Nucleosynthesis in low-mass stars: shedding light on the cosmic origin of heavy elements

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Abstract. Low-mass, low-metallicity stars while evolving through the asymptotic giant branch (AGB) phase **undergo** significant nucleosynthesis producing **the** majority of slow (s-) and intermedite (i-) neutron capture elements. To understand the contribution of low and intermediate-mass stars to the Galactic chemical enrichment it is therefore important to account for the products of AGB nucleosynthesis. High resolution optical spectroscopic studies of stars in the AGB **phase are**, however, quite challenging due to obscuration by surrounding dust envelopes. The carbon enhanced metal-poor (CEMP) stars ([C/Fe] ≥ 0.7), with enhanced abundances of neutron-capture elements, namely the CH, CEMP-s, CEMP-r/s, CEMP-i stars are known to be mostly binaries. The **overabundance** of carbon and the heavy elements observed in these stars are believed to have originated in a former AGB companion and subsequently transferred to the stars. The surface chemical composition of these stars can therefore be used to get insight into the origin and evolution of heavy elements and some poorly-understood aspects of AGB nucleosynthesis, such as, mixing of protons in C-rich layers that is needed to produce the required **neutron** source for neutron-capture nucleosynthesis. The CEMP-no group with no evidence of **overabundance** of neutron-capture elements dominate the population at the lowest metallicities and are mostly found to be single stars. The abundances of heavy neutron-capture elements as produced in their unseen precursors reveal important characteristics of first stellear populations. In the past few years, we have studied a large sample of Ba, CH, CEMP-s, CEMP-r/s and CEMP-no stars based on high resolution spectroscopy to better understand the role of low-mass stars in the chemical enrichment of the Galaxy. In this talk, some highlights of the results obtained from these studies are presented. Our efforts towards providing an improved classification scheme for accurate classification of CEMP-s and CEMP-r/s stars and in characterizing the companion asymptotic giant branch (AGB) stars of CH, CEMP-no, CEMP-s and CEMP-r/s binary systems are briefly discussed.

1 Introduction

The initial mass function of the local solar neighbourhood indicates that the majority ($\sim 90\%$) of stars have mass less than 0.8 $M_\odot$, massive stars comprise much less than 1% of all the stars, and about 10% of all the stars in the Galaxy have masses in the range 0.8 to 8 $M_\odot$ Ref.[1].

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Stars progressively enrich the interstellar medium with the products of stellar nucleosynthesis. Massive stars explode as supernovae, releasing vast quantities of processed material, and lower mass stars as they evolve through different stages of stellar evolution enrich the interstellar medium (ISM) through stellar outflows, slowly losing their outer envelopes by stellar winds. About 90% of the ISM dust **is** believed to have come from low- and intermediate-mass (LIM) stars Ref.[2].

AGB stars are a significant site of nucleosynthesis for the production of carbon, nitrogen, fluorine, sodium and heavy elements such as barium and lead in the universe. Knowledge of AGB evolution and nucleosynthesis is crucial to derive an estimate of the contribution of LIM stars to the chemical evolution of galaxies. The majority of the elements heavier than Fe are produced by LIM stars through slow (s-) and intermediate (i-), neutron-capture processes. The origin and evolution of these heavy elements, however remain poorly understood. Stars with surface chemical composition enhanced in heavy elements abundances, such as, the Ba, CH, and different types of CEMP stars are important probes to study the origin and evolution of heavy elements. In the past two decades high resolution spectroscopic studies have unraveled many interesting results about these stars. Among the heavy elements, the s-process elements are often found enhanced in Ba, CH, and in CEMP-s the metal-poor counterparts of CH stars Ref.[3]. The CEMP-r stars show enhancement in r-process elements, and CEMP-r/s stars show enhancement in both s- and r-process elements. The CEMP-no stars show little or no enhancement of heavy elements.

The majority of Ba, CH, CEMP-s and CEMP-r/s stars are found to belong to binary systems, and binary mass transfer from former AGB companion stars **has** been identified as the source of their observed heavy elements abundance pattern. The i-process in low-mass low-metallicity AGB stars **is** also shown to successfully explain the abundances of CEMP-r/s stars in many studies Ref.[4–11]. These stars with chemical peculiarities are also important to probe some poorly understood aspects of stellar nucleosynthesis, such as, mixing of protons in C-rich layers that is needed to produce the required neutrons source for neutron-capture nucleosynthesis. The CEMP-no stars with enhanced carbon and no evidence of overabundance of neutron capture elements dominate the population at lower metallicities and are believed to be the most chemically primitive objects presently known Ref.[12, 13]. In particular, the abundances of heavy neutron capture elements as produced in their unseen precursors reveal important characteristics of the first stellar populations. Being **among** the oldest stars that can be directly observed at present, valuable information can be derived from them, such as the formation and nucleosynthesis pathways of the first stars, initial conditions for stars and galaxy formation Ref.[13–15], and early nucleosynthesis Ref.[16]. Further, these stars are expected to shed light on the physical processes resulting in the transitions from massive Population III (Pop III) stars to normal Population II (Pop II) stars Ref.[17]. Different scenarios have been suggested by various authors for the origin of CEMP-no stars, however, the exact origin of these stars still remains unknown. A recent study by Ref.[18] **has** shown that the binary mass-transfer from an extremely metal-poor AGB companion could also be a possible progenitor of the CEMP-no stars. If the binary mass-transfer scenario holds true for the origin of CEMP-no stars, this will help to understand extremely metal-poor AGB stars and provide robust observational constraints to the AGB nucleosynthesis and mass-transfer models for metallicity [Fe/H]<-2.

We have performed high resolution spectroscopic studies of a selected sample of Ba, CH, CEMP-s, CEMP-r/s and CEMP-no stars with primary objectives **being** to derive crucial clues about the production sites and mechanisms of heavy element nucleosynthesis. Some highlights of the results obtained from these studies are presented here. In section 2, we have briefly discussed shortcomings of current CEMP stars' classification criteria and presented a revised classification scheme for identifying the CEMP-s and CEMP-r/s stars. In section 3, we have discussed about charaterizing the companion AGBs of the CH, CEMP-s and CEMP-r/s stars. A discussion on deriving clues for the origin of CEMP-r/s stars is presented in section 4. Observational evidences for multiple origins for CEMP-no stars are discussed in section 5. The unique star HE 1005-1439 that shows evidence of occurrence of dual nucleosynthesis in the companion AGB star is discussed in section 6. A few concluding remarks are presented in section 7.

2 A revised classification scheme for CEMP-s and CEMP-r/s stars

Among the CEMP stars, distinguishing the CEMP-*s* and CEMP-*r/s* stars is crucial in order to understand the various astrophysical and nucleosynthetic processes responsible for the abundance patterns of **these** two sub-classes. We have examined if abundance ratios such as [hs/ls] (where hs represents heavy s-process elements and ls the light s-process elements), [Sr/Ba], [Ba/Eu], [La/Eu], [La/Ce], [As/Ge] and [Se/Ge] could be used as classifiers to distinguish the CEMP-s and CEMP-r/s stars effectively. Based on a detail investigation we found that the best criteria to distinguish the CEMP-*s* and CEMP-*r/s* stars are:

- CEMP: [C/Fe] ≥ 0.7
- CEMP-*r/s*: [Ba/Fe] ≥ 1.0, [Eu/Fe] ≥ 1.0

  i) 0.0 ≤ [Ba/Eu] ≤ 1.0 and/or 0.0 ≤ [La/Eu] ≤ 0.7;

- CEMP-*s*: [Ba/Fe] ≥ 1.0

  i.)[Eu/Fe] < 1.0, [Ba/Eu] > 0.0 and/or [La/Eu] > 0.5;
  ii.)[Eu/Fe] ≥ 1.0, [Ba/Eu] > 1.0 and/or [La/Eu] > 0.7.

This scheme of classification based on the abundance ratios of three key neutron-capture elements Ba, La and Eu **has** proven to be highly effective in distinguishing the CEMP-s and CEMP-r/s stars. A critical investigation on the formation scenarios of the CEMP stars and a thorough discussion on their classification criteria along with the new classification scheme put forward by us are presented in Ref.[5].

3 Characterizing the companion AGB stars of CH, CEMP-*s* and CEMP-*r/s* stars

As mentioned before, the CH, CEMP-s and CEMP-r/s stars are mostly binary systems, and binary mass transfer from former AGB companion stars **has** been identified as the source of overabundance of heavy elements observed in these stars. As 'mass' plays a crucial role in a star's evolution and nucleosynthesis history, we have investigated the mass of **the** companion AGB stars using several diagnostics such as C, N, O, Na, Mg abundances, and abundance ratios of certain key elements such as [hs/ls] and [Rb/Zr] ratios. Details on these studies can be found in our papers, i.e., Ref.[5, 7, 9–11, 19, 20]. Here some results are mentioned briefly.

3.1 The [hs/ls] ratio as an indicator of neutron source

The [hs/ls] ratio is a useful indicator of neutron source in the former companion AGB star. At higher neutron exposures, more second peak (hs) s-process elements are produced over the first peak (ls), resulting in high [hs/ls] ratio. As the neutron exposure increases with decreasing metallicity, [hs/ls] ratio increases with decreasing metallicity, showing anti-correlation with metallicity. The anti-correlation of [hs/ls] suggest the operation of $^{13}C(\alpha, n)^{16}O$ neutron source, since $^{13}C(\alpha, n)^{16}O$ is found to be anti-correlated with metallicity. Hence positive values for [hs/ls] ratio could be seen in low-mass, low metallicity AGB stars Ref.[21]; whereas, in the case of massive AGB stars (5 - 8$M_{\odot}$), where the neutron source is $^{22}Ne(\alpha, n)^{25}Mg$, negative values for this ratio **are** observed Ref.[22, 23]. Mg enrichment is expected in the stars where the reaction $^{22}Ne(\alpha, n)^{25}Mg$ takes place. None of the CEMP stars studied by us shows Mg enhancement, ruling out the possibility of $^{22}Ne(\alpha, n)^{25}Mg$ reaction as a possible neutron source. The positive values of [hs/ls] obtained for the studied CEMP-r/s stars and CEMP-s stars indicate low-mass of the companion AGB stars with $^{13}C(\alpha, n)^{16}O$ reaction as the neutron source.

3.2 [Rb/Zr] ratio as a probe of neutron density and mass of the companion AGBs

The AGB star models predict higher Rb abundances for massive AGB stars where the neutron source is $^{22}Ne(\alpha,n)^{25}Mg$ reaction Ref.[24]. Detail nucleosynthesis models for the stars with masses between 5 - 9 $M_{\odot}$ at solar metallicity predict [Rb/(Sr,Zr)]>0 Ref.[25]. A positive value of [Rb/Sr] or [Rb/Zr] ratio indicates a higher neutron density, whereas a negative value indicates a low neutron density with $^{13}C(\alpha, n)^{16}O$ reaction acting as the neutron source. A comprehensive discussion on Rb as a probe of the mass of the companion AGB star can be found in Ref.[10, 11, 26]. The negative values obtained for [Rb/Zr] and [Rb/Sr] ratios for stars in our sample for which these ratios could be estimated indicate low-mass nature of the companion AGB stars.

3.3 Parametric model based analysis: mass of the companion AGBs

We have performed a **detailed** parametric model based analysis to derive the mass of the companion AGB stars Ref.[5–7, 10, 11], by comparing the observed abundance of heavy elements (Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Sm and Eu) with the predicted abundance from FRUITY models Ref.[27]. The best fitting mass of the companion AGB is obtained by fitting the observed abundance with the parametric model function of Ref.[28] by minimizing the χ^2 value. All the stars in these studies are found to have low-mass AGB companions with M $\leq$ 3 $M_{\odot}$.

4 Origin of CEMP-r/s stars: clues from parametric model based analyses

We have used the i-process model yields [X/Fe] from Ref.[4], and compared with the observed [X/Fe] (X indicates neutron-capture elements) of the CEMP-r/s stars in our sample for the neutron densities ranging from 10^9 to 10^{15} cm^{-3}. The neutron-densities responsible for the observed abundances in the CEMP-r/s stars are derived by fitting the observed abundance with the dilution factor incorporated parametric model function:

$$X = X_i \cdot (1-d) + X_{\odot} \cdot d$$

where X represents the final abundance, X_i the i-process abundance, d is the dilution factor, and $X_{\odot}$ the solar-scaled abundance. Here d is a free parameter that can be varied to find the best fit between the model and the observational data for each constant neutron density. The best fit model is found using χ^2_{min} method. Our analysis shows that the observed abundances in CEMP-r/s stars could be explained by i-process model yields. The details of these studies can be found in Ref.[5, 10, 19].

5 Observational evidence for multiple origins for CEMP-no stars

In Ref.[8] we have studied two extremely metal-poor CEMP-no stars HE 2148−2039 and HE 2155−2043 that are found to have similar metallicities ([Fe/H], − 3.32 and −3.46 respectively) and enhanced carbon with [C/Fe] values 1.27 and 2.05 respectively. While Mg is found to be under abundant in HE 2148−2039 with [Mg/Fe] = −0.35, it is highly enhanced in HE 2155−2043 with [Mg/Fe] = 1.57, indicating different origins as far as the α-elements are concerned. In contrary to HE 2148−2039 showing a very strong feature of Ba II 4934.06 Å and a weak feature of Sr II 4215.52 Å , the object HE 2155−2043 shows a strong feature of Sr II 4215.52 Å and a weak feature of Ba II 4934.06 Å . The estimated [Sr/Fe] and [Ba/Fe] are (−2.02, −0.84) for HE 2148−2039 and (−0.04, −1.64) for HE 2155−2043. These differences are clear observational evidences for multiple origins for CEMP-no stars.

6 HE 1005-1439: evidence of dual nucleosynthesis in the companion AGB star

This object which is an extremely metal-poor ([Fe/H] = − 3.03) star with a unique abundance pattern that shows signatures of dual nucleosynthesis in the companion AGB star was reported for the first time in Ref.[19]. A parametric-model-based analysis of the abundances of the heavy elements indicated that the star's surface chemical composition is being influenced by similar contributions from both the s- and i-process nucleosynthesis providing observational evidence of dual nucleosynthesis in the former companion AGB star. A formation scenario involving mass transfer from a now extinct AGB companion, with proton ingestion episodes (PIEs) triggering i-process, followed by s-process AGB nucleosynthesis with a few third-dredge-up episodes is proposed for this object. The observational constraints derived from this study can provide important clues for a better understanding of the interplay between PIEs and partial mixing of protons in the intershell region and also about the conditions resulting in a pure s- or i-process surface abundance pattern in low-mass, low metallicity AGB stars.

7 Concluding Remarks

During the course of evolution, the LIM stars pass through the AGB phase of evolution, a phase that acts as a major factory for the production of various elements in the universe. Considering binary systems such as CH, CEMP-s, CEMP-r/s stars with former AGB companions, AGB nucleosynthesis is studied in detail through the chemical analysis of the surface chemical composition of these stars. Some highlights of the results obtained from high-resolution spectroscopic analysis are presented. A new classification scheme put forward in Ref.[5] clearly distinguishes CEMP-s and CEMP-r/s stars. Detailed abundance analysis of CH, CEMP-s and CEMP-r/s stars re-confirms pollution from low-mass AGB companions, Parametric model based analyses also confirm low-mass for their former companion AGB stars. Our analysis also confirms i-process to be responsible for the observed abundance pattern in CEMP-r/s stars. The i-process models could successfully reproduce the observed abundance in CEMP-r/s stars. Peculiar abundances of HE 1005-1439 present signatures of dual nucleosynthesis in the companion AGB star, with PIEs triggering i-process followed by s-process during third-dredge-up episodes. Multiple origins for CEMP-no stars are evident from the surface chemical composition and spectral signatures of two extremely metal-poor CEMP-no stars HE 2148−2039 and HE 2155−2043.

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