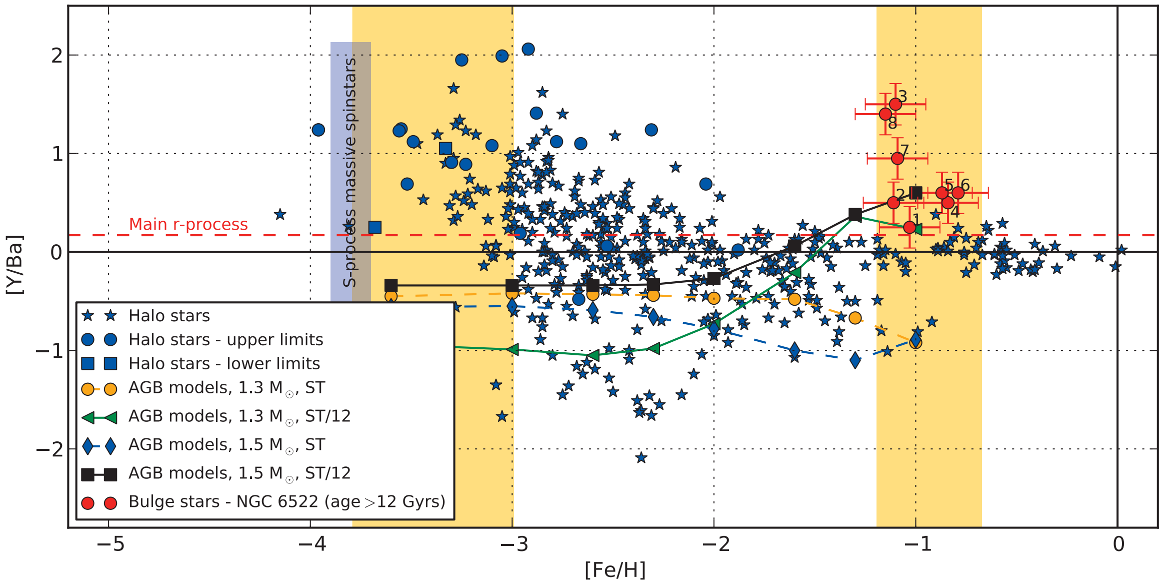


Fig. 3 Observed [Y/Ba] scatter in eight stars of NGC 6522, a bulge GC with a metallicity around [Fe/H] $= -1$ (red circles with error bars) compared to that observed in VMP halo stars with [Fe/H] < -3 (blue circles and stars). The two (yellow) shaded areas mark the early Universe phase sampled by halo and Bulge stars. Note the similar scatter in [Y/Ba] between the most metal-poor halo stars and NGC 6522 stars (compare the scatter inside the two shaded areas). The [Y/Ba] scatter predicted by spinstars stellar models is also indicated (vertical blue column). The dashed line indicates the [Y/Ba] ratio predicted from pure r-process. The curves show the predictions for the [Y/Ba] ratio by AGB mass-transfer models of different masses (Bisterzo et al. 2010). AGB models with lower ^{13}C-pocket efficiencies than the one considered here, with ST/12 (where ST is for standard), would produce too low [Y/Fe] and [Ba/Fe] incompatible with what is observed in the stars with the largest [Y/Ba] values. Figure adapted from Chiappini et al. (2011).

Our result that prodigious amounts of C, and especially N, could have been ejected by spinstars, believed to have existed at very low metallicities, needed to be further tested by comparing our model predictions with a more robust chemical signature (i.e., an abundance ratio for which the observational uncertainties were smaller than in the case of N/O and C/O studied before). The carbon isotopic ratio is a good choice both from the observational and theoretical points of view. Indeed, the mixing in massive stars promoted by rotation brings to the surface not only large quantities of ^{14}N but also ^{13}C. In addition, the ^{12}C/^{13}C ratio is largely unaffected by uncertainties in the adopted atmosphere parameters. In Chiappini et al. (2008) we show that, if fast spinstars were a common phenomena in the early Universe, the VMP normal halo stars should have ^{12}C/^{13}C ratios around 30 at [Fe/H] $= -5$, whereas without fast rotators one would expect a ratio around 30000 at this same metallicity (see Fig. 1, right panel). The observed low ^{12}C/^{13}C in VMPs (Spite et al. 2006) are in better agreement with the predictions when including spinstars.

We next studied the impact of strictly zero metallicity spinstars with rotational velocities around 800 km/s (Ekström et al. 2008a). Although non-zero metallicity stellar models predict the production of primary nitrogen to increase with decreasing metallicity (Meynet & Maeder 2002; Hirschi 2007), we found ^{14}N to be produced at systematically lower quantities at $Z = 0$ than at $Z = 10^{-8}$, contrary to what would be expected (but still larger than in standard models without rotation). This is due to the fact that $Z = 0$ stars burn their hydrogen at temperatures hot enough to also burn some He and do not evolve into the red part of the HR diagram. No redward evolution means that the gradient of the angular velocity at the border of the He-burning core remains much shallower and triggers much less mixing. Although our new computations, including $Z = 0$ stars, predict a reduction of the N/O and C/O ratios at extremely low metallicities (Fig. 1, blue dotted curves in left panel), this effect soon disappears due to the contribution of stars of larger metallicities. According to our results, an early generation of spinstars offers an elegant solution to the observed high N/O (and C/O) and low ^{12}C/^{13}C ratios observed in very metal-poor normal halo stars. In the case of the N/O and ^{12}C/^{13}C ratios, predictions with and without spinstars differ by at least 3 orders of magnitude.

A fourth signature was recently suggested by Prantzos (2012) who argue that the observed primary-like evolution of Be and B can be explained if Galactic cosmic rays are accelerated from the wind material of rotating massive stars, rich in CNO, hit by the forward shock of the subsequent supernova explosions.

These four footprints have been found in the very metal-poor Universe ([Fe/H] < -3). Can other signatures of first stars (and in particular, spinstars) be found in other MW components also hosting old stars, not necessarily extremely metal-poor? We argue that the answer to this question is *yes* and that we have found the first signature of fast rotating stars in the Galactic bulge (see next section and Chiappini et al. 2011).

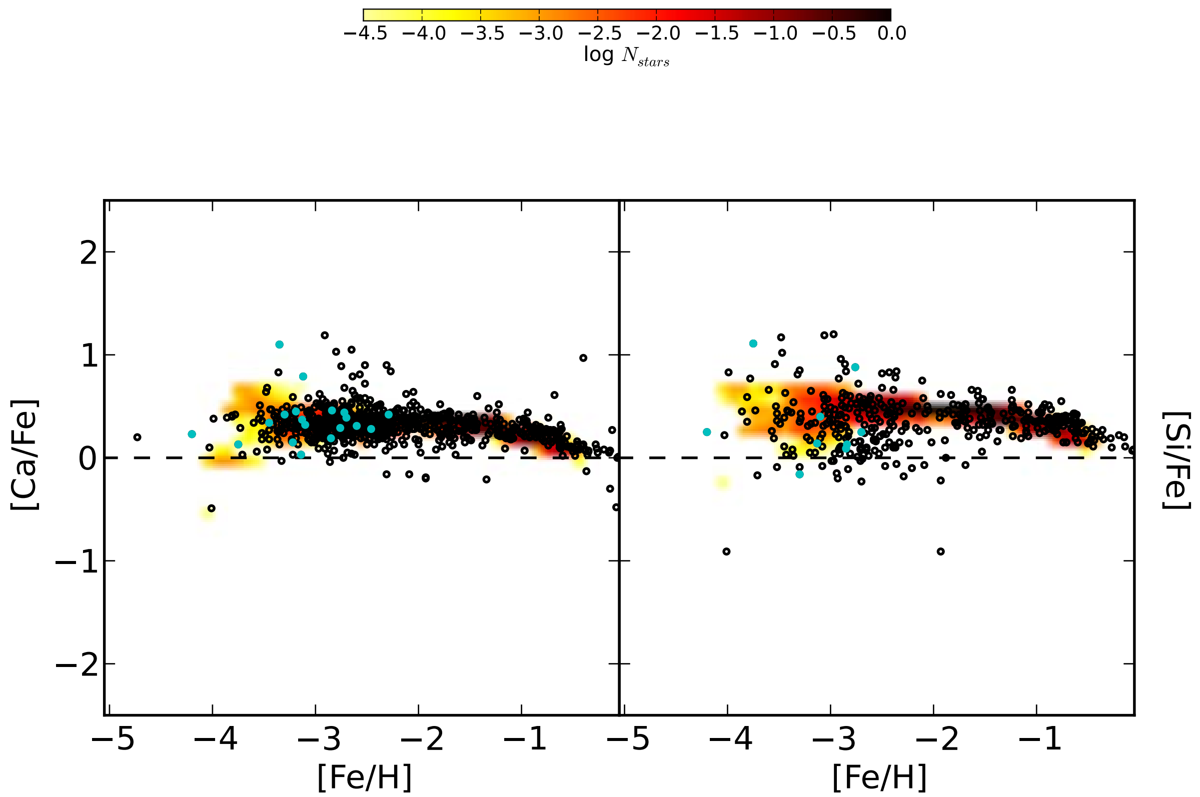


Fig. 4 [Ca/Fe] and [Si/Fe] vs. [Fe/H]. The density plot is the distribution of simulated long-living stars for our model; the density is on a logarithmic scale, normalized to the peak of the distribution and the bar over the plot describes the assumed color scale. Superimposed on the density plot, we show the abundances ratios for halo stars from Frebel (2010) (the cyan filled circles represent CEMP-no stars, see text). Note the very small scatter predicted by the model for these two [α/Fe] ratios and the good agreement with the observational data. Figure taken from Cescutti et al. (2013).

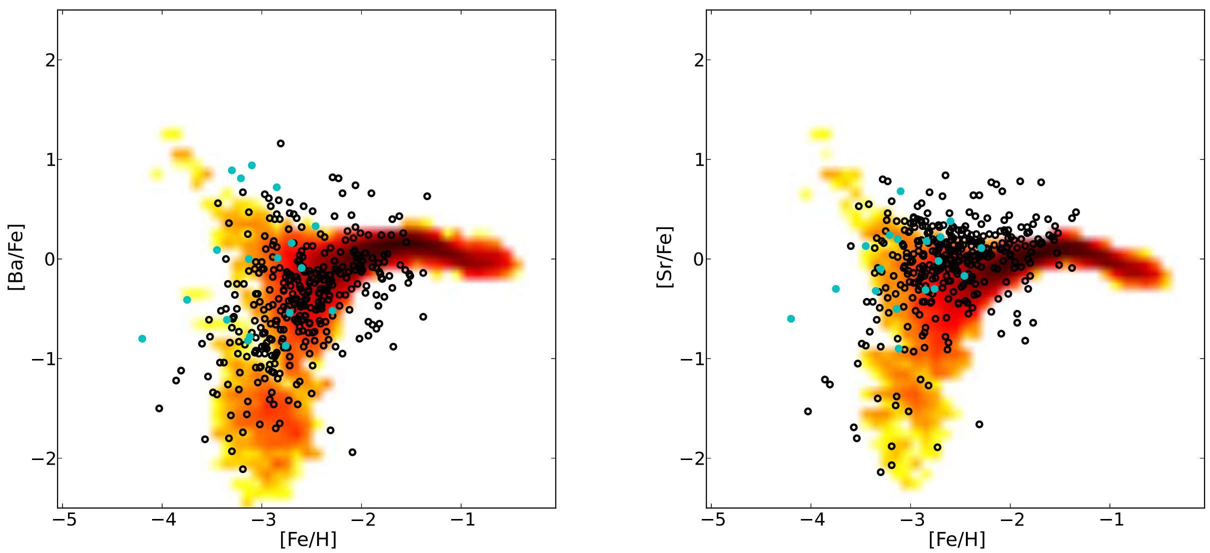


Fig. 5 [Ba/Fe] and [Sr/Fe] vs. [Fe/H]. The different symbols represent: normal stars (black open circle) and CEMP-no (cyan filled circle), and one CEMP-r star (red cross). As CEMP-s are most probably the result of mass transfer in binary systems and are not plotted here. The good agreement with the observations is obtained here by a model including spinstars plus an r-process taken place in 8–10 solar mass stars, here referred to as "standard r-process". Figure adapted from Cescutti et al. (2013).

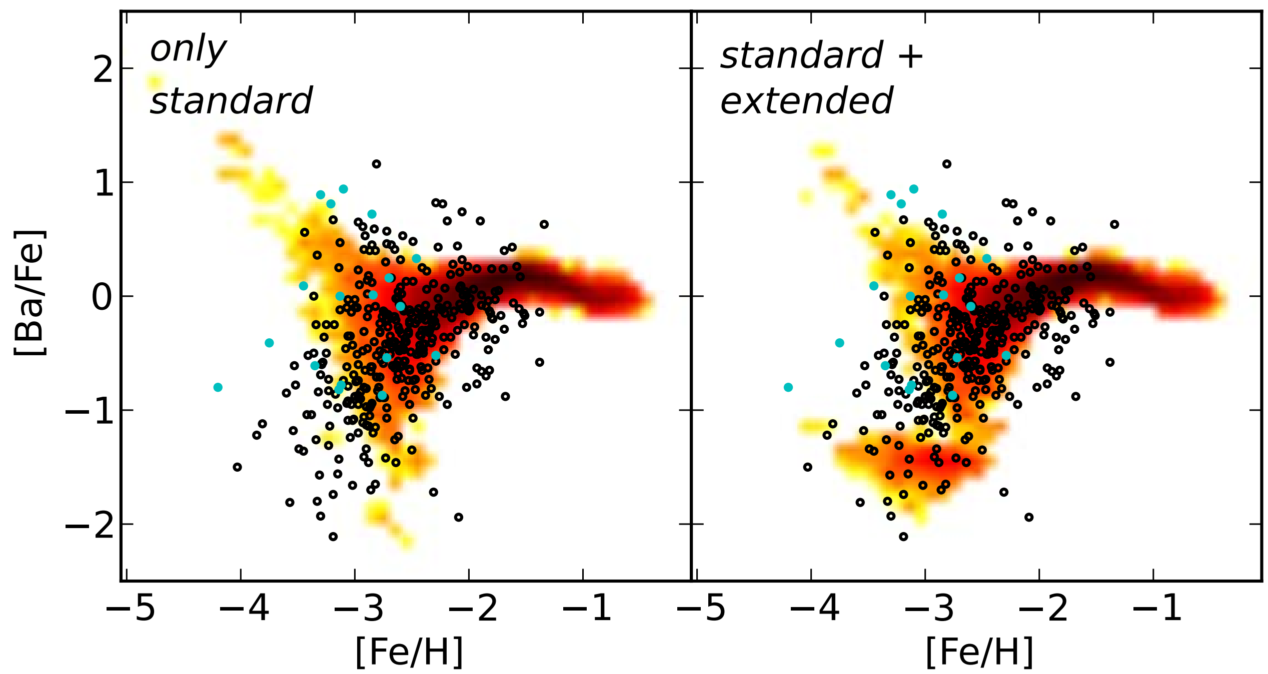


Fig. 6 This figure presents the results of our inhomogeneous model without any contribution from spinstars. On the *left* we show a model with an extended site for r-process (see text), whereas on the *right* a contribution from the more massive stars to the r-process is included. Notice that in both cases no scatter would be predicted for the [Sr/Ba] ratio. Figure adapted from Cescutti et al. (2013).

5 Heavy Elements: the fifth signature?

The above results were obtained by using chemical evolution models where the instantaneous mixing approximation was assumed. These models were useful to show the impact of spinstars in the mean observed trends in VMP stars. However, to make use of the precious information encoded in the scatter (or lack of) in the abundance ratios of VMP stars, inhomogeneous chemical evolution models are needed.

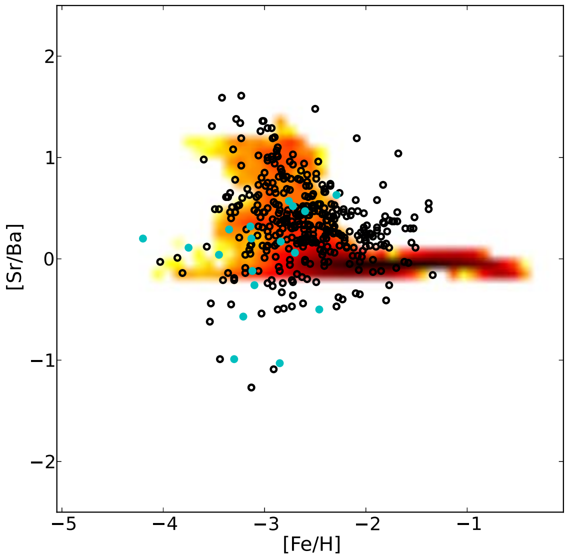
Two examples of puzzling results related to the observed scatter in abundance ratios are given below.

We have shown (Cescutti & Chiappini 2010) that a large C, N, O scatter is obtained when assuming that stars with masses above 40 solar masses do contribute to the chemical enrichment of the early Universe via stellar winds, before collapsing directly to black holes (as predicted to happen above this mass limit Heger et al. 2003). In these models the contribution to the n-capture elements comes from massive stars below that limit (Cescutti 2008), via supernovae explosion. These models can account for the observed scatter in CNO and n-capture elements, and the lack of scatter in alpha-elements (Fig. 2, left and middle panels). Interestingly, the same models cannot reproduce the observed scatter in the ratio of two s-process elements from different s-process peaks (such as [Ba/Y], Fig. 2 right panel) at very-low metallicities (early Universe). This failure suggests some missing physics in the adopted yields of n-capture elements.

Another interesting problem, again related to Ba and Y, was found in NGC 6522, a bulge globular cluster (GC) shown to be the oldest GC in the galaxy, and hence a witness of the earliest phases of the chemical enrichment in the Bulge, despite its metallicity being a tenth of the Sun ($[Fe/H] = -1$).

Barbuy et al. (2009) studied eight stars in this GC, finding that all of them had abundance ratios [O/Fe], [Mg/Fe], [Si/Fe], [Ca/Fe] and [Ti/Fe] which were enhanced with respect to solar, clear signature of chemical enrichment due to massive stars. For elements heavier than iron, the abundances ratios of [Eu/Fe], [Ba/Fe], and [La/Fe] are also enhanced with respect to solar, with a puzzling large scatter from star to star. Whereas an enhancement in Eu would be expected from the r-process believed to arise in massive stars, the observed anomalous enrichment for Ba and La in some of the NGC 6522 stars cannot be reconciled with present understanding of nucleosynthesis processes. Indeed, most of the Ba and La available today in the solar system and in the Galaxy have been produced by low-mass AGB stars (Sneden et al. 2008), which however, due to their long lifetimes, would not have had time to evolve and pollute the gas from which the NGC 6522 cluster formed. Following the work of Barbuy et al. (2009), a re-analysis of the same spectra (Chiappini et al. 2011) provided measurements for [Y/Fe] (and [Sr/Fe] although uncertain), and upper limits for [C/Fe], showing an even stronger enhancement for Sr and Y, and no enhancement for C.

For 5 out of 8 stars in NGC 6522, Chiappini et al. (2011) discussed in detail two possible scenarios: the enrichment of Sr, Y, Ba and La is due to either the s-process activation in early generations of spinstars (Pignatari et al. 2008),



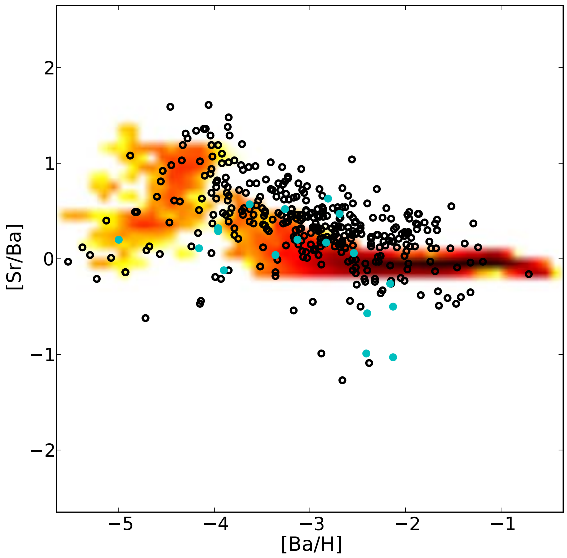


Fig. 7 The observed scatter in [Sr/Ba] as a function of [Fe/H] (*top*) and [Ba/H] (*bottom*). Our inhomogeneous model, including both the contribution of spinstars to the s-process and of a narrower range of massive stars to the r-process (8 to 10 solar masses) is able to account for the observed scatter. Given the large uncertainties in the iron yields, we show on the right panel a diagram independent of iron. Also in this case remarkable agreement is obtained. Figure adapted from Cescutti et al. (2013).

or the s-process due to the contamination from a low-mass AGB stars in a binary system, with initial metallicity coincident with the metal content of the cluster (Fig. 3). In the first case the chemical enrichment is from stars polluting the primordial material before forming the cluster, whereas in the second case the chemical enrichment would happen via AGB-mass transfer at whatever point in the history of NGC 6522, thus polluting the stars we are now observing. The remaining 3 stars showing the highest [Y/Ba] (Fig. 3, points 3, 7 and 8) are not compatible with s-process nucleosynthesis in AGB stars and can be explained only from early enrichment from spinstars. Indeed, more recent and complete calculations of VMP fast rotating stellar models show that the s-process yields can be boosted (Frischknecht 2011; Frischknecht et al. 2012).

In summary, the above results suggest the existence of an early generation of spinstars, and that these stars could have played a crucial role in the early chemical enrichment of the Universe in C, N, O, and s-process elements. If proved true, this would have an impact in theories which suggest that trace amounts of metals in the early Universe could control the transition from a top-heavy IMF to a standard one, where the formation of long-lived low-mass stars can happen. Furthermore, the above results suggest that stars from the lower end of the Bulge metallicity distribution could have preserved the signatures of the first stars.

5.1 Spinstars' contribution to the s-process – a new twist in the VMP data interpretation

Could spinstars also be the solution for the two puzzling results described in the previous section? To answer this question two important ingredients are necessary, namely: a) stellar evolution models with rotation, for different masses and initial metallicities including s-process isotopes (and thus a complete reaction network up to Bi) and b) underlying assumption on the r-process contribution. Indeed, as the s-process in fast-rotating massive stars will not be the only contributor to the Sr and Y (and probably Ba) in the early Universe, the models shown here also include a contribution from the r-process. As discussed in Hansen et al (2013), the latter process is still very uncertain and only a few groups do provide r-process stellar yields (e.g. neutrino wind models, Arcones & Montes 2011, and O-Ne-Mg core collapse models, Wanajo et al. 2011). Moreover, although these few models do produce Y and Sr, they do not produce Ba. Other processes, more promising for Ba production, such as neutron star merging or magneto-rotationally driven SN have not yet led to detailed stellar yield computations. Given this situation we are forced to adopt what we call "empirical yields" (see Cescutti et al. 2006 and 2013 for a description of this approach and for the adopted r-process yields in the model predictions shown here). It turns out that the empirical yields we estimate are within the uncertainties of the present r-process models (see Hansen et al. 2013). We are now in a position to quantify the impact of spinstars on the early enrichment of heavy elements.

Figures 4 and 5 show the results of our models computed with the following assumptions (for more details see Cescutti et al. 2013: a) for the s-process yields we used the computations by Frischknecht et al. (2012) for fast rotating massive stars (i.e. $v_{\rm ini}/v_{\rm crit} = 0.5$, similar to the values adopted in Chiappini et al. 2006a,b, 2008); b) we consider the case where the reaction rate ^{17}O(α,γ) is one tenth of the standard one (indeed the current uncertainties in the ^{17}O(α,γ) rate are still large, and the value we adopted here is well within both the theoretical and recent experiments uncertainties); c) we assume a "standard" r-process contribution (see below). This models can well reproduce the observed scatter both, in [Ba/Fe] and [Sr/Fe] as function of [Fe/H], and at the same time the very small scatter observed in the [Ca/Fe] and [Si/Fe] abundance ratios of the same stars.

Although this result is similar to a model adopting only r-process and no contribution from spinstars (illustrated both in Fig. 2, left panel for the models of Cescutti (2008), and in Fig 6 for the present model) some differences do exist. This is illustrated in Fig. 6 where on the left panel we show a model with the contribution of r-process only from 8–10 solar mass stars (our empirical "standard r-process") and on the right the same model where we extend the contribution to the r-process to the whole massive star mass-range (here labelled "extended r-process"). Two things can be noticed: a) a model which takes into account only the standard r-process cannot account for the most metal-poor stars with low [Ba/Fe]; and b) when adding an ad hoc contribution of more massive stars to the r-process a better agreement is found, but not much better than what is obtained with a model including the spinstars contribution, as shown in Fig. 5. However, by definition, both models shown in Fig. 6 would not produce any scatter in the [Sr/Ba] ratios, but just a constant ratio (e.g. Sneden et al. 2008).

A scatter in the [Sr/Ba] vs [Fe/H] diagram is instead obtained once the contribution of spinstars is taken into account (as illustrated in Fig. 7). Finally, Fig. 8 shows the model predictions compared with the observed scatter in N/O, C/O (see Cescutti & Chiappini 2010) and [Sr/Ba] as a function of the oxygen abundance. This is the first time an inhomogeneous model is able to reproduce simultaneously the observed the trends and scatter in the [α/Fe], [C/O], [N/O], [Sr/Fe], [Ba/Fe], and [Sr/Ba] measured in very metal poor halo stars as a function of metallicity (iron and oxygen). In this elegant solution, we are able to explain the results with just two different sites of production for Sr and Ba, without requiring more complicated scenarios.

Finally, note that in Figs. 4, 5, and 7 the CEMP-no shows no distinction with respect to the normal (non-CEMP) stars. On the other hand, as shown in Cescutti & Chiappini (2010) the same models cannot not explain the locus of the CEMP-no stars in the nitrogen diagrams, even when using stellar yields from the winds only (and not the SN ones), which produce a lot more nitrogen. At that time we suggested (Meynet et al. 2010) these objects to have been born directly from the gas expelled by the wind of fast rotating massive stars without mixing with the surrounding ISM. This idea could in principle be tested by looking at the abundances of ^{7}Li, ^{12}C/^{13}C, and helium in CEMP-no stars, because the wind material should be depleted both in ^{7}Li and ^{13}C. The lack of the same effect in heavy elements such as Ba and Sr would be expected in this framework, as the stellar winds are not enriched in the latter chemical elements.

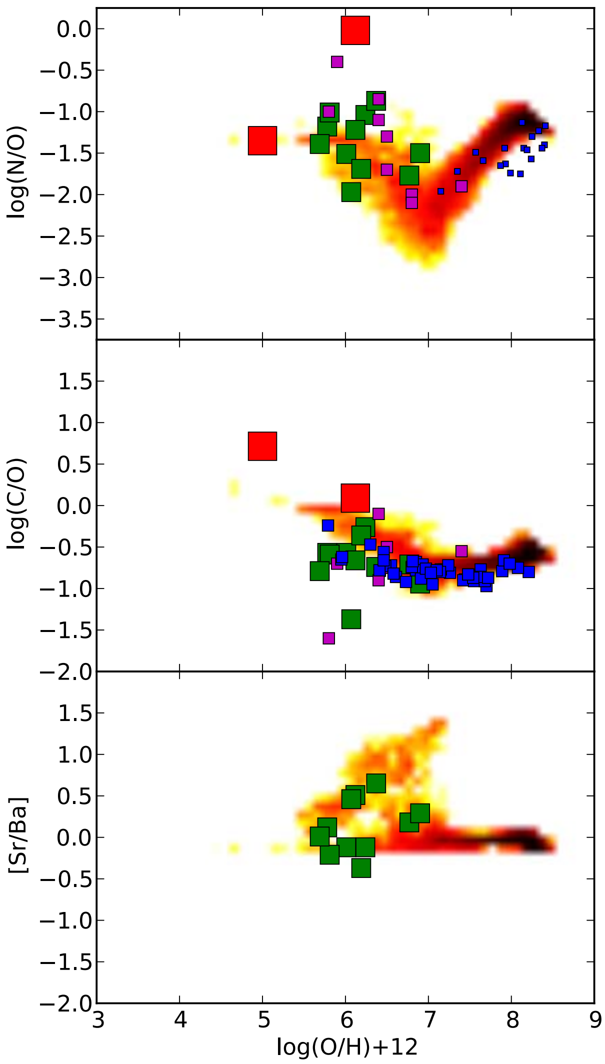


Fig. 8 Here we show our best model predictions (including spinstars) for N/O, C/O and Sr/Ba versus the oxygen abundance (*top to bottom*). The two large squares show HE0107-5240 and HE1327-2326 (left, and right, respectively). The green squares show the data from Spite et al. (2006). The magenta squares (up and middle panels) are data from Lai et al. (2008). The small squares in the upper panel are from Israelian et al. (2004), where the blue squares in the middle panel are from Fabbian et al. (2009). Figure adapted from Cescutti & Chiappini (2010) and Cescutti et al. (2013).

6 Did spinstars play an important role in the reionization of the Universe?

The impact of spinstars in the early Universe could have been manifold. The high CNO content can be a key for producing the cooling needed for low-mass stars to form, even at the very first phases of the Universe. Moreover, a profound impact is to be expected with respect to the progenitors of long-duration gamma-ray bursts (l-GRBs), promissory tracers of the earliest phases of the Universe (Campisi et al. 2011): the larger initial rotational velocities of massive stars in very metal-poor environments would lead to the large core rotational velocities required by the GRB collapsar model to work (see Ekström et al. 2012; Georgy et al. 2012). Finally, since fast rotating massive stars have longer main-sequence lifetimes and show bluer tracks in the HR diagram with respect to non-rotating stellar models, they were most probably an important UV ionizing flux source. This may have a significant impact on the budget of ionizing photons in the early Universe providing a source for re-ionization (Ekström et al. 2008b).

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