Letter to the Editor

A new imprint of fast rotators: low $^{12}\text{C}/^{13}\text{C}$ ratios in extremely metal-poor halo stars

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Abstract

Context. Fast stellar rotation is currently the most promising mechanism for producing primary nitrogen in extremely metal-poor massive stars. Chemical evolution models computed with the inclusion of the yields of fast rotating massive stars at a metallicity $Z = 10^{-8}$ can account for the high N/O abundances observed in normal extremely metal-poor halo stars. If, as believed, intermediate mass stars did not have enough time to contribute to the interstellar medium enrichment at such low metalicities, the above result constitutes a strong case for the existence of fast rotators in the primordial Universe.

Aims. An important result of stellar models of fast rotators is that large quantities of primary $^{13}\text{C}$ are produced. Hence, our goal is to investigate the consequence of fast rotation on the evolution of the $^{12}\text{C}/^{13}\text{C}$ ratio in the interstellar medium at low metallicity.

Methods. We compute the evolution of the $^{12}\text{C}/^{13}\text{C}$ ratio for the first time at very low metalicities upon the inclusion of fast rotators at $Z = 10^{-8}$.

Results. We predict that, if fast rotating massive stars were common in the early Universe, the primordial interstellar medium of galaxies with a star formation history similar to the one inferred for our Galactic halo should have $^{12}\text{C}/^{13}\text{C}$ ratios between 30-300. Without fast rotators, the predicted $^{12}\text{C}/^{13}\text{C}$ ratios would be 4500 at $[\text{Fe/H}] = -3.5$, increasing to 31000 at $[\text{Fe/H}] = -5.0$. Current data on very metal-poor giant normal stars in the Galactic halo agree better with chemical evolution models including fast rotators. The expected difference in the $^{12}\text{C}/^{13}\text{C}$ ratios, after accounting for the e ects of the small dredge-up, between our predictions with/without fast rotators is of the order of a factor of 2-3. However, larger di erences (a factor of 60-90) are expected for giants at $[\text{Fe/H}] = 5$ or turn-off stars already at $[\text{Fe/H}] = 3.5$. To test our predictions, challenging measurements of the $^{12}\text{C}/^{13}\text{C}$ in more extremely metal-poor giants and turn-off stars are required.

Key words. Stars; rotation; Galaxy evolution

1. Introduction

In the last few years, a burst of new information on cosmic abundances, provided by high-resolution spectra of very metal-poor stars in the halo has had a considerable impact on our understanding of both stellar nucleosynthesis and the chemical enrichment of the interstellar medium (ISM). In particular, it is in the halo of the Milky Way that the oldest and most metal-poor stars in the Universe are observable, born at times (or equivalent redshifts) still out of reach of the deepest surveys of primordial galaxies.

Several teams (e.g., Cayrel et al. 2004; Cohen et al. 2007, Barklem et al. 2005;ACK 2007) have studied the chemical composition of halo metal-poor stars (stars with less than $1000$ solar mass) at $Z = 10^{-8}$. These low-mass stars have lifetimes comparable to the age of the Universe, and they retain in their atmospheres the elemental abundances of the gas at the time of their birth. Hence, these stars contain a memory of the unique nucleosynthesis contribution of the first stellar populations to the enrichment of the ISM, owing a local benchmark for cosmology. These massive stars are long dead, but there are hopes of observing them directly in very high-redshift galaxies. The current way to constrain the properties of the first generations of stars and check whether the very different primordial environment has produced noticeable effects concerning their properties is to search for their prints on the oldest extreme metal-poor stars (EMPs) in our Galactic halo.

Recently a sample of EMP ($[\text{Fe/H}] < -3$) halo stars has been available. Using UVES on the VLT, Cayrel et al. (2004) provided abundance measurements of unprecedented accuracy for several elements in a fairly large sample of metal-poor normal stars (to distinguish from the C-rich EMP stars, see Beers & Christlieb 2005). Their data have revealed a striking homogeneity in the chemical properties of halo stars. In particular, a very low scatter for the [$\text{[Fe}/\text{H]}$] ratio was found. In a subsequent paper, the authors (Spite et al. 2005) again report some unexpected results, namely: these same metal-poor stars show a high N/O ratio suggesting higher levels of production of primary nitrogen in massive stars (see below). Furthermore, a large scatter in their N/O ratios (much larger than their...
quoted error bars) was found. S05 also report a slight increase in the $C/O$ of the same $r$ stars with decreasing $m$ etallicity.

As discussed in Chiappini et al. (2005, 2006a, b), the data of S05 happen to be in a very interesting metallicity range: at such low $m$ etallicities, their observed stars are probably a made of only massive stars ejecta diluted by the primordial ISM. Indeed, chem evolution models (CEM) of the halb of Chiappini et al. (2006a, b; Prantzos 2003) show that an 8 $M_\odot$ star dies at [Fe/H] $= 3.5$. This means that, below this metallicity, the ISM is enriched exclusively by massive stars. Moreover, according to these CEMs, the contribution of AGB stars is negligible below [Fe/H] = 2.5. More in particular, these theoretical predictions seem to be confirmed by very recent observations. Molenberg & Coher (2007) have shown that the $^{12}$C/ $^{13}$C ratio in halo dwarfs is low and that AGB stars would have played a more important role below [Fe/H] = 2.0.

If AGB stars indeed had not had enough time to contribute to the ISM enrichment at such low $m$ etallicities and massive stars are not producers of prim any nitrogen (as predicted by standard stellar models, e.g., Woosley et al. 2002), one would expect to observe a decline in the N/O or N/Fe ratios towards low $Z$, contrary to what has been found by S05. Hence, the high levels of N/O observed in halo stars have to be a result of the nucleosynthesis taking place in the metal-poor massive stars, suggesting a revision of standard metal models for the nucleosynthesis in massive stars.

The e ejects of stellar rotation axis are normal and at low $m$ etallicity may lead to a drastic revision of current wisdom (see Meynet et al. 2004, Hirsh 2007). The CEMP models of the Geneva group, including rotation Meynet & Maeder (2003, 2004), have proved to be successful in explaining some observations that could not be explained by non-rotating models, namely, the observed number ratio of W C to $O$-type stars for different $m$ etallicities, the observed ratio of $W$ N to $O$ C for meteorites lower than solar, and the observed ratio of type Ib/Ic to type II supernovae at different $m$ etallicities. One of the consequences of rotation is that carbon and oxygen, produced in the He-burning core, are transported by rotational mixing into the H-burning shell, where they are transformed into prim any $^{13}$C and $^{14}$N. Interestingly, the efficiency of this process increases when the initial mass and rotational velocity increase (see Meynet & Maeder 2003, Meynet & Maeder 2004), producing a more $N$ for fast rotators. Another fundamental prediction from models including rotation is that the rotational mixing also increases with decreasing $m$ etallicity.

Chiappini et al. (2006a) computed CEMs adopting the new calculations of Hirsh 2007) for the evolution of massive stars at very low $m$ etallicities under the assumption of an almost constant initial ratio $^{13}$C/ $^{12}$C (i.e. where the $^{13}$C/ $^{12}$C ratio increases towards lower $m$ etallicities). It was shown that, in such a framework, massive stars can produce large amounts of nitrogen, and this explains the data of S05. Moreover, these same CEMP models naturally predict a $C/O$ upturn at low $m$ etallicities. It should be noticed that this is currently the only way to explain the CNO $C/O$ abundances of normal stars giving strong support to the idea that stars rotate faster at low $m$ etallicities. One must be very careful in systematics non negligible corrections due to 3D and NITE e ejects (see A. S. 2003). Are there other inprints of fast rotators that are less affected by the above uncertainties? The $^{12}$C/ $^{13}$C ratio is largely unobserved by uncertainties in the adopted atm. parame opt. eters Spinat et al. 2008, hereafter S06), although in this case the stellar evolution e effects taking place in these old, low-$m$ mass stars have to be correctly accounted for in order to recover their pristine values.

In this Letter we suggest that fast-rotating massive stars could also have left an imprint on the evolution of the $^{12}$C/ $^{13}$C ratio in the earliest phases of the ISM enrichment. In fact, the same rotationally mixing responsible for the nitrogen production would also produce non negligible of any $^{13}$C. We predict, for the first time, that the in satellite of an early population of fast rotators on the evolution of the $^{12}$C/ $^{13}$C abundance ratio in the very metal-poor ISM is huge. If fast rotators existed, low (300 3000) $^{12}$C/ $^{13}$C ratios should be observed in the very metal-poor ISM of galaxies polluted essentially only by massive stars. This Letter is organized as follows. The adopted stellar yields are briefly presented in Sect. 2. Our results are shown in Sect. 3. Section 4 is devoted to our conclusion and to a discussion of this result in the context of different research areas.

2. $^{13}$C yields for very metal-poor stars

As this Letter focuses on the very metal-poor range (below [Fe/H] = 3 or log O/H) $= 7$), we have not had time to contribute to the ISM enrichment (see M. Coher 2001), we concentrate on the evolution of $^{13}$C on the stellar yields of metal-poor massive stars.

The $^{13}$C is produced in H-burning regions, where the CH cycle converts $^{12}$C into $^{13}$C. As discussed in the previous section, rotation triggers the production of prim any $^{13}$C, by allowing the diffusion of $^{12}$C produced in H-burning zones into H-burning ions. As a numerical illustration, a 40 $M_\odot$ star at $Z = 10^{-8}$ ejects a quantity of newly synthesized $^{13}$C equal to 63 $10^{-2}$ M when $v_{r i t} = 700$ km s$^{-1}$ (Hirschi 2007). For comparison, an $M_\odot$ star without rotation predict a $^{13}$C yield of $38$ $10^{-5}$ M for $Z = 10^{-6}$ and $M = 35 M_\odot$ (Chie & Limongi 2004), or a $^{13}$C yield of 0.2 $10^{-4}$ M for $Z = 0$, $M = 40 M_\odot$ (Tom Imaga et al. 2007).

Here we adopt the $^{12}$C and $^{13}$C yields of Hirschi 2007) computed for $Z = 10^{-8}$ and initial rotational velocities, $v_{r i t} = 600$ to $800$ km s$^{-1}$, depending on the stellar mass. For higher $m$ etallicities the adopted yields are from Meynet & Maeder 2003), hereafter M 02), for $v_{r i t} = 300 300$ km s$^{-1}$. The justication for the higher velocities

1. Classically the best candidates for the production of prim any $N$ through hot-bottom burning during the asymptotic giant branch (AGB) phase are W C stars (2007).

2. $^{13}$C/ $^{12}$C is the critical rotational velocity, i.e. the equatorial velocity such that the centrifugal acceleration compensates for the gravity.
Figure 1. Predicted evolution of the $^{12}\text{C}/^{13}\text{C}$ ratio according to a CEM computed with different stellar yield sets for metallicities $Z = 10^{-5}$: a) solid line - a model computed under the assumption that the lowest metallicity yield table of MM02 ($Z = 10^{-2}$) is valid down to $Z = 0$ (without fast rotators) and b) dashed line (in black in the on-line version) of a model computed with the contribution of $Z = 10^{-8}$ fast rotators. The data are the unobserved stars of S06. The open symbols represent lower limits. The arrows indicate the $^{12}\text{C}/^{13}\text{C}$ observed in giants, starting from the initial values given by models with (light/magenta arrow) and without fast rotators (dark arrow).

at $Z = 10^{-8}$ relies on the following assumption: stars begin their evolution on the ZAMS with a rotational velocity such that the ratio $\text{rot} = \text{crit}$ remains almost constant (around 0.5-0.6) with mass and metallicity, implying higher rotational velocities at lower metallicities. As a consequence the stellar yields of $^{12}\text{C}/^{13}\text{C}$ of Chiappini et al. (2003) are greater by $Z$ to $3$ orders of magnitude than the ones of M02 for $Z = 10^{-5}$ and $\text{rot} = 300\text{km s}^{-1}$.

3. Results

Here we show the impact of the stellar yields discussed above on the predictions of the $^{12}\text{C}/^{13}\text{C}$ evolution in the galactic halo. We adopt the same CEM of Chiappini et al. (2006), briefly described below.

Our model assumes that the galactic halo was formed by a combination of infall plus outflow. Our main assumptions are: a) a Gaussian inflow $f(t) / e^{(t - t_0)^2 / 2}$ with $t_0 = 0.1\text{Gyr} \text{ and } \tau = 0.05$; b) an outflow rate of $8\text{ km s}^{-1}$ the star formation rate; c) a Schonell kick law for the star formation rate (see also Pflammala et al. 2003). This model is able to reproduce the observed halo $^{12}\text{C}/^{13}\text{C}$ metallicity distribution (see Fig. 4 of Chiappini et al. 2006), while in our previous model, without outflow (Chiappini et al. 2006), a $8\text{ M}_\odot$ star would die at a metallicity $[\text{Fe}/H] = 2.2$, in the new model, with outflow, the same star would die when the metallicity in the ISM was $[\text{Fe}/H] = 3.8$. The latter model is favoured by the observed halo metallicity distribution.

In Fig. 4 we show our model predictions. The different curves show the same CEM computed with different sets of stellar yields at low metallicity. A model computed without fast rotators predicts very high $^{12}\text{C}/^{13}\text{C}$ ratios at low metallicities, namely: 2400 at $[\text{Fe}/H] = 3\Delta$, 4500 at $[\text{Fe}/H] = 3\Delta$, increasing to 31000 around $[\text{Fe}/H] = 5\Delta$. When the contribution of the fast rotators is taken into account, much lower $^{12}\text{C}/^{13}\text{C}$ ratios are predicted: 295 at $[\text{Fe}/H] = 3\Delta$, 80 at $[\text{Fe}/H] = 3\Delta$ and 30 at $[\text{Fe}/H] = 5\Delta$. In other words, we predict smaller ISM $^{12}\text{C}/^{13}\text{C}$ ratios (by a factor of 1000 at $[\text{Fe}/H] = 5\Delta$ and of 60 at $[\text{Fe}/H] = 3\Delta$) upon the inclusion of fast rotators. We notice that the impact of fast rotators could be even greater than what has been computed here. This would be the case if, for instance, fast rotators would still play some role at slightly higher metallicities. However, at present, stellar yields computed with high rotational velocities for higher metallicities ($Z > 10^{-4}$) are not available.

Currently, the only data available in the literature for the $^{12}\text{C}/^{13}\text{C}$ ratio at such low metallicities is from S06. They obtained new $^{12}\text{C}/^{13}\text{C}$ isotopic ratios for the same stars as studied in S05. Here we only plot their so-called unrotated stars, which are giants that have undergone the first dredge-up but are still below the luminosity function bump and hence are not experiencing the thermochronology (e.g., Chiappini et al. 2007). To recover their initial $^{12}\text{C}/^{13}\text{C}$ ratio relevant to the comparison with our CEM predictions, we have computed the evolution of the carbon isotopic ratio in stellar models of $0.85\text{M}_\odot$, $[\text{Fe}/H] = 3\Delta$ (typical of the Spite sample) from the pre-main sequence up to the end of the first dredge-up on the red giant branch, assuming different initial values for the $^{12}\text{C}/^{13}\text{C}$ ratio.

Starting from an initial $^{12}\text{C}/^{13}\text{C}$ ratio corresponding to the prediction of a CEM without fast rotators at $[\text{Fe}/H] = 3\Delta$, we obtain a post-dredge-up value of 106. This value is clearly higher than the observed ratio in the Spite unrotated sample (20-30). In the case of an initial value of 80 as predicted by a model that takes the contribution of the fast rotators at this same metallicity into account, a value of 47 is obtained, i.e., slightly higher than, but marginally consistent with, the observational data. Starting from an initial value of 50 (see previous discussion), the observational values can be reached (30). Thus, even though our predictions for the $^{12}\text{C}/^{13}\text{C}$ ratio with and without fast rotators differ by a factor of 60 at $[\text{Fe}/H] = 3\Delta$, in the case of very metal-poor giants, the expected effect would be smaller (a factor of 2-3), but still significant. Larger discrepancies are obtained at lower metallicities. At $[\text{Fe}/H] = 5\Delta$, starting from an initial value of 3100 (predicted by CEM without fast rotators), we obtain a post-dredge-up value of 1790 (Fig. 3). On the other hand, essentially no change is obtained when starting from the initial values of our CEM which include fast rotators (in the latter case the $^{11}\text{C}$ is already so high that the effect of the first dredge-up turns out to be negligible). Thus, at such low metallicities the expected effect is greater (a factor of 60).

In summary, we have a robust theoretical prediction both for the ISM of primordial galaxies and for the EMFs in our galactic halo. Our predictions could in principle be checked, once $^{12}\text{C}$ isotopic ratios had been measured in normal EMFs in stars at $[\text{Fe}/H] = 3\Delta$ or giants at lower metallicities. An additional test of our predictions will probably come from the fast evolving edge of abundance measurements in the ISM of high-redshift galaxies (Pettini et al. 2006). The edge of fast rotators should appear in systems where the main contributors to the gas enrichment are the massive stars. From an observational point of view, the most suitable system for measuring the $^{12}\text{C}/^{13}\text{C}$ are the dimmest Ly systems (DLAs) because of the absence of strong galactic winds which would not allow the measurement of the isotopic shifts. Leveskov et al. (2004) reported a lower
predicted had essentially due to massive stars (\[Fe/H\] of the Milky Way. We predict that, if fast rotating massive stars were common in our galaxy in the early Universe, the ISM at an epoch where the chemical enrichment was essentially due to massive stars (\[Fe/H\] \approx 3\sigma) should have had $^{12}$C/$^{13}$C ratios between 30-300. Without fast rotators, the predicted $^{12}$C/$^{13}$C ratios would be 4500 at \[Fe/H\] = 3.5, increasing to 31000 around \[Fe/H\] = 5.6.

We also computed the expected surface abundances and radial velocities of stars in the Galaxy. The ISM at an epoch where the chemical enrichment was essentially due to massive stars (\[Fe/H\] \approx 3\sigma) should have $^{12}$C/$^{13}$C ratios between 30-300. Without fast rotators, the predicted $^{12}$C/$^{13}$C ratios would be 4500 at \[Fe/H\] = 3.5, increasing to 31000 around \[Fe/H\] = 5.6.

4. Discussion and conclusions

In this Letter we have studied the importance of fast rotating massive stars on the chemical evolution of the $^{12}$C/$^{13}$C ratio in the halo of the Milky Way. We predict that, if fast rotating massive stars were common in the early Universe, the ISM at an epoch where the chemical enrichment was essentially due to massive stars (\[Fe/H\] \approx 3\sigma) should have $^{12}$C/$^{13}$C ratios between 30-300. Without fast rotators, the predicted $^{12}$C/$^{13}$C ratios would be 4500 at \[Fe/H\] = 3.5, increasing to 31000 around \[Fe/H\] = 5.6.

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