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The origin of nitrogen

Implications of recent measurements of N/O in Galactic metal-poor halo stars

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Abstract. Recent new high-precision abundance data for Galactic halo stars suggest important primary nitrogen production in very metal-poor massive stars. Here, we compute a new model for the chemical evolution of the Milky Way aimed at explaining these new abundance data. The new data can be explained by adopting: a) the stellar yields obtained from stellar models that take into account rotation; and b) an extra production of nitrogen in the very metal-poor massive stars. In particular, we suggest an increase of nearly a factor of 200 in ^{14}N for a star of 60 $M_{\odot}$ and $\simeq$40 for a star of 9 $M_{\odot}$, for metallicities below $Z = 10^{-5}$, with respect to the yields given in the literature for $Z = 10^{-5}$ and rotational velocity of 300 km s^{-1}. We show that once we adopt the above prescriptions, our model is able to predict high N/O abundance ratios at low metallicities and still explains the nitrogen abundances observed in thin disk stars in the solar vicinity. The physical motivation for a larger nitrogen production in massive stars in very metal-poor environments could be the fact that some stellar models as well as observational data suggest that at low metallicities stars rotate faster. If this is the case, such large nitrogen production seen in the pristine phases of the halo formation would not necessarily happen in Damped Lyman-α systems which have metallicities always above [Fe/H] $\simeq -2.5$, and could have been pre-enriched. We also compute the abundance gradient of N/O along the Galactic disk and show that a negative gradient is predicted once we adopt stellar yields where rotation is taken into account. The latter result implies that intermediate mass stars contribute less to the primary nitrogen than previously thought.

Key words. stars: rotation – Galaxy: evolution – Galaxy: formation

1. Introduction

Investigating the origin of nitrogen in galaxies has been a major topic of research in the past few years. The reason is at least two-fold: *i)* there are many processes involved in the computation of the stellar yields of nitrogen and hence there are still many uncertainties present in these calculations (see Meynet & Maeder 2002a – hereafter MM02). Meynet & Maeder have shown that stellar rotation and mass loss can affect the predictions of the stellar yields especially for He, C, N and O. Chemical evolution models can thus be used to test and constrain the stellar yields (see François et al. 2004); *ii)* a large amount of data is available for the N/O abundance ratio in different environments, ranging from spiral galaxies (e.g. Pilyugin et al. 2004, and references therein) to dwarf galaxies (see Mouhcine & Contini 2002; Larsen et al. 2001, and references therein) and damped Lyman alpha systems, hereafter DLAs (e.g. Centurion et al. 2003; Prochaska et al. 2002; Pettini et al. 2002). In the latter case, the nitrogen evolution carries important information on the still-debated nature of these systems.

It has been recently shown (Chiappini et al. 2003, hereafter CMM03) that models of chemical evolution computed with the MM02 yields for the whole range of masses, predict a slower increase of nitrogen than what is obtained with other sets of stellar yields, with important implications for the interpretation of the DLA abundance data. Due to the slower increase of nitrogen in time, the DLA abundance patterns can be reproduced by "bursting models" (see also Lanfranchi & Matteucci 2003) and in this framework, the "low N/O" and "high N/O" groups of DLAs (first identified by Prochaska et al. 2002) could be explained as systems that show differences in their star formation histories rather than an age difference. We were able to obtain models that show both a low log(N/O) and a low [O/Fe] (of the order of [O/Fe] $\sim$ 0.2−0.3 dex, in agreement with observations – Centurion et al. 2003) during almost all their evolution. Alternative interpretations (e.g. Prochaska et al. 2002; Centurion et al. 2003) of the "low N/O" DLAs suggested in the literature would imply [O/Fe] ratios larger than the observed ones. DLAs could also be identified with outer regions of spiral galaxies (Hou et al. 2001; Calura et al. 2003) but in this case DLAs with low log(N/O) necessarily would be quite young systems (younger than ~150 Myr – see Fig. 11 of CMM03) and no discontinuity in the log(N/O) vs. log(O/H) diagram would be expected.

However, as pointed out in CMM03, it remains to be seen to what extent the MM02 yields for ^{14}N in the intermediate mass star range would increase once hot bottom burning (HBB) is taken into account. Although MM02 did not formally include the third dredge-up and HBB, it is worth studying the effects of their yields on chemical evolution models for the following reasons: a) The MM02 yields for nitrogen at low metallicity result from a new process whose importance for chemical evolution has still to be studied. In the absence of a real quantitative assessment of the importance of the HBB it is interesting to study the importance of this new process, which produces "non-parametric" yields, independently of HBB; and b) this is particularly justified in view of the fact that this new process gives primary nitrogen yields at low metallicity not very different from those obtained from parametric studies such as van den Hoek and Groenewegen (1997 – hereafter vdHG97). This questions the importance of the HBB[1]. Only by studying the effects separately it will be possible to understand the different consequences of the two processes.

In the massive range, the yields of MM02 predict some primary nitrogen production[2]. In CMM03 we showed that models for the MW computed with this new set of yields show a plateau in log(N/O), due to massive stars with initial rotational velocities of 300 km s^{-1}, at $\log(\mathrm{N/O}) \sim -4$. This value is below the value of -2.2 dex observed in some DLAs and hence we suggested that in these systems both massive and intermediate mass star, would be responsible for the nitrogen enrichment (in agreement with the conclusions of Chiappini et al. 2003 and Henry et al. 2000). This is instead at variance with recent claims that massive stars are the only ones to enrich systems that show a $\log(\mathrm{N/O}) \sim -2.2$. However, one should keep in mind that stellar evolution calculations for N and O in massive stars depend strongly on the adopted rotational velocities and mass loss rates, respectively.

More stringent constraints on nitrogen nucleosynthesis come from the study of the nitrogen abundances in stars in the MW since they represent a true evolutionary sequence, where the stars with lower metallicity are the oldest ones (Matteucci 1986). Moreover, the halo very metal poor stars play a fundamental role since, at metallicities below $[\mathrm{Fe/H}] = -3$, only type II supernovae have had time to contribute to the interstellar medium enrichment from which these stars formed, thus offering a way to constrain the nitrogen production in massive stars at low metallicities (the same is true for other elements as shown by François et al. 2004). On the other hand, an important constraint on the nitrogen production in intermediate mass stars (and thus also on the HBB) is the variation of the N/O abundance ratio with galactocentric distance. As shown by Diaz & Tosi (1986), in spiral galaxies, the steepness of the abundance gradient of N/O decreases as the primary nitrogen production in intermediate mass stars increases (see also Chiappini et al. 2003).

When we published our two last papers on the evolution of CNO in galaxies (Chiappini et al. 2003 and CMM03) no conclusive data was available for nitrogen in metal-poor halo stars. This situation has now greatly changed. New data on nitrogen abundances in metal-poor stars (by Spite et al. 2005 and Israelian et al. 2004) show a quite surprising result: a high N/O ratio suggestive of high levels of production of primary nitrogen in massive stars. Moreover, the N/O abundance ratios in metal-poor stars show 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.

In the present paper we will study the implications of these new data sets for our understanding on the nitrogen enrichment in our galaxy. In Sect. 2 we briefly present our model for the MW and the adopted stellar yields. Section 3 is devoted to the comparison between our models for the MW and the new data now available for the solar vicinity. We will show that currently there is no set of stellar yields able to explain the very metal-poor data of Spite et al. (2005). Invoking the so-called population III stellar yields available in the literature does not solve the problem as it still leads to inconsistencies if one considers other abundance ratios, for instance C/Fe. This section also includes, for the first time, our predictions for the abundance gradients of N/O and C/O once the MM02 stellar yields are adopted. We will show that the N/O abundance gradient represents a powerful tool to assess the importance of HBB in intermediate mass stars. In Sect. 4 a discussion is presented where we point out ways to account for these new observations and check their implications for our previous conclusions on the nature of DLAs.

2. Stellar yields and chemical evolution model

In the present work we adopt the stellar yields described in MM02 and CMM03[3]. In Fig. 1 we plot the nitrogen yields of MM02. Filled squares show stellar yields resulting from models with rotation ($V_{\mathrm{rot}} = 300\ \mathrm{km\,s^{-1}}$), while open symbols stand for models computed with $V_{\mathrm{rot}} = 0\ \mathrm{km\,s^{-1}}$. MM02 computed stellar yields for the following metallicities: $Z = 0.020$ (solid lines), $Z = 0.004$ (short-dashed lines) and $Z = 0.00001$ (long-dashed lines). The asterisks connected by the long-dashed line show the stellar yields we adopted for metallicities $Z < 10^{-5}$ in our heuristic model (see Sect. 3).

Two important findings can be seen in Fig. 1: *i)* in the lowest metallicity case, rotation increases the nitrogen production in stars of all masses and *ii)* the increase of nitrogen, at $Z = 0.00001$, is especially important in low and intermediate

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[1] Marigo (2003) showed that variable molecular opacities may decrease the efficiency of HBB – or even prevent it in some cases – especially in the more massive AGB stars.

[2] We call attention to the fact that the MM02 yields for helium are currently the only ones to ensure a good agreement between chemical evolution models for the Milky Way (hereafter MW) and the solar helium abundance – see CMM03. This is essentially due to mass loss in massive stars. In the massive range, the yields computed by MM02 for He, C, N and O would be essentially unchanged by explosive nucleosynthesis and can thus be considered robust calculations which take into account important physics (i.e. rotation and mass loss – see Hirschi et al. 2004 for a detailed description of these models for massive stars).

[3] For type Ia SNe we adopted the stellar yields of model W7 of Thielemann et al. (1993).

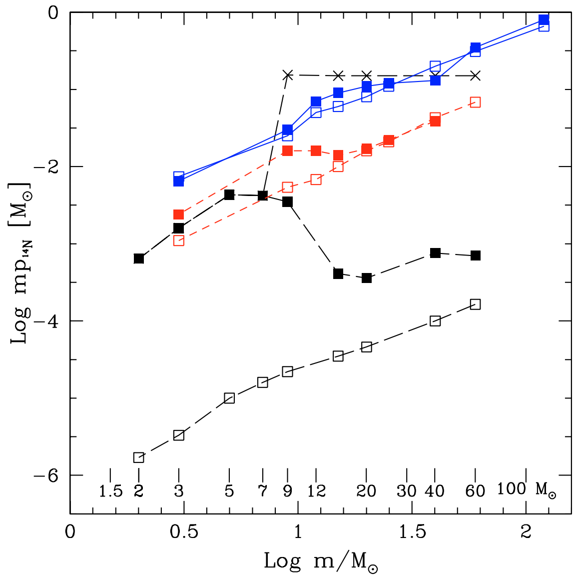

Fig. 1. MM02 stellar yields for ^{14}N, for the whole stellar mass range, for different metallicities. The yields of MM02 for stellar models where rotation is not taken into account are shown as open squares. Filled squares stand for models with rotation. Stellar yields are shown for 3 different values of metallicities (solid lines: solar, dashed line: $Z = 0.004$ and long dashed line: $Z = 0.00001$). The asterisks connected by the long-dashed line show the stellar yields adopted only for the lowest metallicity case in our heuristic model (see text).

mass stars (at least for the case of $V_{\rm rot} = 300$ km s^{-1}). However, for other metallicities the ^{14}N yields of MM02 for the intermediate mass stars are lower than the ones of vdHG97 as MM02 did not formally include the HBB (see CMM03 their Fig. 2).

The adopted chemical evolution model for the MW is the so-called "two-infall model" of Chiappini et al. (1997, 2001) where a detailed description can be found. The fundamental idea of this model is that the formation of the MW occurred in two different infall episodes, one forming the halo and part of the thick disk on a relatively short timescale and another one forming the thin-disk on a longer timescale. In this model a threshold gas density is assumed and, as a consequence, the star formation rate becomes zero every time the gas density drops below the threshold value. The two-infall approach, combined with such a threshold, leads to a gap in the star formation before the formation of the thin-disk. During the "gap" in the star formation only elements produced by type Ia SNe and low and intermediate mass stars (LIMS), born before the "gap", are restored into the ISM. As a consequence this model predicts an increase in the abundance ratios of elements restored on long-timescales (e.g. Fe or C) over α-elements (produced mainly by massive short-lived stars) around a metallicity of [Fe/H] ~ -0.6 dex (which corresponds to the time of the halt in the SFR which we predict to be around 1 Gyr after the start of the halo phase – see Chiappini et al. 1997, for details). A star formation halt between the formation of the halo and thin disk is suggested by observations (e.g. Gratton et al. 1996, 2000, 2003; Fuhrmann 1998, 2004). The required amount of infall seems to agree well with current estimates and is supported by recent observations both in our galaxy and in M31 (Sembach et al. 2004; and Thilker et al. 2004).

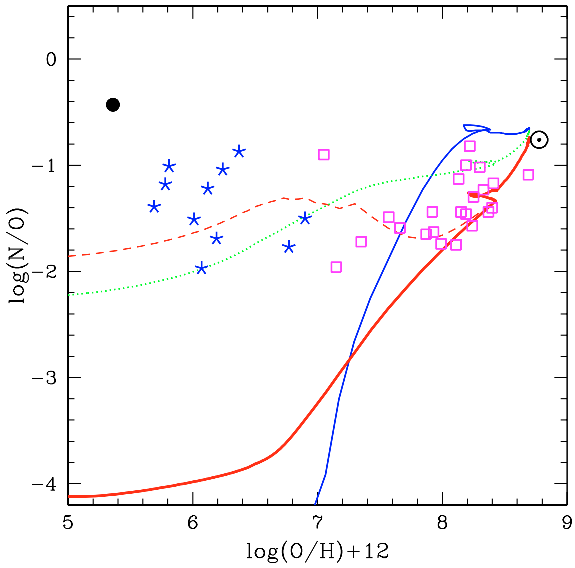

Fig. 2. Solar vicinity diagram log(N/O) vs. log(O/H)+12. The data points are from Israelian et al. 2004 (large squares), Spite et al. (2005) (asterisks). Also shown is the very metal-poor star found by Christlieb et al. (2004). Solid curves show the prediction of MW models computed with vdHG+WW yields (thin solid line) and MM02 yields (thick solid line). The latter flattens for log(O/H) + 12 < 6.6 due to the contribution by massive stars to the nitrogen production at low metallicities. The dotted curve shows a model computed according to the suggestion of Matteucci (1986), where all massive stars, in all metallicities, contribute a fixed amount of primary nitrogen of 0.065 $M_\odot$. The dashed line shows the prescriptions of our heuristic model computed with MM02 yields but assuming that massive stars with metallicities less or equal to 0.00001 produce much more nitrogen than the quantities computed by MM02, as shown in Fig. 1.

3. Results

3.1. The solar vicinity

We will concentrate the following discussion on the log(N/O) vs. log(O/H) diagram, instead of the usual [N/Fe] vs. [Fe/H] one for two main reasons. The first one is that since MM02 did not compute stellar yields for Fe it is more consistent to compare N/O abundance data with our theoretical predictions. The second reason is that in the case of the sample by Israelian et al. (2004) the uncertainties in N and O should cancel out once one considers the N/O ratio which is thus less prone to observational uncertainties compared to the N/Fe abundance ratios.

One of the main assumptions when comparing chemical evolution predictions with abundance data is that they represent the pristine abundances from the ISM from which the stars formed. This means that we should avoid using objects that could have undergone mixing processes. Israelian et al. (2004) published homogeneous N/O abundance ratios for a sample of 31 unevolved dwarf metal-poor stars (shown in Fig. 2 as open squares).

Spite et al. (2005) obtained nitrogen abundances for a sample of stars of even lower metallicities. Because in this case the abundances were measured in giants, the authors also measured the surface abundance of lithium as a diagnostic for CNO dredged-up material to the surface. They were in principle able to select a subsample of "unmixed" stars (plotted as asterisks in Fig. 2). In reality this sample should be seen as an upper limit for N/O as some mixing could still have taken place. It should also be noticed that although their abundance sample is unique and reaches a metallicity never reached before (especially for N), the absolute value of their data points can be still affected by *i)* the 3D corrections applied to their oxygen values; and *ii)* the fact that the nitrogen abundances were derived from the NH band for most of the stars. These abundances show a systematic shift of +0.4 dex with respect to abundances obtained from measurements of the CN band (they had both measurements for 10 stars – see Spite et al. 2005, for details). Figure 2 also shows the N/O solar ratio (the solar values were taken from Allende Prieto et al. 2001, for oxygen; and Holweger 2001, for nitrogen).

Also shown in Fig. 2 is the very metal poor star (giant) of Christlieb et al. (2004). It can be seen that this star has a N/O abundance ratio which is clearly larger than the typical ratios of the other two data samples. However, in this case a self-enriched scenario or a contamination by a binary companion star still cannot be excluded (see Chrislieb et al. 2004, for a detailed discussion).

In the same figure we show our model predictions for different assumptions of stellar yields. The solid curves are the same models shown in CMM03 (their Fig. 7): the thin line represents a model computed with the stellar yields of vdHG97 and Woosley & Weaver (1995 – hereafter WW95), the thick line shows a model computed with MM02 stellar yields. When comparing these two models, two things can be noticed a) as WW95 do not produce primary nitrogen in massive stars the thin curve computed with their stellar prescriptions does not flatten at low metallicities (contrary to what happens to the thick curve because in this case, according to the prescriptions of MM02, the massive stars produce some primary nitrogen); and b) the increase of the N/O ratio as a function of metallicity in the model represented by the thin curve is faster than the one shown by the thick curve. This is mainly due to the large amount of ^{14}N produced during the HBB in intermediate mass stars according the calculations of vdHG97.

Before discussing the other two models plotted in Fig. 2, notice that the new points of Israelian et al. (2004) are not far from the thick solid curve computed with the MM02 stellar yields, especially for $\log(\mathrm{O/H}) + 12 > 8.0$. As discussed in the previous section, because MM02 did not formally include HBB, one would expect the curve to lie much below the data points. The fact that the thick curve is close to the abundance ratios measured by Israelian et al. (2004) in unevolved stars suggests that HBB is less efficient than in vdHG97 models[4]. In fact, the thin curve lies above most of the Israelian et al. (2004) data points[5].

The dotted curve was computed according a suggestion made by Matteucci (1986) that all massive stars should produce around 0.065 $M_{\odot}$ solar masses of primary nitrogen (it is the same model shown by the thick solid curve in Fig. 2 except that in this case we assume that all massive stars, for all metallicities, contribute a fixed amount of 0.065 $M_{\odot}$ of N). This suggestion was based on the little data available at that time which seemed to suggest a flat [N/Fe] ratio at low metallicities. As it can be seen, the dotted line can reproduce the locus of the Spite et al. (2005) data sample but tends to overproduce nitrogen at higher metallicities (this curve is above most of the Israelian et al. data, even though it can reproduce the solar N/O abundance ratio).

The dashed line shows what we call our heuristic model. This model is the same as the thick solid line except that for the metallicities $Z < 0.00001$ we increased the yields of nitrogen given by MM02 for massive stars in the following way: we added 0.15 $M_{\odot}$ of nitrogen in the table of MM02 for $Z = 0.00001$ (which translates into a factor of 200 increase in ^{14}N for a 60 $M_{\odot}$ star and around a factor of 40 for a 9 $M_{\odot}$ star). This is shown in Fig. 1 by the asterisks connected by a long-dashed line. As our code then interpolates (linearly) the stellar yields for metallicities between $Z = 0.0$ and $Z = 0.00001$, this model produces more nitrogen at the beginning of galaxy evolution, leading to large N/O ratios at low metallicities but not changing its behavior for metallicities more close to solar (in fact the dashed curve coincides with the thick curve for oxygen abundances above 8.0).

The physical motivation for this heuristic model would be an increase of the rotational velocity in very metal-poor stars. As shown by MM02, the nitrogen yields increase with increasing rotational velocities. It might be that the initial distribution of the rotational velocities is different at different metallicities. There are some indirect indications that, at low metallicities, there are more fast rotators. For instance, the observed fraction of Be stars (which, being very fast rotators, are near the break up limit) appear to be more frequent in the SMC than in the MW (Maeder et al. 1999). Keller (2004) found that the rotation velocities of early B-type stars in the LMC are higher than the rotation velocities of comparable stars in the MW. Part of the reason for this is that a zero metallicity star having the same amount of angular momentum as a solar metallicity star rotates much faster due to its greater compactness (see Meynet & Maeder 2002b). Thus it might be that only stars at low metallicity rotate sufficiently fast to enable massive stars to contribute large amounts of nitrogen. Whether these suggestions are physically plausible remains to be assessed by future stellar evolution models, including rotation and mass loss.

If the nitrogen production in very-metal poor massive stars depends strongly on the rotational velocity of the star, this could explain the large scatter observed in N/O at low

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[4] Here we adopted their standard models and took their tables where the mass loss parameter varies with metallicity – see CRM03 for details. vdHG97 also computed another set of models where less HBB was assumed. We also computed a chemical evolution model where the latter stellar prescriptions were adopted. In Fig. 2 this model would fall in between the two solid curves discussed here – it is not shown to make the figure less crowded.

[5] Romano & Matteucci (2003) have shown that by adopting the vdHG97 set of stellar yields with less HBB it is possible to reproduce the trend of ^{12}C/^{13}C, which decreases in time in the solar neighbourhood.

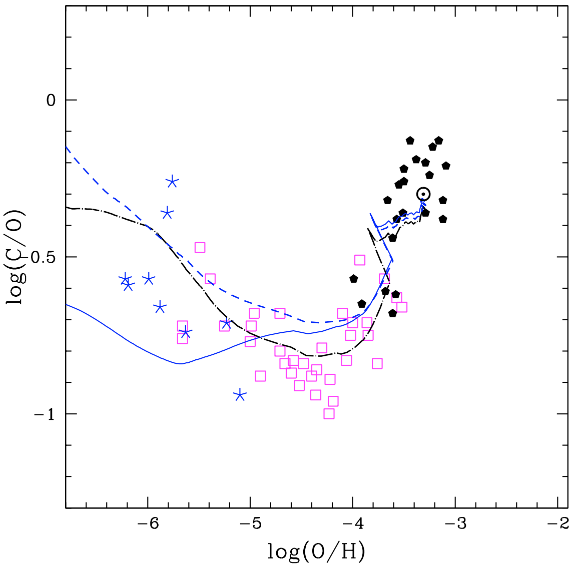

Fig. 3. Log(C/O) vs. log(O/H) diagram. The data are from Spite et al. (2005 – asterisks), Israelian et al. (2004 – squares), Nissen (2004 – filled pentagons). The different curves show our model predictions computed with different stellar yields as follows: a) dot-dashed curve – a model computed according the prescriptions of Akerman et al. (2004); b) thin solid curve – vdHG97 and WW95, where the latter refer to their solar tables and c) dashed line – vdHG97 and WW95 (where in this case the oxygen as a function of metallicity was adopted as suggested by François et al. 2004). This figure shows an alternative to the model suggested by Akerman et al. (2004) to obtain an upturn of C/O at low metallticities.

metallicities. Moreover, the scatter could be related to the distribution of the stellar rotational velocities as a function of metallicity (being more biased to larger values as the metallicity decreases). Clearly, the above suggestion needs to be confirmed but it can in principle be tested by observations.

3.2. Is there an alternative explanation to rotation?

An alternative way to explain the high N/Fe ratios at low metallicities is to assume that the first stars to enrich the ISM were population III stars (hereafter PopIII). Recently, Akerman et al. (2004) found an upturn in C/O at low O/H, and suggested that this could also be explained by adopting PopIII stellar yields (see Fig. 8 of Akerman et al. 2004). In particular, they adopted stellar yields computed by Chieffi & Limongi (2002) for metal-free supernovae which, according to the latter authors, should be C-rich[6] and assumed that PopIII stars were born with a "top heavy" IMF. Soon afterwards, Spite et al. (2005) confirmed that the upturn in C/O at low O/H values found by Akerman et al. (2004) extends to lower metallicities (see Fig. 3, where the open squares show the abundances measured by Akerman et al. 2004 and the asterisks show the Spite et al. 2005 data).

In this section we will check if current stellar yield calculations for the so-called PopIII stars are able to ensure a good fit of the log(N/O) vs. log(O/H) diagram and, at the same time, still explain the almost flat behaviour of [C/Fe] found by Spite et al. (2005). The only set of stellar yields for PopIII able to produce a high enough N/Fe at low metallicities is the one of Chieffi and Limongi (2002, 2004) (for a more detailed discusssion on the role of PopIII stars in the ISM enrichment of several other elements and models adopting different prescriptions for PopIII stars, see Ballero et al. 2005).

Here we find that although the latter stellar yields can explain the C/O vs. O/H upturn at low metallicities they fail to reproduce the almost flat [C/Fe] abundance ratios found to extend down to the low metallicities sampled by Spite et al. (2005). This can be clearly seen in Figs. 3 and 4 where the dot-dashed lines show a model similar to the one of Akerman et al. (2004), i.e. a model where the prescriptions for PopIII stellar yields of Chieffi & Limongi (2002, 2004) are adopted for $Z < 10^{-6}$. The latter value corresponds to the threshold metallicity ($\simeq 10^{-4}\,Z_{\odot}$) below which the IMF should be "top-heavy", as suggested in the literature for the so-called PopIII stars (where PopIII stands not only for "zero metallicity stars" but also stars born with a different IMF, where low and intermediate mass stars did not form – see Ballero et al. 2005, for details). Therefore, this model was computed following the Akerman et al. (2004) prescriptions also for the IMF, i.e. a "truncated" Scalo (1986) IMF, with $M_{\rm low} = 10\,M_{\odot}$ for $Z < 10^{-6}$ and a normal Scalo (1986) IMF for higher metallicities. The dot-dashed model can well explain the C/O vs. O/H observations but leads to C/Fe ratios that are above the observed values (see dot-dashed curve in Fig. 4, upper panel – the data are from Cayrel et al. 2004) and is not able to produce the amount of N required at low metallicities to explain the new data points of Spite et al. (2005 – see dot-dashed curve in Fig. 4, bottom panel).

Also shown in Fig. 4 is our heuristic model (dashed-line). This model can well explain the C/Fe ratios found in very metal-poor stars by Cayrel et al. (2004) (as expected since our heuristic model is identical to the CMM03 model as far as C and Fe are concerned) and also provides a good agreement with the N/Fe abundance ratios of Spite et al. (2005). However, in this case our heuristic model predicts a "valley" at intermediate metallicities (although less pronounced than the one shown by the dot-dashed model where the PopIII contribution was taken into account), whereas the data show a more flat behavior of N/Fe for the whole metallicity range. An easy way to obtain a flatter curve is to assume that the low and intermediate mass stars at low metallicities also should have higher nitrogen yields than the ones computed for $Z = 10^{-5}$. It is not excluded that intermediate mass stars of that same low metallicity could also produce large amounts of nitrogen if this production is linked to high rotational velocities (as discussed in Sect. 3.1). However, in this paper we wanted to change as little as possible the already-existing stellar yields of MM02 and thus we increased the nitrogen yields only for massive stars. Our main goal here is to explain the very metal-poor data of Spite et al. (2005) and for this we need massive stars because intermediate mass stars would not have had time to contribute to the ISM enrichment at such low metallicities, given their longer lifetimes. In Fig. 4 we also show a model in which we assumed a constant N production in massive stars of all metallicities (Matteucci 1986 – dotted curve, also shown in Fig. 2. In

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[6] Notice that Chieffi & Limongi (2002) do not include rotation in their computations.

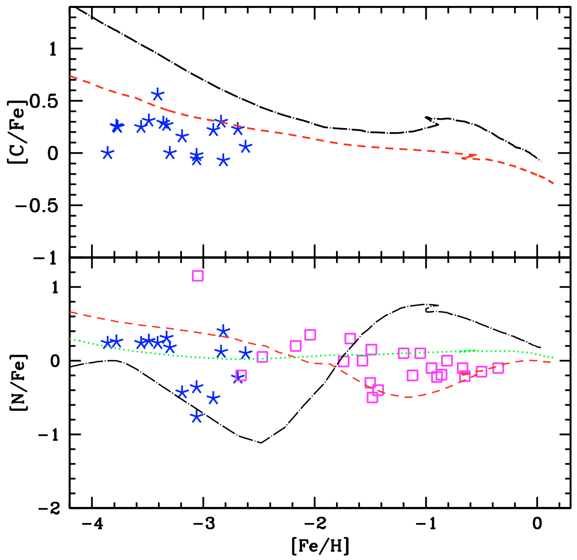

Fig. 4. The data points are from Cayrel et al. (2004), Spite et al. (2005) (asterisk) and Israelian et al. (2004) (squares). The dashed line shows the predictions of our "heuristic model". The dot-dashed lines refer to models computed with Chieffi & Limongi (2002, 2004) for metallicities below 10^{-6} and a top-heavy IMF (see text). In the lower panel a model that assumes a constant N production in massive stars of all metallicities (Matteucci 1986) is also shown. In this figure the models are normalized to the solar N and Fe of Holweger (2001) and to the C of Allende-Prieto et al. (2001).

this case a flat N/Fe vs. Fe/H is also obtained (see Ballero et al. 2005).

It is beyond the scope of the present paper to discuss in detail the problems related to carbon nucleosynthesis (for that see our previous papers CMM03 and Chiappini et al. 2003), but Fig. 3 illustrates that, for the low metallicity end, an upturn in C/O can also be obtained without the need to invoke PopIII stellar yields/IMF. In this figure the solid thin curve shows model 7 of Chiappini et al. (2003). The dashed curve shows the same model but adopting the WW95 stellar yields of oxygen as a function of metallicity (as suggested by François et al. 2004; and Goswami & Prantzos 2000). In this case a C/O upturn can be obtained at low metallicities. This is because WW95 predict a decrease in oxygen rather than an increase in carbon for $Z = 0$. As a consequence, such a model still fits the [C/Fe] abundance ratios as a function of metallicity[7]). Notice that in this case the model computed with the stellar yields of MM02 cannot fit the C/O observations either, although they provide a good fit for [C/Fe] (see CMM03, their Fig. 6). The above results illustrate the importance of testing PopIII stellar yield predictions simultaneously on different abundance ratios (see Ballero et al. 2005, for a discussion of several other abundance ratios).

In summary, our results suggest that a large ^{14}N yield in massive stars is required to fit the new abundance data for very low metallicities. Rotation seems to be the most promising way to explain the new data and its scatter, whereas current PopIII stellar yields able to produce a high N/Fe at low metallicities tend to overproduce carbon at variance with the flat C/Fe vs. Fe/H observed . Current stellar models that take into account rotation (MM02) do not provide the required amount of nitrogen to fit the data. However, it is worth noticing that MM02 computed stellar yields down to $Z = 10^{-5}$. It has to be seen if computations to even lower metallicities will be able to produce more N, at the levels suggested by our results. Another alternative could be an enhanced nitrogen production in massive close binaries (see Wellstein et al. 2001; Langer 2003, and references therein).

However, if future stellar evolution models for very low initial metallicities are able to produce large amounts of nitrogen, it should still be checked to what extent C would also be produced. A large production of C at low metallicities would make it difficult to explain the flat behaviour observed in [C/Fe] from solar metallicities to [Fe/H] as low as −5. The results discussed above suggest that a better agreement in all plots would be obtained if the low-Z calculations were able to simultaneously increase the stellar yields of ^{14}N, keeping C almost unchanged and decreasing the stellar yields of oxygen.

3.3. Present abundance gradients

In this last section we check the effect of the MM02 stellar yields on the abundance gradients predicted for our galaxy. As shown by Prantzos (2003), not much difference is seen when plotting the C/H, N/H and O/H abundances as a function of the galactocentric distance for models computed with WW95+vdHG97 or MM02 stellar yields. We confirm this result. However, as shown by Chiappini et al. (2003) this is not the case for the N/O, C/O and C/N abundance ratios. Figure 5 shows our predictions for the variation of these abundance ratios as a function of galactocentric distance obtained with MM02 stellar yields (thick lines) compared with model 7 of Chiappini et al. (2003 – thin line), which was computed with WW95+vdHG97 stellar yields. Important differences can be seen when the different sets of yield are adopted.

In Fig. 5 we see a large scatter in the data points, especially for C/O abundance ratios (upper panel). Moreover, in the upper panel, where the open symbols stand for HII regions and the filled symbols and asterisks represent B stars, it can be seen that the latter tend to show systematically lower C/O abundance ratios. More data is necessary to use these abundance gradients as tools to better constrain the carbon and nitrogen nucleosynthesis (especially in intermediate-mass stars). We recall (see Chiappini et al. 2003) that the C/O predictions shown by the thin curve were computed with vdHG97 yields for the case where the mass loss parameter increases with metallicity. This leads to a larger C production at lower metallicities[8]. As a consequence this model predicts an increase of the C/O abundance

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[7] Some mechanism able to increase ^{14}N at low metallicities is still needed in this case as models computed with WW95 stellar yields are not able to fit the new Spite et al. (2005) data for N/O, as shown by the thin solid curve in Fig. 2. WW95 also did not include rotation in their calculations.

[8] Lower mass loss rates lead to longer stellar lifetimes. As a consequence the star undergoes more dredge up episodes thus increasing the amount of C brought to the surface and later ejected into the interstellar medium.

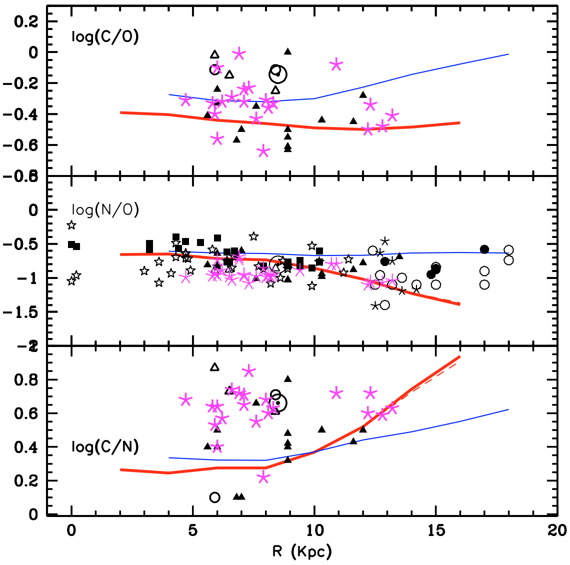

Fig. 5. Abundance gradients of C/O, N/O and C/N predicted by models adopting vdHG+WW yields (as model 7 of Chiappini et al. 2003 – thin solid line) and the same models computed with MM02 yields (as described in CMM03 – thick solid line). The dashed line barely seen in the bottom diagram corresponds to the predictions of our heuristic model (see text). In the middle panel both models overlap. Therefore, it is clear that the dominant factor of the N/O gradient in the MW is nitrogen production in LIMS and not the primary nitrogen in massive stars. For the abundance data see Chiappini et al. (2003), and references therein. Here we added the recent abundance data of Daflon & Cunha (2004, large asterisks).

ratio towards the outer parts of the disk, where the contribution of low metallicity stars dominates. The model computed with MM02 stellar yields leads to a flat C/O abundance ratio along the disk (see thick solid curve in the upper panel of Fig. 5). This is because, due to the lack of the third dredge up, intermediate-mass stars contribute in a negligible way to the abundance gradients and what is seen in this case is essentially the result of the enrichment due to massive stars. This also explains why the absolute C/O abundance ratios in this case are systematically lower than in the thin-curve model (see Henry 2004; and CMM03).

The middle panel of Fig. 5 shows a very interesting result: a model computed with vdHG97+WW95 stellar yields (thin curve) leads to a flat N/O gradient, whereas the model computed with MM02 (thick curve) leads to a decrease of the N/O abundance ratio as a function of the galactocentric distance. This is a very important result. As discussed in Chiappini et al. (2003), other galaxies, like M 101, clearly show a negative N/O gradient. In that paper we showed that if the vdHG97 stellar yields were adopted it was impossible to obtain a negative gradient for M 101 and attributed this to the fact that vdHG97 predict too much nitrogen in intermediate-mass stars (due to a very efficient HBB). The fact that the curve computed with the MM02 stellar yields leads to a negative gradient for N/O in the MW (still consistent with the data[9]) again suggests that the quantity of nitrogen "missing" in their calculations, due to the fact that these authors do not include the HBB, should be small.

Negative abundance gradients for N/O have been observed in many other spiral galaxies as shown recently by a compilation of more than 1000 published spectra of HII regions in spiral galaxies by Pilyugin et al. (2004). Previous determinations of O/H abundance gradients (e.g. Diaz et al. 1991) in galaxies could have been overestimated in inner disks (see Garnett et al. 2004), which would lead to flatter N/O abundance gradients.

In the middle and lower panels of Fig. 5 we also plotted our heuristic model (which is essentially like the thick curve but where we increased the yields of ^{14}N in massive stars at low metallicities – see previous section). This model (dashed curve) can be barely seen as it almost overlaps with the thick line model. This shows that the abundance gradients in the MW depend on the stellar yields in intermediate mass stars (as the metallicities do not reach the low values seen in Figs. 2 or 3 even in the outermost parts of the galactic disk – see also Diaz & Tosi 1986).

4. Discussion and conclusions

In this paper we computed chemical evolution models for the MW aimed at explaining the new nitrogen abundances measured recently in halo stars (Spite et al. 2005; and Israelian et al. 2004). In particular, we computed what we call our heuristic model for the MW where nitrogen stellar yields of massive stars were increased only for the lowest metallicity with respect to the ones published by MM02. Our main conclusions are:

- A mechanism able to produce more ^{14}N in massive stars at low metallicities relative to the existing stellar yields is necessary in order to explain the new data. If this large nitrogen production is linked to the fact that, at low metallicities, stars should in principle rotate faster (as discussed by Meynet & Maeder 2002b) it would also offer a way to explain the scatter in N/O measured at these metallicities.
- To also reproduce the observed abundances of C/O and C/Fe in Galactic halo stars, it is important that the production of primary nitrogen in massive stars at metallicities below $Z = 10^{-5}$ is accompanied by a decrease in oxygen and almost no change in carbon. Whether these suggestions are physically plausible is still to be assessed by future stellar evolution models, including rotation and mass loss.
- Rotation in intermediate mass stars is also able to produce primary nitrogen. We show that even if MM02 did not formally include the HBB, models computed with their stellar yields are not far from the abundance data in the solar vicinity (in the metallicity range where the IMS are supposed to contribute) and are still compatible with the abundance gradient for N/O along the Galactic disk. Although the data for the MW are not yet conclusive about the existence of a N/O abundance gradient, abundance gradients

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[9] Optical data suggest a flat N/O abundance gradient for the MW, whereas infrared data suggest a negative one (Simpson et al. 1995). Moreover, the recent data by Daflon & Cunha (2004) also show a gradient in N/O very similar to the one obtained by our model once the MM02 stellar yields are adopted (compare asterisks and thick line shown in the middle panel of Fig. 5).

are clearly observed in other spiral galaxies. The existence of abundance gradients of N/O in spiral galaxies imposes limits on the efficiency of HBB since for high efficiencies the gradients would vanish (see also Chiappini et al. 2003).

If the new case presented here (shown by the dashed curve in Fig. 2) is accurate then it might be that only stars at such low metallicities rotate sufficiently fast to enable massive stars to contribute large amounts of nitrogen. If this is the case, our interpretation of the two DLA groups observed in the N/O vs. O/H diagram as being the result of different star formation histories rather than an age difference (given in CMM03) would still be possible: it could be that in DLAs the ISM was never as metal poor as the one from which the halo stars studied by Spite et al. (2005) formed. In fact, as DLAs show metallicities higher than $[\mathrm{Fe/H}] \simeq -2.5$. This could happen if, for instance, the ISM in DLAs suffered a pre-enrichment phase before the start of star formation.

This is easier to envisage in the case of outer spiral disks as progenitors of DLAs. As shown by Chiappini et al. (2001), the outer parts of spiral disks could have been pre-enriched by halo/thick disk gas. If this is the case, the large nitrogen production seen in halo stars would not necessarily have taken place in DLAs. In other words, in DLAs very fast rotating massive stars probably never existed and this explains why these systems still show the lowest N/O ever measured.

Although the data analyzed here are the best at currently available, there is still the possibility that the so-called "unmixed stars" receive a minor contribution from CNO processing material and that the nitrogen abundance could have been overestimated.

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References

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63

Akerman, C. J., Carigi, L., Nissen, P. E., Pettini, M., & Asplund, M. 2004, A&A, 414, 931

Ballero, S., Matteucci, F., & Chiappini, C. 2005, NewA, submitted

Calura, F., Matteucci, F., & Vladilo, G. 2003, MNRAS, 340, 59

Cayrel, R., Depagne, E., Spite, M., et al. 2004, A&A, 416, 1117

Centurion, M., Molaro, P., Vladilo, G., et al. 2003, A&A, 403, 55

Chiappini, C., Matteucci, F., & Gratton, R. 1997, ApJ, 477, 765

Chiappini, C., Matteucci, F., Beers, T. C., & Nomoto, K. 1999, ApJ, 515, 226

Chiappini, C., Matteucci, F., & Romano, D. 2001, ApJ, 554, 1044

Chiappini, C., Romano, D., & Matteucci, F. 2003, MNRAS, 339, 63

Chiappini, C., Matteucci, F., & Meynet, G. 2003, A&A, 410, 257 (CMM03)

Chieffi, A., & Limongi, M., 2002, ApJ, 577, 281

Chieffi, A., & Limongi, M., 2004, ApJ, 608, 405

Christlieb, N., Gustafsson, B., Korn, A. J. et al. 2004, ApJ, 603, 708

Daflon, S., & Cunha, K., 2004, ApJ, 617, 1115

Diaz, A. I., & Tosi, M. 1986, A&A, 158, 60

Diaz, A. I., Terlevich, E., Vilchez, J. M., Pagel, B. E. J., & Edmunds, M. G. 1991, MNRAS, 253, 245

François, P., Matteucci, F., Cayrel, R., et al. 2004, A&A, 421, 613

Fuhrmann, K. 1998, A&A, 338, 161

Fuhrmann, K. 2004, Astron. Nachr., 325, 3

Garnett, D. R., Kennicutt, R. C., & Bresolin, F. 2004, ApJ, 607, L21

Goswami, A., & Prantzos, N. 2000, A&A, 359, 191

Gratton, R. G., Carretta, E., Matteucci, F., & Sneden, C. 1996, in Formation of the Galactic Halo... Inside and Out, ed. H. Morrison, & A. Sarajedini, ASP Conf. Ser., 92, 307

Gratton, R. G., Carretta, E., Matteucci, F., & Sneden, C. 2000, A&A, 358, 671

Gratton, R. G., Carretta, E., Desidera, S., et al. 2003, A&A, 406, 131

Henry, R. B. C., Edmunds, M. G., & Köppen, J. 2000, ApJ, 541, 660

Henry, R. B. C., 2004, in Origin and Evolution of the Elements, ed. A. McWilliam and M. Rauch (Cambridge Univ. Press), p. 44

Hirschi, R., Meynet, G., & Maeder, A. 2004, A&A, 425, 649

Holweger, H. 2001, in Joint SOHO/ACE Workshop: Solar and Galactic Composition, ed. R. F. Wimmer-Schweingruber

Hou, J. L., Boissier, S., & Prantzos, N. 2001, A&A, 370, 23

Israelian, G., Ecuvillon, A., Rebolo, R., et al. 2004, A&A, 421, 649

Keller, S. 2004, PASA, 21, 310

Lanfranchi, G., & Matteucci, F. 2003, MNRAS, 345, 71

Langer, N. 2003, in Cosmochemistry: The melting pot of the elements, ed. C. Esteban, R. J. Garcia Lopez, A. Herrero and F. Sánchez (Cambridge University Press), 31

Larsen, T. I., Sommer-Larsen, J., & Pagel, B. E. J. 2001, MNRAS, 323, 555

Maeder, A., Grebel, E. K., & Mermilliod, J.-C. 1999, A&A, 346, 459

Marigo, P. 2003, in CNO in the Universe, ed. C. Charbonnel, D. Schaerer and G. Meynet, ASP Conf. Ser., 304, 312

Matteucci, F. 1986, MNRAS, 221, 911

Meynet, G., & Maeder, A. 2002a, A&A, 390, 561 (MM02)

Meynet, G., & Maeder, A. 2002b, A&A, 381, L25

Mouhcine, M., & Contini, T. 2002, A&A, 389, 106

Pettini, M., Ellison, S. L., Bergeron, J., & Petitjean, P. 2002, A&A, 391, 21

Prantzos, N. 2003, in CNO in the Universe, ed. C. Charbonnel, D. Schaerer and G. Meynet, ASP Conf. Ser., 304, 361

Prochaska, J. X., Henry, R. B., O'Meara, J. M., et al. 2002, PASP, 114, 933

Pilyugin, L. S., Vilchez, J. M., & Contini, T. 2004, A&A, 425, 849

Romano, D., & Matteucci, F. 2003, MNRAS, 342, 185

Sembach, K. R., Wakker, B. P., Tripp, T. M., et al. 2004, ApJS, 150, 387

Scalo, J. M. 1986, Fund. Cosmic Phys., 11, 1

Spite, M., Cayrel, R., Plez, B., et al. 2005, A&A, 430, 655

Thielemann, F. -K., Nomoto, K., & Hashimoto, M. 1993, in Origin and Evolution of the Elements, ed. N. Prantzos et al. (Cambridge University Press), 297

Thilker, D. A., Braun, R., Walterbos, R. A. M., et al. 2004, ApJ, 601, 39

van den Hoek, L. B., & Groenewegen, M. A. T. 1997, A&AS, 123, 305 (vdHG97)

Wellstein, S., Langer, N., & Braun, H. 2001, A&A, 369, 939

Woosley, S. E., & Weaver, T. A. 1995, 101, 181 (WW95)