Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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Chemistry and binarity in the early Universe: what is the role of metal-poor AGB stars?

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Abstract. Carbon-enhanced metal-poor stars are probes of the early universe, that teach us about metal-poor AGB stars and supernovae physics in the very first stars. We find a large fraction of CEMP-no stars with large absolute carbon abundance to be in binary systems. This may be an indication of binary interaction with ultra or extremely metal-poor AGB stars, curiously without enhancement in *s*-process elements.

Keywords. stars: chemically peculiar – binaries: spectroscopic – stars: AGB and post-AGB – Galaxy: halo – galaxies: formation

1. Introduction

It is possible to study the conditions in the early universe using stars in our own neighbourhood. Extremely metal-poor stars have abundance patterns reflecting the chemical composition of the interstellar medium (ISM) out of which they were born and can be used as archeological probes. The most metal-poor stars are often enhanced in carbon and the fraction of these so called carbon-enhanced metal-poor (CEMP) stars increases with decreasing metallicity (e.g. Lee *et al.* 2013). There are two main classes of CEMP stars, the CEMP-s stars and the generally more metal-poor CEMP-no stars, see the left-hand panel of Fig. 1. The former type is enhanced in *s*-process elements and is almost always part of a binary system, while the latter is not enhanced in *s*-process elements and seems to be in binary systems only about 20% of the time (Hansen *et al.* 2016a,b). The enhanced carbon and *s*-process elements in CEMP-s stars can be explained by binary transfer from a former asymptotic giant branch (AGB) star companion. The abundance patterns of CEMP-no stars however are thought represent the ISM out of which the stars have been formed, which has been polluted by e.g. spinstars or faint supernovae with large carbon yields. Yoon *et al.* (2016) have additionally proposed that two groups of CEMP-no stars can be distinguished from each other, the Group II and Group III stars (roughly below and above the dashed line in Fig. 1 respectively).

We have studied more CEMP-no stars with radial velocity monitoring to further constrain the influence of binarity in this type of star, using high-resolution spectra from the CFHT and SALT telescopes.

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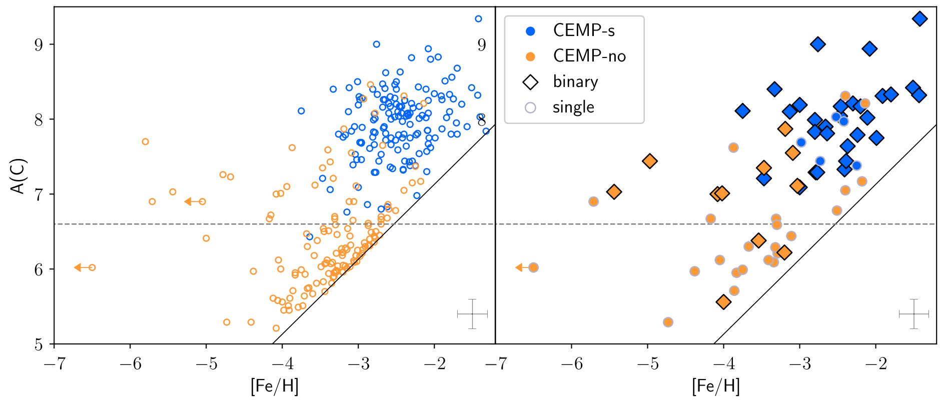

Figure 1. Absolute carbon abundance A(C) vs. metallicity [Fe/H] for CEMP-s and CEMP-no stars, where the former are shown in blue and the latter in orange. In the left-hand panel, we show a compilation of CEMP stars from Yoon *et al.* (2016). In the right-hand panel, we include binary information for 34 stars. Binary stars are indicated with diamonds and single stars with solid dots, where the information in binarity comes from our program combined with the binary flags compiled by Yoon *et al.* (2016) (mostly from Hansen *et al.* 2016a,b). The solid line in both panels indicates the CEMP criterion of [C/Fe] $> +0.7$, and the dashed line at A(C) $= 6.6$ divides the CEMP-no sample with binarity information in two equally sized groups.

2. Results

In our radial velocity monitoring sample we find four new CEMP-no binary systems: HE 2139−5432, SDSS J1422+0031, SDSS J0140+2344 and HE 0107−5240. We add stars from previous radial velocity monitoring programs (Starkenburg *et al.* 2014, Hansen *et al.* 2016b) and three individually studied stars in the literature, which results in a sample of eleven CEMP-no binary systems. From previous studies, there are also 23 known single CEMP-no stars, based on monitoring of their radial velocities. This compilation is inhomogeneous, and a general binary fraction cannot be determined properly. However, if we look at the distribution of the binary stars compared to the single stars in the [Fe/H] – A(C) plane in the right-hand panel of Fig. 1, an interesting pattern starts to emerge. As previously mentioned, almost all CEMP-s stars are in binary systems (however, there are five single CEMP-s stars, which is also interesting to note). Regarding the CEMP-no stars, there seems to be a difference in binary fraction between the higher A(C) and the lower A(C) stars (here separated by a dashed line). For the high A(C) CEMP-no stars, the binary fraction is 47^{+15}_{-14} % whereas for the low A(C) stars it is only 18^{+14}_{-9} %. More data is clearly needed to confirm this hypothesis, but among these low numbers, it is striking that so many of the high A(C) CEMP-no stars are in binary systems, especially below [Fe/H] $= -3$. What could be possible explanations for this phenomenon?

2.1. *Binary interaction*

The CEMP-s stars have such large absolute carbon abundances because they have had an interaction with a binary companion, which previously went through the AGB stage. In the AGB phase of a star, a large amount of carbon is created and finally dredged up to its surface due to thermal pulses in the star. Additionally, the slow neutron capture process creates *s*-process elements which will also be dredged up to the surface of the star. These materials from the surface of an AGB star can be transferred to a binary companion. The orbital periods of the CEMP-no binaries are very similar to those of the CEMP-s stars (typically a few 100 to a few 1000 days). There is a possibility that the high A(C) CEMP-no stars have also experienced mass-transfer from an AGB star, increasing

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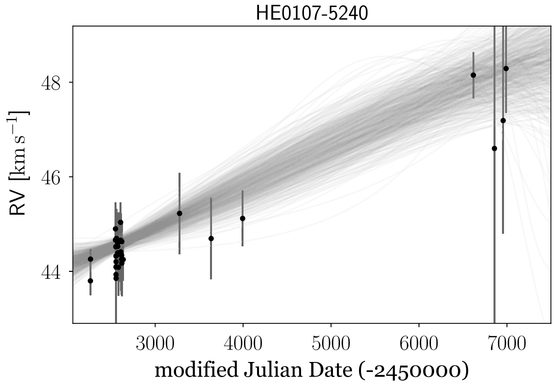

Figure 2. Radial velocities for HE 0107−5240, with possible orbits from *the Joker* (Price-Whelan *et al.* 2017). The four measurements around day 7000 are new from our work (Arentsen *et al.* submitted), which provide evidence that the star is varying in radial velocity over a long timescale.

their carbon abundance to something higher than for the other CEMP-no stars. However, this can only be the case if their companions did not create significant *s*-process elements, since the CEMP-no stars are (by definition) not enhanced in *s*-process elements. Could this indicate that something different is going on inside extremely metal-poor AGB stars?

One hyper metal-poor star whose abundance pattern has previously been explained by interaction with a binary companion is HE 0107−5240 (Suda *et al.* 2004; Lau *et al.* 2007 and most recently Cruz *et al.* 2013). At the time there was no indication that this star was variable in radial velocity so there was no further support for this hypothesis. However, when we add our radial velocity measurements to those from the literature, we find that the star actually varies in radial velocity, see Fig. 2. The orbital period for the star is between $10\,000 - 30\,000$ days (more measurements are needed to constrain it better). This is in the regime where the star could have had an interaction with the wind from an AGB star, which through loss of angular momentum could have widened the orbit to the current state.

If all high A(C) CEMP-no stars would have experienced mass-transfer from a binary companion, this could explain the two different groups of CEMP-no stars (Group II and III). However, some of the high A(C) stars are single. Therefore, even if binary companions do play a role, binarity is likely not the only explanation for the two groups.

2.2. *Other possible explanations for the Group II and III stars*

Based on preliminary comparisons of abundances for some elements, Yoon *et al.* (2016) suggest that the Group II and III stars might have formed from an ISM that has been polluted mainly by faint supernovae or mainly by spinstars for the two groups respectively. A different explanation is that of Chiaki *et al.* (2017) who study the properties of dust in regions of varying carbon enhancement. They find that in the region of the Group III stars carbon dust cooling is most efficient while in the region of the Group II stars it is silicate dust that is more efficient. In between, there is a region where cooling is not efficient at all, producing naturally a gap between the two groups. Another implication of a difference in dust cooling between the two regions could be an effect on the binary fraction of forming stars. If this would be the case (this is truly speculative), that might additionally be able to explain a higher binary fraction among the high A(C) CEMP-no stars. It could also (partly) be a metallicity effect, that at lower metallicity more stars are in binary systems. A last explanation for the two groups is presented by Sharma *et al.*

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(2018) who claim that the difference is due to the bursty nature of the progenitors of the Milky Way, where Group II stars formed in the first burst of star formation and the Group III stars formed in a later star formation event when AGB stars have had the time to enrich the ISM in carbon, and in-falling pristine gas has diluted the ISM to a very low overall metallicity.

3. Conclusion

CEMP-no stars are important for constraining physical processes in the early universe, since many of them are among the most metal-poor stars that we know. It is generally assumed that their abundance patterns are directly reflecting physics of the very first stars and their supernova deaths. However, we find that many of the CEMP-no stars with high absolute carbon abundances are in binary systems. Their orbital periods are similar to those of the CEMP-s stars, which are all expected to have been through interaction with a former AGB companion. If the companions of those CEMP-no binary stars are currently white dwarfs, it is very likely that the surfaces of the CEMP-no stars we see today have been polluted by their companion. This should be kept in mind as it complicates the interpretation of their abundance patterns.

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Discussion

Fekel: What is the maximum orbital period of your binary stars?

Arentsen: Maximum: 10 000–30 000 days, but typically several 100s–1000s days.

Whitelock: May be worth looking at the kinematics, including proper motions, in case they came from disrupted binaries.

Arentsen: Thank you, good idea.

Lugaro: What could be the origin of the single CEMP-*s* stars?

Arentsen: One idea is that they may be the result of massive spinstars that have produced some *s*-processes in the early universe.

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