Proc. 15th Int. Symp. Origin of Matter and Evolution of Galaxies (OMEG15)
JPS Conf. Proc. **31**, 011010 (2020)
https://doi.org/10.7566/JPSCP.31.011010

Early Rotating Massive Stars and Abundances of Extremely Metal-Poor Stars

Arthur CHOPLIN[1]

[1]*Department of Physics, Faculty of Science and Engineering, Konan University, 8-9-1 Okamoto, Kobe, Hyogo 658-8501, Japan*

E-mail: arthur.choplin@konan-u.ac.jp

(Received August 31, 2019)

The study of the long-dead early generation of massive stars is crucial in order to obtain a complete picture of the evolution of the Universe. The nature of these stars can be inferred indirectly by investigating the origin of low-mass metal-poor stars observed in our neighborhood, some of which are almost as old as the Universe. The material forming these living fossils is thought to have been inherited from the ejecta of one or very few previous massive stars. After discussing the impact of rotation on nucleosynthesis in low metallicity massive stars, I investigate whether the ejecta of massive stars with various initial rotation velocities can reproduce the abundance pattern of 128 individual metal-poor stars with [Fe/H] < -3 and $\log g > 2$ (i.e. not so evolved). A reasonable fit can be found for ~ 50 % of the sample. The initial velocity distribution of the best massive star models reaches a maximum for velocities of $\sim 500 - 600$ km s^{-1}.

KEYWORDS: massive stars, rotation, metal-poor stars, nucleosynthesis, abundances

1. Introduction

The long-dead first massive stars are crucial objects to understand the entire history of the Universe [1, 2]. After their short lives of a few Myr, they released the first metals (elements heavier than helium) in the interstellar medium (ISM), setting the conditions for the next stellar generations. The nature of the first massive stars, still largely unknown, can be inferred indirectly by observing low-mass, extremely metal-poor (EMP) stars (with [Fe/H] < -3) in our neighborhood [3]. EMP stars likely formed very early in the Universe, with the ejecta of one or a few previous massive stars, hereafter called the source star(s). By determining which kind of source star models are able to account for the abundance patterns of observed EMP stars, one can constrain the nature (e.g. initial mass, rotation, kind of explosion) of the first massive stars. EMP stars were found to have a wide variety of chemical abundance patterns, especially for light elements such as C, N, O or Na for instance [3, 4]. About 40 % of EMP stars are Carbon-Enhanced Metal-Poor stars (CEMP, [5]), generally defined with [C/Fe] > 0.7. What characteristics the massive source stars should have so as to account for EMP stars has been and is still intensively discussed. Among them, rotation and explosions with strong fallback may be important ingredients (e.g. [6 - 10]).

Here I first discuss the possible impact of rotation on nucleosynthesis during the core He-burning of low metallicity massive stars. Then, I investigate the origin of 128 EMP stars while considering 20 $M_{\odot}$ source star models with various initial rotation velocities and assuming an explosion with strong fallback.

2. Nucleosynthesis in the H and He-burning regions of rotating massive source stars

During the core He-burning phase of low/zero-metallicity massive stars, the possibly strong rotation-induced mixing triggers exchanges of material between the H and He-burning zone [11 - 13]. For instance, the ^{12}C and ^{16}O synthesized in the He-burning core are transported to the H-shell and boost the CNO cycle, so that extra ^{14}N is formed. Some of the ^{14}N, engulfed by the growing convective He-core, creates extra ^{22}Ne through $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(e^{+}\nu_{e})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$. When $T_c \gtrsim 220$ MK, the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ reaction is efficiently activated and releases neutrons that boost the s-process (compared to non-rotating models), provided some heavy seeds, like Fe, are present [14 - 17].

Fig. 1 shows the [X/H] ratios in the ejecta (only the layers above the CO core are considered) of low metallicity 20 $M_{\odot}$ models, computed at 3 rotation rates, $\upsilon_{\rm ini}/\upsilon_{\rm crit}$ = 0, 0.4 and 0.7 ($\upsilon_{\rm ini}$ being the initial equatorial velocity and $\upsilon_{\rm crit} = \sqrt{\frac{2}{3}\frac{GM}{R_{\rm p,c}}}$ the initial critical velocity with M the stellar mass and $R_{\rm p,c}$ the polar radius at the critical limit). The differences in Fig. 1 are due to the mixing process mentioned previously. With increasing initial rotation, the efficiency of the mixing process is increased, leading to the overproduction of light (~ C - Al) and heavy (~ Cu - Ba) elements. The ~ Si - Fe elements are barely affected by this mixing process.

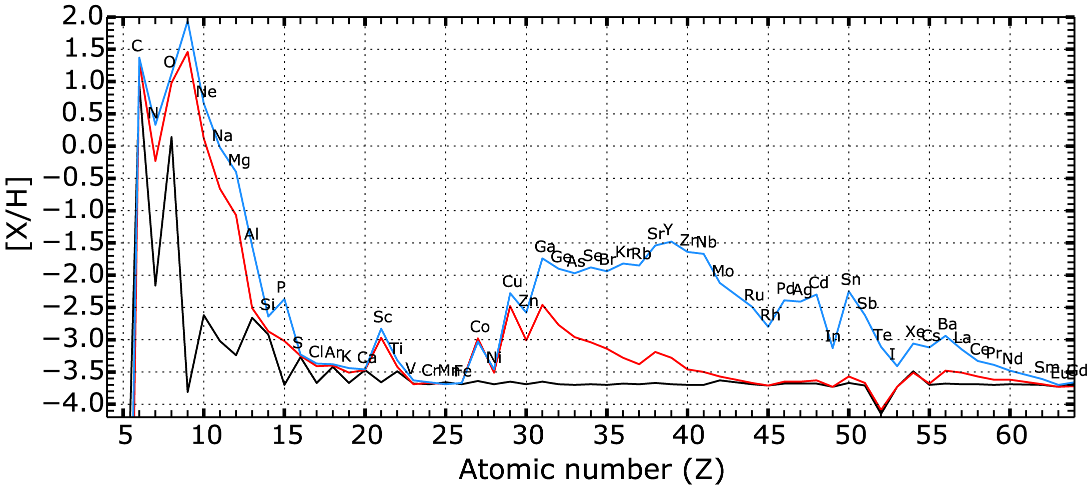

Fig. 1. [X/H] ratios in the ejecta of 20 $M_{\odot}$ at metallicity $Z = 10^{-5}$ and with initial rotation rates of $\upsilon_{\rm ini}/\upsilon_{\rm crit}$ = 0 (black), 0.4 (red) and 0.7 (blue). It corresponds to initial equatorial velocities of 0, 364 and 644 km s^{-1}. The mass cut is set at the bottom of the He-shell (around a mass coordinate of ~ 4 $M_{\odot}$).

3. Comparison to −4 < [Fe/H] < −3 EMP stars

3.1 Source star models and fitting procedure

In what follows, we compare the chemical composition of the ejecta of 20 $M_{\odot}$ models at metallicity $Z = 10^{-5}$, computed with 8 initial rotation rates ($\upsilon_{\rm ini}/\upsilon_{\rm crit}$ = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 and 0.7) with the chemical composition of EMP stars with −4 < [Fe/H] < −3. According to Sect. 2, two groups of elements (~ C - Al and ~ Cu - Ba) are the most affected by rotation and may therefore be the most adequate to constrain the initial rotation of the source stars. As a first step, only the light elements C, N, O, Na, Mg, Al and the ^{12}C/^{13}C ratio were considered. The EMP stars with −4 < [Fe/H] < −3 and having at least 3 abundances measured among C, N, O, Na, Mg, Al and ^{12}C/^{13}C were selected. The most evolved EMP stars, having $\log g$ < 2, were excluded. Indeed, such stars may have undergone significant modifications of their surface chemical composition because of internal mixing processes (e.g. dredge-up, thermohaline mixing). If so, this would make more difficult the link with the EMP star and its source star. The final sample comprises 128 EMP stars.

For a given EMP star and a given source stars model, the best fit model is determined by varying the mass cut (at the time of the explosion, the mass cut is the mass coordinate delimiting the part of the source star that is expelled from the part that is locked into the remnant) freely between the stellar surface and the top of the CO core. It would correspond to explosions with strong fallback. The mass of added ISM to the source star ejecta is also varied freely between 10^2 and 10^6 $M_\odot$. The p-value associated to the χ^2 of the best fit is used as a weight for the considered source star (better fits give larger weights). This procedure was done for the 128 EMP stars.

3.2 Results

The left panel of Fig. 2 shows the cumulative χ^2 distribution for the CEMP, C-normal EMP and entire sample. Overall, reasonable fits ($\chi^2 \lesssim 2-3$) can be found for $\sim$ 50% of the entire EMP star sample. While $\sim$ 60 % of CEMP stars have $\chi^2 \lesssim 2$, only $\sim$ 30 % of C-normal EMP stars have $\chi^2 \lesssim 2$. This is mainly because many C-normal EMP stars have [Mg/C] $\gtrsim$ 0, which cannot be reproduced by the considered source star models (they predict [Mg/C] $\lesssim$ 0, Fig. 1). By contrast, CEMP stars have, by definition, high [C/Fe] ratios and then smaller [Mg/C] ratios, in general. [Mg/C] > 0 may be obtained in the CO core of the source star (e.g. thanks to C-burning). Considering the ejection of deeper source star layers could provide solutions for EMP stars with [Mg/C] > 0. It may be that the assumption of an explosion with strong fallback made here is more suitable to CEMP stars compared to C-normal EMP stars, that may require more standard explosions.

The right panel of Fig. 2 shows the $\upsilon_{\rm ini}/\upsilon_{\rm crit}$ distribution of the best source star models, derived from the CEMP, C-normal EMP stars and entire sample. The C-normal EMP stars have generally rather low [X/H] ratios, that can be reproduced by any model, rotating or not. Then, the velocity distribution derived from C-normal EMP stars is almost flat (green distribution). On the opposite, the CEMP stars have generally high [X/H] (not only [C/H] but also [N/H], [Na/H]...) that are preferentially obtained if the source star model is rotating (Fig. 1). Hence, it gives a source star velocity distribution increasing toward high initial velocities (red distribution). The overall distribution is also increasing toward high initial velocities.

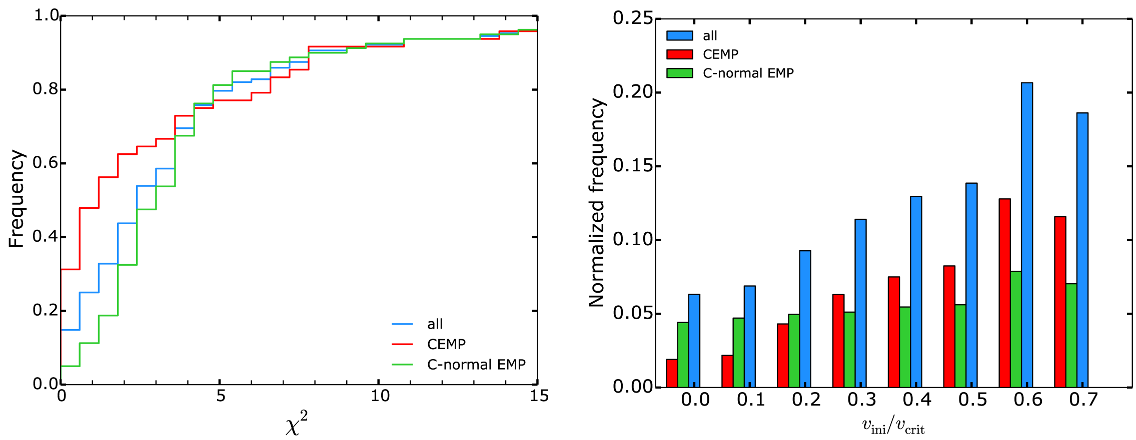

Fig. 2. Results of the abundance fitting of the 128 EMP stars. *Left:* cumulative χ^2 distributions for the CEMP sample, C-normal EMP sample and entire sample. *Right:* $\upsilon_{\rm ini}/\upsilon_{\rm crit}$ distributions of the best source stars derived from the CEMP sample, C-normal EMP sample and entire sample.

4. Summary and conclusion

The impact of the rotation-induced mixing on the nucleosynthesis in the H and He layers of low metallicity rotating massive stars was discussed. Because of the exchange of material triggered by rotation and operating in between the H and He-burning region, during core He-burning, light (~ C - Al) and heavy (~ Cu - Ba) elements are overproduced. The yields of low metallicity 20 $M_{\odot}$ models with various initial rotation were compared to the abundance pattern (only for C - Al elements) of 128 EMP stars with $-4 <$ [Fe/H] < -3. The source stars were assumed to undergo explosions with strong fallback. Reasonable solutions can be found for about ~ 50 % of the EMP sample. The best source star models have preferentially high initial rotation velocities (~ $500-600$ km s^{-1}). It suggests that early massive stars may have been preferentially fast rotators. Also, CEMP stars are significantly better fitted than C-normal EMP stars. This may suggest that most of the CEMP stars could have formed from previous rotating massive stars that experienced strong fallback while most of the C-normal EMP stars may have formed differently (e.g. from more standard explosions)

As a word of caution, we note that the physics of rotational mixing is likely affected by large uncertainties. It may significantly affect the results of this work. The different prescriptions existing for modeling the transport of chemicals inside rotating stars can give different chemical yields [18]. Also, asteroseismic observations revealed that an angular momentum transport is likely missing in small mass stars [19], and therefore, maybe also in massive stars.

Acknowledgments

I acknowledge funding from the Swiss National Science Foundation under grant P2GEP2_184492.

References

[1] K. Nomoto, C. Kobayashi and N. Tominaga, Ann. Rev. Astron. Astrophys. **51**, 457 (2013).
[2] T. Karlsson, V. Bromm and J. Bland-Hawthorn, Rev. Mod. Phys. **85**, 809 (2013).
[3] A. Frebel and J. E. Norris, Ann. Rev. Astron. Astrophys. **53**, 631 (2015).
[4] T. C. Beers and N. Christlieb, Ann. Rev. Astron. Astrophys. **43**, 531 (2005).
[5] V. M. Placco, A. Frebel, T. C. Beers and R. J. Stancliffe, Astrophys. J. **797**, 21 (2015).
[6] G. Meynet, S. Ekström and A. Maeder, Astron. Astrophys. **447**, 623 (2006).
[7] R. Hirschi, Astron. Astrophys. **461**, 571 (2007).
[8] A. Maeder, G. Meynet and C. Chiappini, Astron. Astrophys. **576**, A56 (2015).
[9] H. Umeda and K. Nomoto, Astrophys. J. **565**, 385 (2002).
[10] N. Iwamoto, H. Umeda, N. Tominaga, K. Nomoto and K. Maeda, Science **309**, 451 (2005).
[11] G. Meynet and A. Maeder, Astron. Astrophys. **381**, L25 (2002).
[12] S. Ekström, G. Meynet, C. Chiappini, R. Hirschi, and A. Maeder, Astron. Astrophys. **489**, 685 (2008).
[13] K. Takahashi, H. Umeda and T. Yoshida, Astron. Astrophys. J. **794**, 40 (2014).
[14] M. Pignatari, R. Gallino, G. Meynet, R. Hirschi, F. Herwig and M. Wiescher, Astrophys. J. **687**, L95 (2008).
[15] U. Frischknecht, R. Hirschi, M. Pignatari, A. Maeder, G. Meynet, C. Chiappini, F.-K. Thielemann, T. Rauscher, C. Georgy and S. Ekström, Mon. Not. R. Astron. Soc. **456**, 1803 (2016).
[16] A. Choplin, R. Hirschi, G. Meynet, S. Ekström, Chiappini and A. Laird, Astron. Astrophys. **618**, A133 (2018).
[17] M. Limongi and A. Chieffi, ApJS, 237, 13, Astron. Astrophys. J. **237**, 13 (2018).
[18] G. Meynet, S. Ekström, A. Maeder, P. Eggenberger, H. Saio, V. Chomienne and L. Haemmerlé, in Lecture Notes in Physics, Berlin Springer Verlag, Vol. **865**, Lecture Notes in Physics, Berlin Springer Verlag, ed. M. Goupil, K. Belkacem, C. Neiner, F. Lignières and J. J. Green, 3-642 (2013).
[19] M. Cantiello, C. Mankovich, L. Bildsten, J. Christensen-Dalsgaard and B. Paxton, Astrophys. J. **788**, 93 (2014).