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Galactic chemical evolution: The role of the first stars

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The massive First Stars (the first ones to contribute to the chemical enrichment of the Universe due to their short lifetimes) are long dead, and even though efforts to directly observe them in high-redshift galaxies are underway, a step forward in this field will have to wait for JWST and ELT. The only way to currently validate the picture arising from the most modern hydro-dynamical simulations of the formation of First Stars is to search for their imprints left on the oldest stars in our Galaxy. Which imprints are we looking for? In the last years our group has found that many chemical anomalies observed in very metal-poor halo stars, as well in the oldest bulge globular cluster, suggest the first stellar generations to have been fast rotators. After giving a brief overview of the aforementioned results, we highlight the impact of fast rotating metal-poor massive stars on the chemical enrichment of heavy-elements such as Sr and Ba. Indeed, in fast rotating massive stars the s-process production is boosted. We will show, by means of an inhomogeneous chemical evolution model, based on stochastic approach to the star formation, that this fact offers a new twist in the interpretation of the abundance patterns and scatter observed in very metal-poor halo stars.

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1. Introduction

Elements with Z >30 are labelled neutron capture elements: they are manly formed through neutron captures, and not through fusion, this process beyond iron (Z=26) being endothermic. The neutron capture process is also split in rapid process (r-process) or slow process (s-process) depending whether the timescale for neutron capture τ_n is faster or slower compared to radioactive beta decay τ_β, according to initial definition by [1]. The neutron fluxes so different suggest very distinct sites of production for these elements and theoretical calculations have confirmed this idea. The s-process takes place in the low intermediate mass stars where a constant flux of neutrons can be provided during the asymptotic giant branch phase; in this case, the site of production can be modelled, and the isotopes involved are experimentally measurable; detailed calculations are possible, even though the uncertainties, in particular in the stellar models, can give rise to important variations in the resulting yields. The site for r-process is still under debate but all the hypotheses lead to the common requirement of an environment in which extremely high neutron densities are generated. The general complexity of the systems, coupled with the inaccessibility of the nuclear data of the isotopes involved, leads to few computations with reliable yields up to now; only recently SNII models has started to explode, so nucleosynthesis is still not provided, with the exception of the work, on O-Mg-Ne core supernovae (SN) by [2].

Even though the r-process is not clearly understood, all the possible hypotheses point to massive stars and this gives rise to a different timescale of enrichment for the two processes: few million years for the r-process (typical lifetime for a massive star), compared to more than half Gyr for the bulk of production of s-process elements. It is also expected that s-process are produced in massive stars, but this has often been neglected due to the overall scarce amount (in practice negligible at very metal-poor regime) predicted by theoretical works (see [3]). For this reason, it has been common to associate the neutron capture elements in the extremely metal-poor (EMP) stars of the halo with r-process production, as pointed out already in [4].

For the first time in the work by [5], the possible importance of s-process production in massive stars was shown in a parametrized way. More recently, [6] used a stellar evolution code with an extended nuclear reaction chain to confirm that fast rotating metal-poor stars can generate heavy elements through s-process; this production of s-process elements in massive stars provides a possible explanation of the high abundance of Sr and Y, measured in metal-poor stars of the Bulge, as highlighted by [7]; moreover, the concept of metal-poor fast rotating massive stars (spinstars) has already proved to play a crucial role in the formation of CNO elements at very low metallicity [8].

Homogenous chemical evolution models have recently shown the importance of spinstars for the early chemical enrichment of the Galaxy [9,10]. However, in the case of neutron capture elements the situation is more complex due to the presence of a huge spread in the observed abundance ratios of the EMP stars, recently confirmed by the results of [11]. An explanation for these inhomogeneities relies on the stochastic formation of massive stars [12]. In this scenario, the spread is generated by the enrichment of different species if they are produced by different ranges of masses, providing a finite length of the mixing zone. This has been shown for heavy neutron capture elements vs iron in the inhomogeneous chemical evolution model by [12]; the same approach has been used also for CNO (see [13]) to investigate the implications of the inhomogeneous modeling in the observed spread (in particular of the ratio N/O) in EMP stars.

It follows that also for the spread between the light and the heavy neutron capture elements we should investigate this model and so in this paper we use this scenario to analyze the impact of the new results for s-process in massive stars boosted by fast rotation [6].

2. Observational data

We adopt observational ratios from literature; the data for the neutron capture elements are those collected by [14] [1], taking into account only the stars belonging to the Galactic halo. Among the halo stars collected, we decide to differentiate the normal stars from the carbon enriched metal-poor (CEMP) stars. We follow the definition given by [15], so CEMP stars present a [C/Fe]>0.9 (for the details of the categories adopted among CEMP stars see [15]).

3. The chemical evolution models

The chemical evolution model is the same as adopted in [13], based on the inhomogeneous model developed by [12]. We consider that the halo consists of many independent regions, each with the same typical volume, and each region does not interact with the others. We decided to have a typical volume with a radius of roughly 90 pc and the number of assumed volumes is 100[2]. The dimension of the volume is large enough to allow us to neglect the interactions among different volumes, at least as a first approximation. In fact, for typical ISM densities, a supernova remnant becomes indistinguishable from the ISM – i.e., merges with the ISM – before reaching $\sim 50pc$ [16], less than the size of our region. We do not use larger volumes because we would lose the stochasticity we are looking for; in fact, as we tested for increasing volumes, the model tends to be homogeneous. In each region, we follow the chemical evolution equation and parameters as the homogeneous model by [10]. Yields for Fe are the same as [17]. The model takes into account the production by s-process from low-intermediate mass stars and SNIa enrichment, as in [18]. However, the bulk of the contribution of SNIa and AGB stars is seen mostly above [Fe/H] ~ -1.5, so the impact on our results is only marginal.

3.1 Stellar yields for heavy elements

3.1.1 *Empirical* yields for the r-process

As mentioned in the Introduction, the site of production of r-process elements is still a matter of debate. In particular, most of the neutron reactions involving r-process elements are out of reach of nuclear physics experiment. In such a situation, we can use observational data to guide the theoretical models for this process.

Given the above, we adopt here the following approach (see also [18]), namely: we compute a homogeneous chemical evolution model where the yields of Ba are chosen such as to reproduce the mean trend of [Ba/Fe] versus [Fe/H] (see Fig. 1). The latter are what we call here *empirical* yields. The *empirical* yields are obtained as the simplest array able to reproduce the observed the

[1] http://cdsarc.u-strasbg.fr/cgi-bin/qcat?J/AN/331/474

[2] We tested a larger number of volumes and find that our results converge after around 100 volumes although increasing considerably the computational time

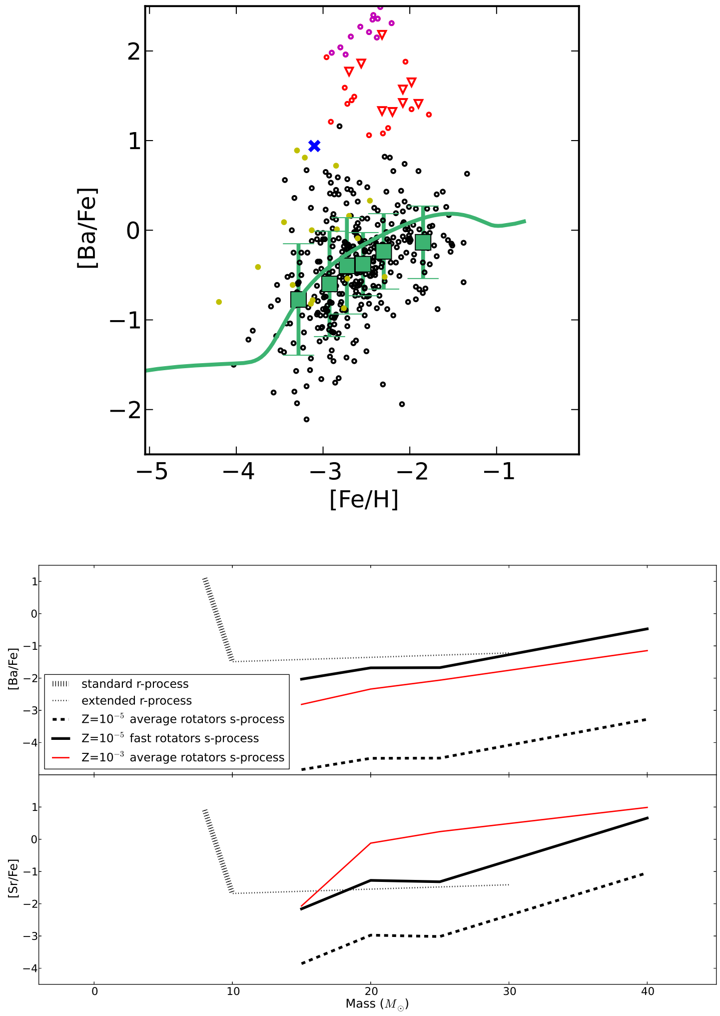

Figure 1: *Top:* [Ba/Fe] vs [Fe/H] abundances ratios of the stars gathered by [14]: black open circle are normal stars, red open circle for CEMP-s stars (open triangles without Eu value) magenta open circle for CEMP-rs, yellow filled circle for CEMP-no and blue x marker for the CEMP-r star. The error bars represent the mean and the standard deviations for the normal stars abundances calculated over different bins in [Fe/H]. The bins are calculated in such a way each bin contain the same number of data. The results of the homogenous model with the assumed "empirical" yields for Ba is shown by the solid line. *Bottom:* Yields used for the ratios of [Ba/Fe] and [Sr/Fe], as a function of the stellar mass and the metallicities. The **as-**, and **fs-model** come from unpublished results by Frischknecht (2011, PhD thesis); for details see Sect 3.1.2.

trend of increasing [Ba/Fe] with metallicity, but also present one important property, namely, the need for two different sites of production (see Fig. 1):

- a strong production in a narrow mass range 8-10$M_\odot$ that we call *standard* r-process site;
- an extended contribution coming from stars with larger masses (from 10 up to 30$M_\odot$), whose contribution is lower by $\sim$ 2 dex than that of the *standard* r-process, and which we name here as *extended* r-process site.

Finally, to find the corresponding r-process yield for Sr, we simply scale it to Ba according to the solar system r-process contribution, as determined by [19].

Interestingly the stellar mass range for *standard* r-process is close to the one predicted by theoretical models of O-Ne-Mg core SN (with initial masses toward the lower end of the massive stars). Notice, however that the recent models [2] do not succeed in producing heavy neutron capture elements such as Ba. On the other hand, similarly to the findings of [18], to be able to reproduce the trend of the stars with [Ba/Fe] ~ -0.7 at metallicities lower than [Fe/H] ~ -3, an r-process production in more massive stars is needed in the absence of any other process able to produce such an element at very-low metallicities. As we will see, this could be different once the contribution of *spinstars* is taken into account.

3.1.2 The contribution of *spinstars*

To illustrate the impact of *spinstars* to the chemical enrichment of Sr and Ba in the earliest phases of the Universe, we now focus on three sets of inhomogeneous chemical evolution models, computed with the following set of stellar yields (see Fig. 1):

- **r-model**: assume only the *empirical yields* for the r-process (*standard* + *extended*) (see Sect 3.1.1);
- **as-model**: assume only the *standard* r-process yields, plus the s-process yields coming from rotating stellar models;
- **fs-model**: similar to the model above, but with s-process yields coming from fast rotating stellar (spinstars) models.

The nucleosynthesis adopted in the **as-model** for the s-process comes from unpublished results by Frischknecht (2011, PhD thesis). In this set of yields, the s-process for massive stars is computed for an initial rotation velocity of v_{ini}/v_{crit}=0.4 [3] and for a standard choice for the reaction $^{17}O(\alpha,\gamma)$; they are composed of a grid of 4 stellar masses (15, 20, 25 and 40$M_\odot$) and 3 metallicities (solar metallicity,10^{-3}, 10^{-5}); in Fig. 1 we show the yields for the 2 lowest metallicity cases. We do not extrapolate the production toward stars more massive than 40$M_\odot$ (although it is realistic to have a production also in this range), but we extended the $Z = 10^{-5}$ grid down to Z=0. In addition to the s-process in massive stars, we take into account our empirical r-process enrichment but coming only from the *standard* r-process site. In this way we are decoupling the sites of production for the

[3] The critical velocity is reached when the gravitational acceleration is exactly counterbalanced by the centrifugal force

two processes. Interestingly, this figure suggests that the role of the "extended r-process" site can be played by the s-process of *spinstars*.

It is worth to point out that the yields we have used for the **as-model** are very conservative among the models computed by [6] for $25M_{\odot}$. A more extreme case of s-process production is what we used in the **fs-model**. This case is achievable if one considers the s-process yields for massive stars computed for a rotation rate of v_{ini}/v_{crit}=0.5 and for a reaction rate $^{17}O(\alpha,\gamma)$ one tenth of the standard choice. We do not have a fully computed grid for these parameters, but we have scaled the previous yields guided by the results obtained with these parameters for a $25M_{\odot}$ of $Z = 10^{-5}$ by [6] (cfr. in their paper Table 2), and applying the same factor to all the masses at $Z = 10^{-5}$, as shown in Fig. 1. Again, for this **fs-model**, in addition to the s-process in *spinstars*, we take into account the contribution by our empirical *standard* r-process.

4. Results

Our main results are summarized in Fig.2. We start by analyzing the results of the **r-model** (upper panel), which assumes only the contribution from massive stars via our *empirical* r-process yields. The spread obtained by this model matches the dispersion of [Ba/Fe] (upper, left panel), confirming that the hypothesis of a contribution by two distinct sites seems to be a good one to explain the data. In the particular case of this model, the two-sites of production are illustrated by a *standard* r-process which takes place in the lower mass range of the massive stars, and an *extended* r-process taking place in more massive stars. The first one is assumed to be much more efficient (larger quantities of ejected material) than the second.

A good match of the observed [Sr/Fe] is also obtained by the same model, especially at very metal-poor metallicities. As the Sr yields adopted here are obtained just by using the Ba/Sr ratio matching the observed solar system r-process [19], this ratio is simply constant with metallicity (as shown in the upper, right panel). This suggests that the some other physical process, taking place in the same mass range of what we have called *extended* r-process might be contributing to produce part of the Sr and Ba in the very early Universe (as the scatter is larger between metallicities -2.5 and -3.5). In other words, the **r-model** is useful to highlight the issue we are trying to solve in the present work.

Lets now turn to the results obtained with our **as-model** (see Fig 2, second row), and see the impact of the s-process production of Ba and Sr by rotating massive stars. In this case we added a rather conservative s-process production from *spinstars*, and turned off the contribution of what we have called *extended* r-process. The results for [Ba/Fe] and [Sr/Fe] are not completely satisfactory as the model cannot reproduce the low [Ba/Fe] ratios observed in extremely metal-poor stars with [Fe/H]< -3 (left and middle panels of the second row). This happens because this rather conservative model predicts not enough amounts of Sr, and particularly, of Ba (this can be seen in Fig. 1 by comparing the stellar yields of the *extended* r-process – dotted line – with the yields of the **as-model** at $Z = 10^{-5}$ – dashed line).

Despite the shortcomings described above, the interesting result of this model resides in the [Sr/Ba] plot (second row, right panel), where it is clear that this new process produces an over-abundance and creates a spread in [Sr/Ba] at [Fe/H] ~ -3. From this one can conclude that the s-process produced in rotating massive stars seems to act in the correct direction. Nevertheless,

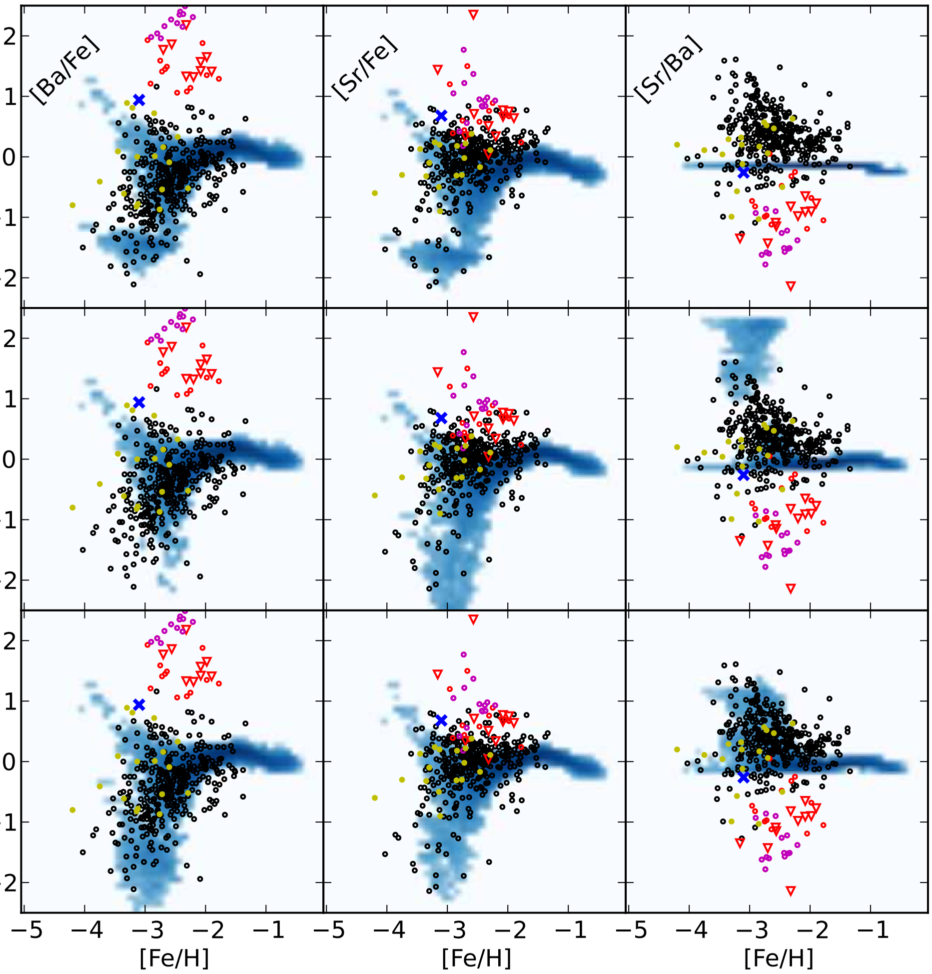

Figure 2: On the left [Ba/Fe], on the center [Sr/Fe], on the right [Sr/Ba], vs [Fe/H]. Upper, center and lower panels for **r-**, **as-** and **fs-model** respectively. The density plot is the distribution of simulated long living stars for the model. Superimposed, we show the abundances ratios of the stars gathered by [14]. The symbols adopted are the same as Fig. 1 (top panel).

these results are affected by the ratio of the yields of Sr and Ba predicted by this specific stellar evolution model (similar to model B1 of [6]). These prescriptions produce [Sr/Ba]>2, whereas the EMP stars show at maximum [Sr/Ba]∼1.5.

Finally for the **fs-model** (Fig 2, bottom panels), where we adopted less conservative stellar models predicting even larger s-process enrichment (essentially due to a larger v_{ini}/v_{crit} and a lower $^{17}O(\alpha,\gamma)$ reaction rate similar to the model B4 of [6] – see Section 3.1), the theoretical predictions and observations show an striking agreement. This model not only reproduces well the [Ba/Fe] and [Sr/Fe] scatter (left and middle bottom panels), but can also account for the observed [Sr/Ba] spread (right bottom panel), at the right metallicity interval. This shows that with a less conservative production of s-process in fast rotating massive stars (as is the case in the **fs-model**), this process could play the same role as our *extended* r-process in the **r-model**. In addition, it shows that a *standard* r-process (taking place in the lower mass range of the massive stars) enters at play with a weight that increases as the metallicity increases (still in the very metal-poor range).

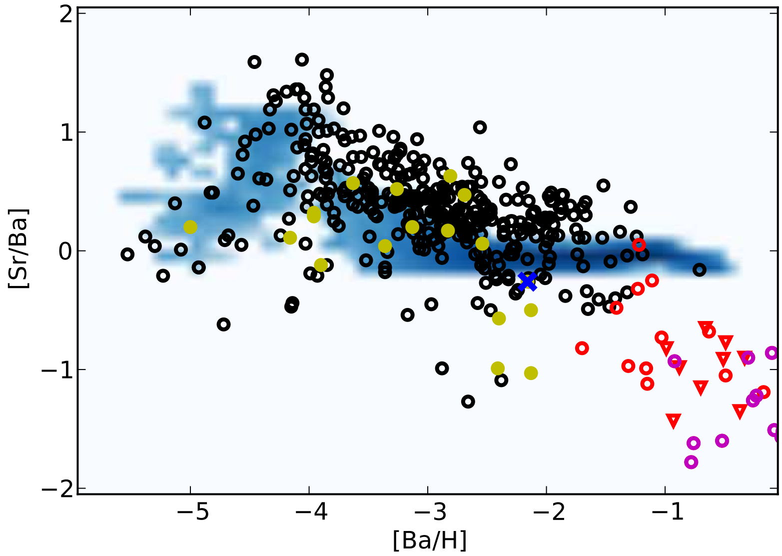

Figure 3: [Sr/Ba] vs [Ba/H], the density plot is the distribution of simulated long living stars for **fs-model**, Superimposed, we show the abundances ratios of the stars gathered by [14]. The symbols adopted are the same as Fig. 1.

In Fig. 3, we show the same results presented in the lower right plot of Fig.2 but using [Ba/H] on the x-axis. Indeed [Fe/H] on the x-axis is the most common way to present these figures but using instead the [Ba/H] we avoid the assumption regarding the iron yields. The point is that these yields are naturally bounded to the still not completely understood SNII explosion mechanism. Our model reproduces also in this case the peculiar behavior seen in EMP stars, namely, a high ratio of [Sr/Ba] at low [Ba/H], and the correct amount of scatter, proving that the assumption on iron yields is not influencing our results.

5. Discussions and conclusions

We have developed an inhomogeneous chemical evolution model for the halo with the aim of explaining the observed scatter (or lack of) in the abundance ratios of key chemical elements in very metal-poor stars. The models presented here serve as a test-bench to study the different nucleosynthetic prescriptions proposed by different stellar evolution groups. The goal is to identify key abundance ratios, as well as the most promising stellar yields, to be then implemented in cosmological simulations (a project that we are already pursuing).

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We first show that one can predict the observed spread of [Ba/Fe] and [Sr/Fe] in EMP stars with an inhomogeneous chemical evolution model taking into account the stochastic formation of stars of different masses in the early phase of the Galactic halo. The latter assumption, when coupled with a production of neutron capture elements coming from: a) a relatively rare, but efficient, site of production (here illustrated by a contribution of stars in the 8-10 $M_{\odot}$ mass range), and b) a second site of production, which is less efficient producing lower amounts of neutron capture (here illustrate with a contribution from stars in the 10-40 $M_{\odot}$ mass range). More importantly, we show that despite the good agreement with the observed spread of [Ba/Fe] and [Sr/Fe], an extra process is needed to explain the observed [Sr/Ba] scatter.

The presence of r-process rich stars, with a common strong r-process signature, is an observational constraint for the first site of production: if this site produces strong enhancement in a relatively rare events, then we can provide a solution for these stars. Here we show that keeping fixed this first site of production, but adding the contribution to the neutron capture elements by fast rotating massive stars (now considered as second site of production), then it is possible to create a scatter in the ratio of [Sr/Ba], as observed.

In particular, if we consider stellar models for fast rotating massive stars (**fs-model**) that are less conservative in their assumptions, we are then able, for the first time in our knowledge, to reproduce simultaneous the [α/Fe], [Sr/Fe], [Ba/Fe] and [Sr/Ba] trends and scatter observed in halo stars with an inhomogeneous chemical evolution model. Although the proposition that the scatter in the observed spread between heavy and light neutron capture elements in EMP stars could be due to the contribution of *spinstars* had been made before ([7]), here we show for the first time quantitative estimates that seem to confirm this hypothesis. Notice that 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.

Our results also show that to reconcile the model to the observations we need an r-process site of production decoupled from the one of s-process. We assumed here the most straightforward solution, which is to consider two different mass ranges for the two processes, but other solutions providing a large amount of r-process production in only a fraction (roughly 15%) of the massive stars would be equally valid, as in the case of magnetorotationally driven supernovae, described by Thielemann in his contribution.

Acknowledgments

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Questions

Chiaki Kobayashi: Can you explain the details of your inhomogeneous models because the results, in particular x-axis, highly depend on these?

Gabriele Cescutti: We set the parameters of our chemical evolution model to be able to reproduce the MDF observed in the halo. The fact that the model is formed by several independent volumes in which the stars are chosen stochastically (cumulatively following the assumed IMF), does not change the overall trend and the average over the different volumes is still reproducing the MDF (see Fig.2). Moreover, if we use in x axis the [Ba/H] relaxing the issue in the assumption of the iron yields, we are still reproducing the observational data.

Chiaki Kobayashi: Can you also explain the distribution of [C/Fe] and [N/Fe] as well?

Gabriele Cescutti: Using the same chemical evolution model, we have shown in Cescutti & Chiappini 2010, that the spinstars predictions for CNO are able to reproduce the [C/Fe] and [N/Fe].

Brad Gibson: What is your predicted distribution of even-to-odd Ba isotopes in the halo? How does it compare to what (little) we know about such ratios (eg. Mashonkina et al 2003)?

Gabriele Cescutti: For the stars showing a high [Sr/Ba] ratio at [Fe/H]< -2 we expect to find a isotopic fraction typical of the s-process, being their abundances produced by s-process from spinstars, according to the presented model. The comparison with the results of Mashonkina et al. (2003) is not straightforward, since they measured isotopic ratios for stars of higher metallicity. Nevertheless, our model predicts in that metallicity range a mixture of r- and s-process, which is in agreement with the results by Mashonkina et al. (2003).