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The impact of stellar rotation on the CNO abundance patterns in the Milky Way at low metallicities

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Cristina Chiappini[*][†]
Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, I - 34131 Trieste, Italia
E-mail: `Christina.Chiappini@obs.unige.ch`

Hirschi, R.
Dept. of Physics and Astronomy, University of Basel, CH-4056, Basel, Switzerland

Matteucci, F.
Dipartimento di Astronomia, Universitá degli Studi di Trieste, Via G. B. Tiepolo 11, I - 34131 Trieste, Italia

Meynet, G., Ekström, S., Maeder, A.
Observatoire Astronomique de l'Université de Genève, CH-1290, Sauverny, Switzerland

We investigate the effect of new stellar models, which take rotation into account, computed for very low metallicities (Z = 10^{-8}) on the chemical evolution of the earliest phases of the Milky Way. We check the impact of these new stellar yields on a model for the halo of the Milky Way that can reproduce the observed halo metallicity distribution. In this way we try to better constrain the ISM enrichment timescale, which was not done in our previous work ([8]). The stellar models adopted in this work were computed under the assumption that the ratio of the initial rotation velocity to the critical velocity of stars is roughly constant with metallicity. This naturally leads to faster rotation at lower metallicity, as metal poor stars are more compact than metal rich ones. We find that the new Z = 10^{-8} stellar yields computed for large rotational velocities have a tremendous impact on the interstellar medium nitrogen enrichment for log(O/H)+12 $<$ 7 (or [Fe/H]< -3). We show that upon the inclusion of the new stellar calculations in a chemical evolution model for the galactic halo with infall and outflow, both high N/O and C/O ratios are obtained in the very-metal poor metallicity range in agreement with observations. Our results give further support to the idea that stars at very low metallicities could have initial rotational velocities of the order of 600-800 km s^{-1}. An important contribution to N from AGB stars is still needed in order to explain the observations at intermediate metallicities. One possibility is that AGB stars at very low metallicities also rotate fast. This could be tested in the future, once stellar evolution models for fast rotating AGB stars will be available.

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[*] Speaker.
[†] Currently on sabbatical at the Observatoire de Geneve, Sauverny, Switzerland

1. Introduction

Recent measurements of nitrogen abundances in metal-poor stars by Spite et al. [20] show a large N/O ratio suggesting high levels of production of primary nitrogen in massive stars. Moreover, the N/O abundance ratios in metal-poor stars exhibit a large scatter (roughly 1 dex, much larger than their quoted error bars) although none of the stars measured so far has N/O ratios as low as the ones observed in DLAs.

Last year, Chiappini et al. [7] studied the implications of this new data set for our understanding of the nitrogen enrichment in the Milky Way (MW). By the time the latter paper was published there was no set of stellar yields able to explain the very metal-poor data of [20]. Using the so-called Z=0 population III stellar yields available in the literature (which in some cases predict large N yields for non-rotating massive stars with masses around 20 $M_{\odot}$ - e.g. [9]) did not solve the problem either. The main reason is that in population III non rotating models the N production is confined to a very narrow mass range and hence chemical evolution models computed with such prescriptions predict a peak in the [N/Fe] ratios at very low metallicities followed by a strong decrease already before [Fe/H] ~ -3 in disagreement with the observations of [20] (see [3]). This happens even when allowing the Z=0 contribution to be valid up to a threshold (Z_{tr}) metallicity above which population III stars stop forming of the order of $Z_{tr}=10^{-6}$. This Z_{tr} metallicity is probably already too high as the physics adopted in the Z=0 models would be valid only up to metallicities $Z\sim10^{-10}$, which represents the metallicity below which massive stars first enter the phase of H-burning via the pp chain, followed by the 3α reaction, which then allows the CNO cycle to proceed, as in Z=0 (population III) stars.

Given the above discussion, [7] suggested that the most promising way to account for the new data was to assume that stars at low metallicity rotate sufficiently fast to enable massive stars to contribute much larger amounts of nitrogen. It was shown that even when adopting the Meynet & Maeder [14] stellar yields (these authors had computed stellar yields down to $Z=10^{-5}$) where the nitrogen production is increased in stars of all masses due to rotation, it was not possible to explain the observations of [20]. The approach of [7] was to assume that the stellar yields computed by [14] were valid down to $Z=10^{-5}$, but that below this metallicity some mechanism should be able to increase even more the N yields. It was then predicted that massive stars born with metallicities below $Z=10^{-5}$ should produce a factor between 10 and a few times 10^2 more nitrogen (depending on the stellar mass) than the values given by [14] for $Z=10^{-5}$ and $\upsilon_{\rm rot}^{\rm ini} = 300\,{\rm km\,s^{-1}}$ in order to reproduce the *mean* locus of the Spite et al. data in a log(N/O) vs. log(O/H)+12 diagram.

The physical motivation for the approach described above would be an increase of the rotational velocity in very metal-poor stars [13, 15] and hence an increase in the nitrogen yields. In this framework it is possible to understand the apparent contradictory finding of [20] namely, a large scatter in N/O and the almost complete lack of scatter in [α/Fe] ratios of the same very metal-poor halo stars [5]. As suggested in [7], if the nitrogen production in very metal-poor massive stars depends strongly on the rotational velocity of the star, this could explain the scatter in the N/O abundance ratios: the scatter would reflect the distribution of the stellar rotational velocities as a function of metallicity whereas the [α/Fe] ratios would remain unchanged.

Whether the above suggestions were physically plausible remained to be assessed by stellar evolution models computed at lower metallicities, which took rotation and mass loss into account.

Novel stellar evolution models have been computed for metallicities Z=10^{-8} [10] for massive stars. The new calculations show that if the stars at all Z start their life on the zero age main sequence (ZAMS) with on the average a fraction of ~ 0.5 the critical velocity, the low Z stars easily reach break-up velocity during MS evolution (see also Meynet et al., this conference). Fast rotation also contributes to produce a more efficient mixing at lower Z, which leads to a large production of N in massive stars. We note that the new models with fast rotation also predict different type of supernova progenitors, final remnants and yields in heavy elements at very low Z ([15] and references therein).

In a recent paper, Chiappini et al. [8] computed chemical evolution models adopting these new stellar prescriptions and show that these new models can explain not only the high N/O in very metal poor stars but also predict an increase in C/O for decreasing metallicity. However the model computed by [8] did not include outflows during the halo phase thus leading to an increase of [Fe/H] with time faster than what would be obtained with an outflow model. Moreover, as shown by [18], halo models that can reproduce the metallicity distribution of halo stars should include both inflow and outflow.

Here we compute such a model and compare our new results with the ones we obtained in [8]. Finally, in [8] we considered only the so-called *normal* very metal-poor stars, since our goal was to explain the mean ISM enrichment at very low metallicities. Here we place the carbon rich ultra metal-poor stars [4] into this context and discuss the implications for the CNO nucleosynthesis.

2. Results obtained with a "halo" model without outflow

In this section we show the results obtained in [8] who computed the evolution of the CNO elements, in the solar vicinity, predicted by a chemical evolution model computed with different stellar yield sets for metallicities below Z=10^{-5} for massive stars[1]. The adopted stellar yields for $Z \leq 10^{-5}$ are shown in Fig. 1.

In Fig. 1, filled squares show stellar yields of [14] for their lowest metallicity case (Z=10^{-5}) resulting from models with rotation ($\upsilon_{\rm rot}^{\rm ini} = 300\,{\rm km\,s^{-1}}$), while open symbols stand for models computed with $\upsilon_{\rm rot}^{\rm ini} = 0\,{\rm km\,s^{-1}}$. The asterisks connected by the long-dashed line show the *ad hoc* stellar yields for metallicities $Z<10^{-5}$ adopted in the *heuristic model* of [7] for massive stars. The dots show the new results obtained by [10] for Z=10^{-8} for massive stars. The stellar yields for the Z=10^{-8} case were computed according to the following assumption: *stars begin their evolution on the ZAMS with approximately the same angular momentum content, regardless of their metallicity*. At solar metallicity, observations indicate a mean rotational velocity of a 60 $M_\odot$ star on the MS of the order of $200\,{\rm km\,s^{-1}}$, which corresponds to an initial angular momentum of the order of $2 \times 10^{53}\,{\rm g\,cm^2\,s^{-1}}$ (see [15] for details). At a metallicity of Z=10^{-8} this corresponds to $\upsilon_{\rm rot}^{\rm ini} = 800\,{\rm km\,s^{-1}}$. In other words, we adopt a rotational velocity such that the ratio between $\upsilon_{\rm rot}^{\rm ini}/\upsilon_{\rm breakup}$ remains almost constant (around 0.5) with mass and metallicity (see [10] for details). The very interesting result is that the new computations by Hirschi [10] for Z=10^{-8} predict a large increase of the N yields for stars above 20 $M_\odot$, similar to the *ad hoc* yields of [7].

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[1] For low and intermediate mass stars we adopt [14] stellar yields with rotation, and assume that their table computed for Z=10^{-5} is valid down to Z=0., as in Chiappini et al. 2003.

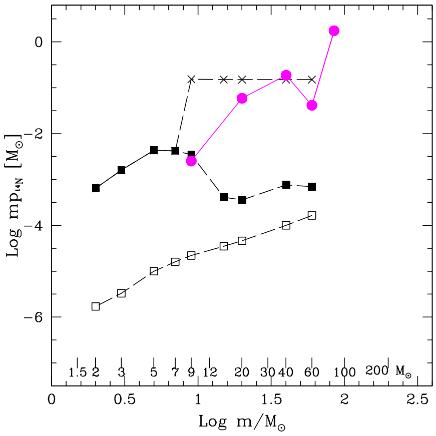

Figure 1: Stellar yields for ^{14}N at low metallicities for the whole stellar mass range. The yields of [14] for stellar models with and without rotation for Z = 10^{-5} are shown by filled and open squares respectively. The asterisks connected by the long-dashed line show the *ad hoc* stellar yields adopted for Z$<10^{-5}$ in the heuristic model of [7] (see text). The filled circles show the new stellar yields computed for massive stars born at Z=10^{-8}. The new computations of Hirschi [10] for Z=10^{-8} lead to a large increase of N yields for masses above ∼20 M$_\odot$, similar to the predictions of [7]. This agreement is striking considering that they were obtained from completely different approaches.

Figure 2 shows the predicted evolution of our chemical evolution model without outflow (see model details in [8]) for N/O and C/O for 3 different cases: a) solid line (black) - a model computed under the assumption that the lowest metallicity yields table computed by [14] for Z=10^{-5} and $\upsilon_{\rm rot}^{\rm ini} = 300\,{\rm km\,s^{-1}}$ is valid down to Z=0. In this case the model flattens (upper panel) for log(O/H)+12 $<$ 6.6 due to the contribution by massive stars to the nitrogen predicted by stellar models where rotation is included. However, it is not enough nitrogen to explain the observations. This model also predicts a C/O ratio that decreases with decreasing metallicity; b) dot-dashed line (red - upper pannel) - the *heuristic* model of [7] were an *ad hoc* larger yield of nitrogen is assumed for metallicities below Z=10^{-5} (as shown by the asterisks in Fig.1); c) dashed curve (black) - the model of [8] computed with 4 yield tables for Z = 0.020, 0.004 and 10^{-5} from [14] (for $\upsilon_{\rm rot}^{\rm ini} = 300\,{\rm km\,s^{-1}}$) and the new stellar yields of [10] for Z=10^{-8} (for $\upsilon_{\rm rot}^{\rm ini} = 500 - 800\,{\rm km\,s^{-1}}$ depending on the stellar mass). The latter model is able to explain the [20] data and confirms the suggestion made in [7] that rotation could be the solution for the *N-problem*. For the C/O ratio this model predicts an increasing C/O ratio with decreasing O/H.

Figure 3 shows the evolution of [C/Fe], [N/Fe] and [O/Fe] as functions of [Fe/H] for the same models (for the meaning of the dotted (blue) curve both in Figs. 2 and 3, see next section).

The results shown both, in Fig. 2 and Fig. 3 for the dashed curve implies that faster rotation is able to explain the observations of Spite et al. ([20] - asterisks in these figures), accounting for the almost solar N/O ratios found by these authors for metal-poor *normal* halo stars. An interesting result is also seen for C/O, where the new model leads to an upturn of this abundance ratio at low metallicities that can be explained in two ways: a) the high production of primary N implies a very active H-burning shell, which contributes a large part of the total luminosity of the star. As a consequence, part of the total luminosity compensated by the energy produced in the helium core is

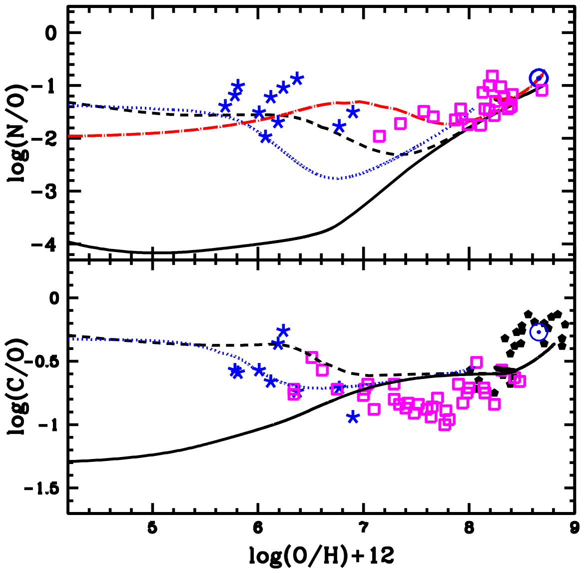

Figure 2: Solar vicinity diagram log(N/O) vs. log(O/H)+12 (upper pannel) and log(C/O) (lower panel). The data points are from: [11] for N/O and [1] for C/O (large squares), [20] for N/O and [5] for C/O (asterisks) and from [16] (filled pentagons). Solar abundances ([2] and references therein) are also shown. For the meaning of the different curves, see Section 2.

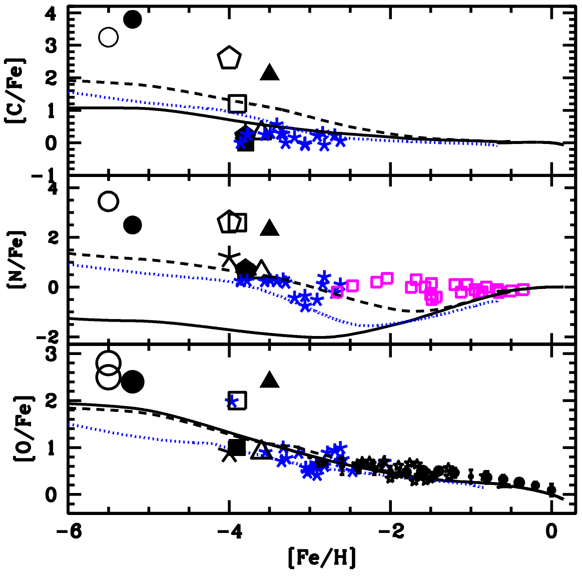

Figure 3: The evolution of [C/Fe], [N/Fe] and [O/Fe] as functions of [Fe/H]. For the meaning of the curves, see Section 2. The small asterisks show the data of Spite et al. [20]. In the middle panel, the small squares are data from [11]. In the bottom panel the small dots are from [12]. The large symbols show some of the very metal poor stars discussed in Beers and Christlieb review ([4] and references therein). These stars are labelled as follows:G77 61 (open pentagon), CS22885-096 (filled pentagon), CS22949-037 (open square), BS 16467-062 (asterisk), CS22172-002 (filled square), CS22968-014 (open triangle) and CS2 29498-043 (filled triangle).

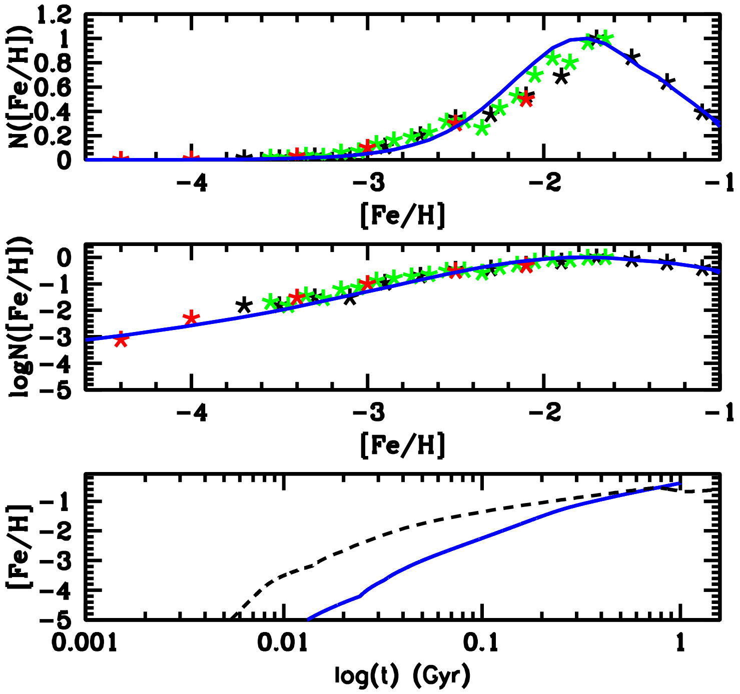

Figure 4: Upper panel: Halo metallicity distribution normalized to one (linear). Middle panel: the same as in the upper panel, but in log-scale. The data points are from [19] (black), [4] and Beers and Christlieb (priv. com) (green) (upper pannel) and from [17] (red). The data points of Beers and collaborators were shifted by -0.4 dex to match the distribution peak of [19] around [Fe/H]=-2. Lower panel: the evolution of the metallicity with time (for the meaning of the curves, see text).

reduced, making the average core temperature and thus the efficiency of the ^{12}C$(\alpha,\gamma)^{16}$O reaction lower; b) more efficient mixing also leads to larger mass loss, decreasing the He-core size. Higher C/O ratios are thus obtained at the end of the He-burning phase.

3. Results obtained with a halo model with outflow

The chemical evolution model discussed above nicely fits the observed data for N/O and C/O ratios at low metallicities. However, as nicely shown by [18], the enrichment timescale (i.e. the time that it takes for the ISM to reach a certain metallicity or, equivalently, the lower mass contributing to the ISM enrichment at a given log(O/H)+12 or [Fe/H]) is still unknown in the case of the galactic halo. The situation is different for the solar vicinity where we have many more observational constraints. Processes like outflows can change the enrichment timescale. However, in the last years more data on metal poor halo stars have been obtained (see Beers, this conference) and it is now possible to better estimate the halo metallicity distribution. The latter is an important constraint on the enrichment timescale of the galactic halo.

In this section we show the results obtained with a different model for the galactic halo. In this case we assume a) a gaussian infall ($f(t) \propto e^{(t-t_0)^2/2\sigma^2}$, with t_0 =0.1 Gyr and $\sigma = 0.05$); b) an outflow rate of 8 times the star formation rate; c) a Schmidt law for the star formation rate. The halo metallicity distribution obtained with the latter model is shown in Fig. 4 and it is in good agreement with observations. In the lower panel of Fig. 4 it is seen that this model (solid blue line) predicts a slower ISM enrichment compared to the model without outflow, as expected. While in our previous model a 8 $M_\odot$ star would die at a metallicity [Fe/H]~ -2.2, in the new model with outflow the same star would die when the metallicity in the ISM was [Fe/H]~ -3.8. The resulting predictions for the abundance ratios of C/O, N/O, C/Fe, N/Fe and O/Fe in this case are shown in Figs. 2 and 3 by the dotted (blue) line.

As it can be seen in these figures, this model gives the same qualitative results as the ones of our previous models ([8] and previous Section). This means that even if the AGB start contributing earlier on (in terms of metallicity) they are still unable to contribute an important amount of N at the very low metallicities sampled by the Spite et al. data. Quantitatively, things change a little bit and the lack of agreement both in the N/O and N/Fe plots at intermediate metallicities (already present in our earlier models, see [8]) becomes even more evident. This means that although these models can well explain the quantities of N at very low metallicities, they underproduce this same element at intermediate metallicities.

However, as already stressed in [8], here we did not take fully into account the contribution of the AGBs to the N enrichment. First, for the low and intermediate mass stars we are adopting the stellar yields of [14] where no 3rd dredge-up was included, and thus these yields represent a lower limit for the N yields. Second, AGB stars could also rotate faster at lower metallicities and this was not implemented in our models as stellar models for fast rotating AGBs in very metal poor environments are still not available. Third, we also did not include the contribution of the super-AGB stars which supposedly contribute essentially to N. In the same intermediate metallicity range we see that our models overestimate the C/O ratios. There is thus room to increase N through processes that consume C as it is for instance the case of HBB.

Finally, we notice that the so called "carbon rich very metal poor stars" [4] are still located above our chemical evolution model curves (see Fig.3). However, for N, their locus is much closer to what is expected for the ISM evolution at such very low metallicities once fast rotation is taken into account than in the case of slowly rotating models (solid line). This means that the "extra" N needed to explain stars like the two most metal poor ones is less than usually assumed. As shown by [15] and [10] it is probably possible to account for this difference by invoking metal enrichment only by stellar winds for stars with $M \geq 30 M_\odot$.

4. Conclusions

In this work, we computed chemical evolution models adopting the very recent calculations of Hirschi [10] for the evolution of massive stars at very low metallicities under the assumption of an almost constant ratio $\upsilon_{\rm rot}^{\rm ini}/\upsilon_{\rm breakup}$ as a function of metallicity (i.e. where the $\upsilon_{\rm rot}^{\rm ini}$ increases towards lower metallicities). In such a framework, massive stars can produce large amounts of nitrogen.

At present, this is the only way to explain the high nitrogen abundances measured recently in *normal* halo stars. This gives further support to the idea that stars rotate faster at very low metallicities. The new stellar evolution models also produce some extra carbon at $Z \leq 10^{-5}$. As a consequence, an upturn is produced in the C/O at low metallicities. This result is obtained without the need of introducing population III stars (here understood as Z=0 stars with a flatter IMF).

The only alternative to explain the observations showing a high N abundances in very metal poor normal stars[2] would be if AGB stars would contribute to the ISM enrichment before [Fe/H]~ -4. This would mean that the timescales for the chemical evolution of the halo would be very different from the ones of [8]. Models assuming outflows could delay the ISM enrichment so that AGBs would have time to contribute. Here we show that a model with outflow, which is able to fit the observed halo metallicity distribution and in which the ISM is enriched on longer timescales than the ones computed by [8], still gives the same qualitative result. In fact, this model still requires to invoke fast rotation at very low metallicities to explain the high N/O observed in metal poor halo stars. Future surveys of very metal poor stars (see Beers this conference) will certainly lead to a more complete halo metallicity distribution and will be extremely useful to constrain even better the halo enrichment timescale.

Here we show the results for the mean ISM enrichment history, assuming that at a given metallicity all stars of a given mass rotate at the same velocity. Further computations are in progress, and we envision to compute chemical evolution models in which a distribution of rotational velocities is assumed for each metallicity. These models would predict a scatter in N/O to be compared to the observed one.

Acknowledgments

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[2] Here, "normal" stands for the assumption that these stars show a pristine N abundance which reflects the one of the ISM gas from which these stars formed and did not come from any internal mixing process or binary mass transfer.

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