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TOWARD THE FIRST STARS: HINTS FROM THE CEMP-NO STARS

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Abstract. CEMP-no stars are iron-deficient, carbon-rich stars, with no or little s- and r-elements. Because of their very low iron content, they are often considered to be closely linked to the first stars. Their origin is still a matter of debate. Understanding their formation could provide very valuable information on the first stars, early nucleosynthesis, early galactic chemical evolution and first supernovae. The most explored formation scenario for CEMP-no stars suggests that CEMP-no stars formed from the ejecta (wind and/or supernova) of a massive source star, that lived before the CEMP-no star. Here we discuss models of fast rotating massive source stars with and without triggering a late mixing event just before the end of the life of the source star. We find that without this late mixing event, the bulk of observed CEMP-no stars cannot be reproduced by our models. On the opposite, the bulk is reproductible if adding the late mixing event in the source star models.

Keywords: stars: abundances – stars: massive – stars: interiors – stars: chemically peculiar – nucleosynthesis

1 Introduction

Carbon-enhanced metal-poor (CEMP) stars are iron-deficient stars with an excess of carbon compared to normal metal-poor stars. Most of these stars are also enriched in N, O, Na, Mg and other light elements. The CEMP-no stars (the term was introduced by Beers & Christlieb 2005) show no enhancements in s- (e.g. Sr) or r- elements (e.g. Eu), contrary to the CEMP-s or CEMP-r stars. The most iron-poor star known today is SMSS 0313-6708, a CEMP-no star with [Fe/H] < 7.1 (Keller et al. 2014). This star, like other CEMP-no stars with almost no iron, was likely born very early in the universe. Understanding the origin of the CEMP-no stars will provide valuable clues on the first stars, early nucleosynthesis, first supernovae and early galactic chemical evolution.

It is commonly accepted that internal processes inside the CEMP-no stars (atomic diffusion, dredge-up...) cannot be fully responsible for the peculiar chemical composition of such stars. An external source is likely needed. The help of a binary companion to explain the chemical abundances of CEMP-no stars does not seem a reliable hypothesis because the binary fraction among CEMP-no stars is only about 20% (Hansen et al. 2016). An alternative is to rely on a massive *source star*, that lived before the CEMP-no star and enriched through winds and/or supernova the interstellar medium in which the CEMP-no star formed later on (this scenario has been discussed in different works, e.g. Umeda & Nomoto 2002; Meynet et al. 2006, 2010; Tominaga et al. 2014; Takahashi et al. 2014; Maeder & Meynet 2014).

Chiappini et al. (2006) and Chiappini et al. (2008) have shown that some abundances of normal metal-poor stars in the Milky Way halo can only be reproduced if there were very fast rotators among the first massive stellar generations. Here we try to see wether the ejecta of fast rotating massive source stars at very low metallicity can provide a material able to reproduce the observed chemical pattern of CEMP-no stars.

2 Results

We focus first on three source stars of 20, 32 and 60 $M_\odot$ at a metallicity $Z = 10^{-5}$ and with* $v_{\rm ini}/v_{\rm crit} = 0.7$. These models were computed with the stellar evolution code GENEC and are evolved until the end of the central silicon burning phase. The $^{12}C/^{13}C$ and [C/N] ratios in the wind ejected by the models are shown on Fig. 1

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*$v_{\rm crit}$ is the velocity at the equator at which the gravitational acceleration is exactly compensated by the centrifugal force.

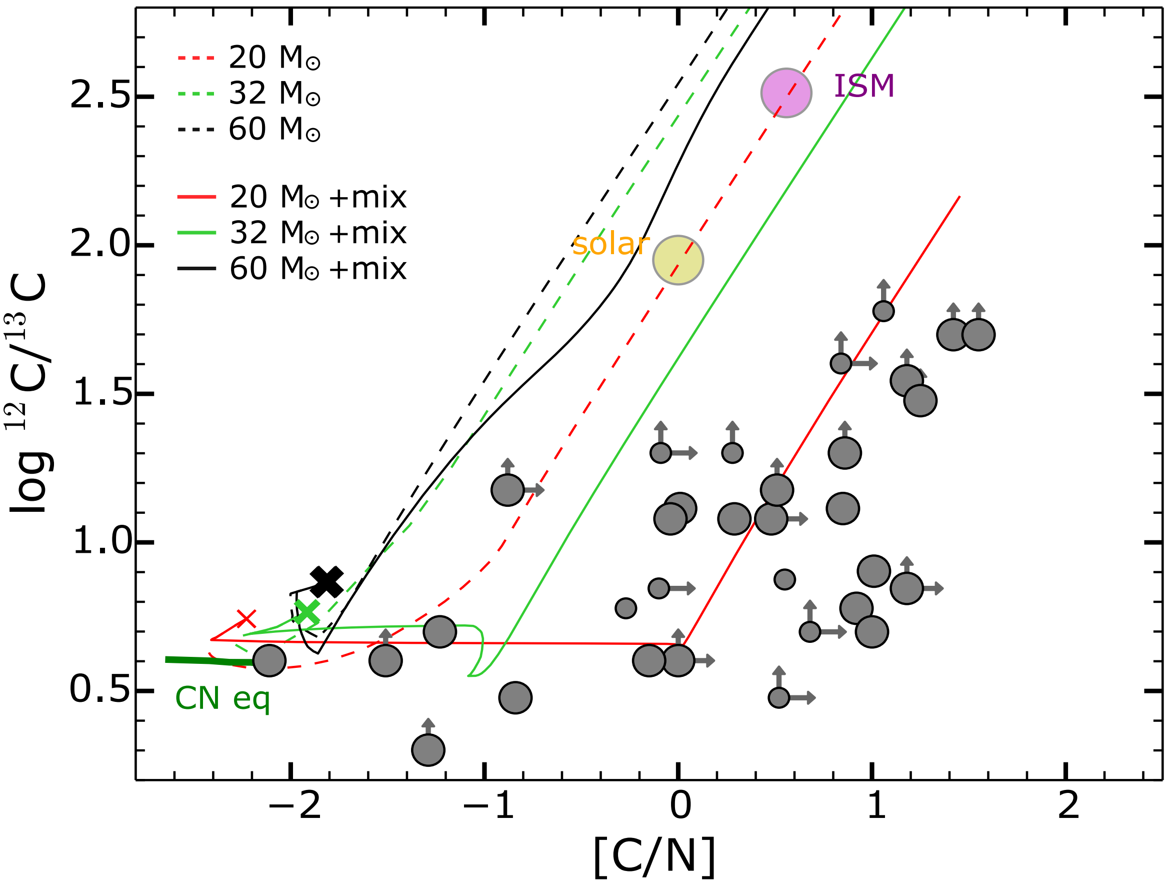

Fig. 1. Small/big grey circles are ratios observed at the surface of MS/RG CEMP-no stars with [Fe/H] < -2.5, [C/Fe] > 0.7 and [Ba/Fe] < 1 (observations from Christlieb et al. 2004; Beers et al. 2007; Johnson et al. 2007; Lai et al. 2008; Masseron et al. 2010; Allen et al. 2012; Norris et al. 2013; Spite et al. 2013; Yong et al. 2013; Cohen et al. 2013; Roederer et al. 2014; Hansen et al. 2015). The arrows indicate that only lower limits are deduced from spectroscopy. The yellow and purple circles represent the solar ratios and the ratio in an α-enhanced ISM, respectively. The crosses show the ratios in the wind at the end of evolution of 20, 32, and 60 $M_{\odot}$ fast-rotating source star models. The tracks represent the integrated ratios as more and more layers of the final structure are ejected and added to the wind. The thick green lines labelled 'CN eq' represent the ratios obtained in a single zone at CN-equilibrium for $30 < T < 80$ MK.

by the three colored crosses. The wind bears the signature of CN-processing (the crosses are close to the 'CN eq' line). This is because of the rotational mixing operating in the source star that brings the CN-processed material from inner layers to the surface of the source star. When mass loss occurs, this material is ejected. Dashed lines on Fig. 1 show the effect of the mass cut[†] for these models. As we move on the lines starting from the crosses, we see the effect of ejecting (and adding to the wind) deeper and deeper layer of the source star. At a given point, layers processed by helium burning are ejected. In such a region, ^{13}C and ^{14}N are depleted so that ^{12}C/^{13}C and [C/N] rise sharply.

Whatever the mass and the mass cut, the models cannot provide a material able to reproduce the bulk of observed CEMP-no stars. We have also found that slower rotators cannot reproduce the observed distribution (not shown on Fig. 1 for clarity).

A possibility to improve the fit is to rely on a late mixing event in the source star. This mixing event is described in details in Choplin et al. (2017). It intervenes during the carbon burning phase, about 200 yr before the end of the evolution, between the He- and H-burning shells of the source star. As schematically shown in Fig. 1, it suddenly brings extra ^{12}C from the He- to the H-shell, boosting the CN-cycle in the H-shell. After

[†]The mass cut delimits the part of the star that is expelled from the part that is locked into the remnant.

the mixing episode, it takes some time to the CN-cycle to go back to equilibrium. The $^{12}C/^{13}C$ ratio goes back to its equilibrium value $\sim$ 10 times faster than C/N. The time left before the end of the evolution is sufficient for $^{12}C/^{13}C$ to go back to equilibrium but not sufficient for C/N. When evolution ends (nucleosynthesis is then stopped), there is a zone in the source star with log $^{12}C/^{13}C$ at equilibrium (about 0.6) but [C/N] above its equilibrium value of ~ -2.4. The solid lines in Fig. 1 show the same models as before but with the late mixing event in addition. Thanks to the mixing event discussed before, these models can give a material with a low $^{12}C/^{13}C$ and a high C/N (e.g. the solid red line). However, as the initial mass of the source star increase, the tracks are shifted to lower C/N. This is because in more massive source stars, the temperature in the H-shell is higher so that the CN-cycle is faster. Hence, at the end of the evolution, C/N in the H-shell is closer to its equilibrium value for more massive stars. In the end, only the 20 $M_\odot$ model can provide a material able to reproduce the bulk of observed CEMP-no stars.

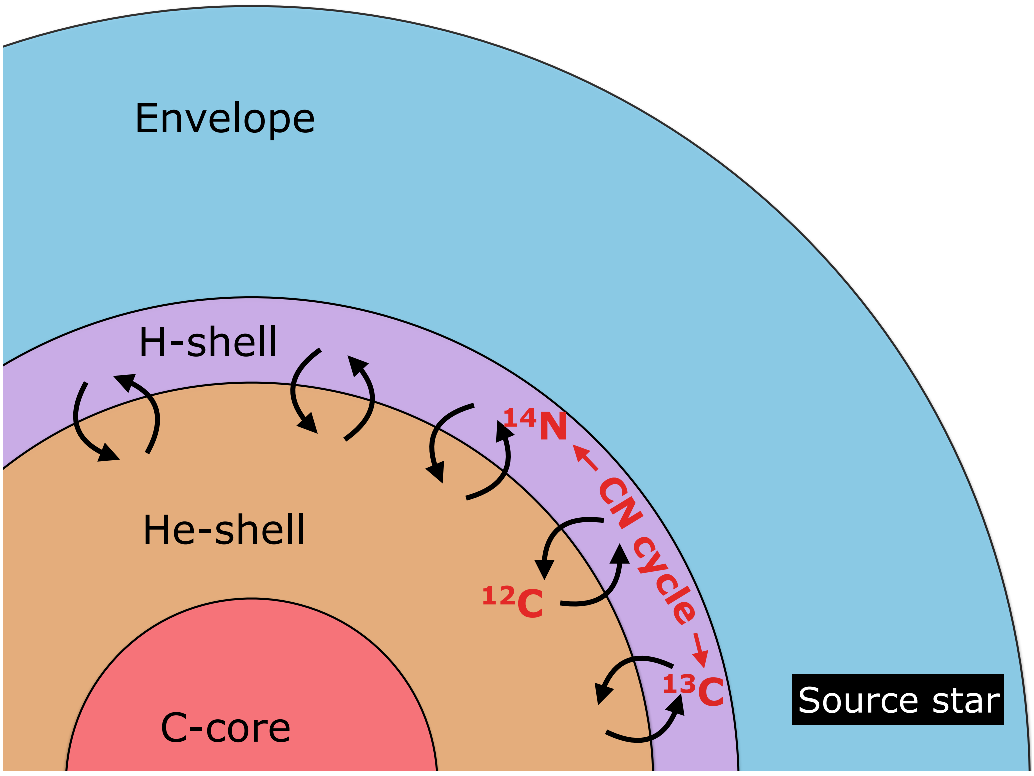

Fig. 2. Schematic view of the late mixing event in the source star, responsible for the tracks labelled '+mix' in Fig. 1.

3 Conclusions

We have investigated the origin of the CEMP-no stars through a comparison between the material ejected by fast-rotating massive source stars and the chemical composition observed at the surface of the CEMP-no stars. The 2D abundance plot $^{12}C/^{13}C$ vs. C/N leads to quite strong constraints on the kind of source star needed. 20-60 $M_\odot$ models of any initial rotation rate between 0 and 70 % of the critical velocity cannot provide a material able to reproduce the bulk of observed CEMP-no stars. A late mixing event operating in between the H- and He-shell of the source star, during the carbon burning phase improves the fit. However, in the end, only the 20 $M_\odot$ model gives a material with the right chemical composition, i.e. with $^{12}C/^{13}C$ close to equilibrium and C/N above its equilibrium value. The temperature in the H-shell of more massive source stars is higher so that the CN-cycle is faster and C/N goes back quicker to equilibrium after the mixing event.

We draw the following conclusions: (1) $\sim$ 20 $M_\odot$ source stars might be better CEMP-no source stars than $\sim$ 60 $M_\odot$ and (2) the late mixing event, artificially triggered in our models, might point toward a missing ingredient in current 1D stellar evolution codes. It might be that this extra mixing process just reflect a too poor description of the convective boundaries in 1D stellar evolution codes. In our code, these limits are sharp. However, multi-dimensional simulation of convective zones tend to show that these limits extend further (Meakin & Arnett 2007; Cristini et al. 2016). This might induce some extra mixing in the source star, especially between the H- and He-burning shell.

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