PROCEEDINGS OF SCIENCE

The i-process and CEMP-r/s stars

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We investigate whether the anomalous elemental abundance patterns in some of the C-enhanced metal-poor-r/s (CEMP-r/s) stars are consistent with predictions of nucleosynthesis yields from the i-process, a neutron-capture regime at neutron densities intermediate between those typical for the slow (s) and rapid (r) processes. Conditions necessary for the i-process are expected to be met at multiple stellar sites, such as the He-core and He-shell flashes in low-metallicity low-mass stars, super-AGB and post-AGB stars, as well as low-metallicity massive stars. We have found that single-exposure one-zone simulations of the i-process reproduce the abundance patterns in some of the CEMP-r/s stars much better than the model that assumes a superposition of yields from s- and r-process sources. Our previous study of nuclear data uncertainties relevant to the i-process revealed that they could have a significant impact on the i-process yields obtained in our idealized one-zone calculations, leading, for example, to ~ 0.7dex uncertainty in our predicted [Ba/La] ratio. Recent 3D hydrodynamic simulations of convection driven by a He-shell flash in post-AGB Sakurai's object have discovered a new mode of non-radial instabilities: the Global Oscillation of Shell H-ingestion. This has demonstrated that spherically symmetric stellar evolution simulations cannot be used to accurately model physical conditions for the i-process.

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1. Introduction

The fraction of C-Enhanced Metal Poor (CEMP) stars (objects with [C/Fe]>1) increases with a decrease in metallicity, reaching 20% at [Fe/H]=-2 [1, 3]. CEMP-r/s stars form a subclass characterized by simultaneous enhancements of both s- (e.g., Ba) and r-process (e.g., Eu) elements. [17, 21, 22]. The prevailing model of a CEMP-r/s star assumes that it is a component of a binary system initially pre-enriched with r-process material that has additionally accreted s-process material from its heavier AGB-star companion, which leads to a superposition of both processes [17]. However, this model fails to explain CEMP-r/s stars with large [hs/ls][1] and low [La/Eu] ratios. An example of such a star is CS 31062-050 shown in Fig. 26 in [5].
The intermediate neutron-capture process (hereafter, the i-process, see [7]) operates at neutron densities between those characteristic of the s- and r-process, when H is convectively entrained and advected into a He-burning zone. When the advected fluid parcel has reached a depth with $T \approx 1.5 \times 10^8$K, ^{13}N is produced in the reaction ^{12}C(p,γ)^{13}N. The beta-decay of ^{13}N to ^{13}C followed by the reaction ^{13}C(α,n)^{16}O result in a production of neutrons with a density $N_n \approx 10^{15}\mathrm{cm}^{-3}$. Possible astrophysical sites for the i-process have been identified in stellar evolution computations. These are the He-shell thermal pulses in the low- and zero-metallicity AGB stars [9], the very late thermal pulse (VLTP) in post-AGB stars (e.g., Sakurai's object, [13]) and the He-core flash in low-metallicity low-mass stars ([6]). The i-process in VLTP models with mixing assumptions motivated by 3D hydrodynamic simulations was found to reproduce the observed abundance distribution in Sakurai's object [13]. It may also explain the excess of ^{32}S and anomalous Ti isotopic ratios in presolar A+B grains [10, 15].
In this paper, we investigate if the i-process nucleosynthesis can explain the observed abundance patterns in peculiar CEMP-r/s stars, such as CS 31062-050. We also briefly discuss the impact of nuclear physics uncertainties on the calculated i-process yields, as well as the results of 3D hydrodynamic simulations of nuclear burning and mixing under conditions relevant to the i-process in Sakurai's object recently reported in [14, 24].

2. A simple i-proces model for the CEMP-r/s stars

We compare the abundance pattern in CS 31062-050 with results of our nucleosynthesis simulations of the i-process in one zone with constant temperature and density corresponding to the physical conditions in a He pulse-driven convective zone (PDCZ) from 1D stellar evolution models of AGB stars. Our assumed values of $T = 2 \times 10^8$ K and $\rho = 10^4\,\mathrm{g\,cm}^{-3}$ prevent destruction of ^{13}N via the (p,γ) channel, but they allow the neutron release via ^{13}C(α,n). In the He PDCZ of a real star, with H entrained by convection from the surrounding H-rich envelope, the reactions ^{12}C(p,γ)^{13}N and ^{13}C(α,n)^{16}O are spatially separated, the first occurring close to the upper and the second close to the lower convective boundary. ^{13}N produced in the first reaction decays to ^{13}C while being transported down by convection. The one-zone model reproduces the characteristic i-process neutron density ($N_\mathrm{n} \sim 10^{15}\mathrm{cm}^{-3}$) and neutron exposures of $10\ldots 50$ mbarn^{-1}. The initial abundances are taken from the solar abundance distribution [11], with isotopic ratios from [20],

[1] hs and ls are the total abundances of selected elements representing the second (high) and first (light) s-process peaks in the solar abundance distribution.

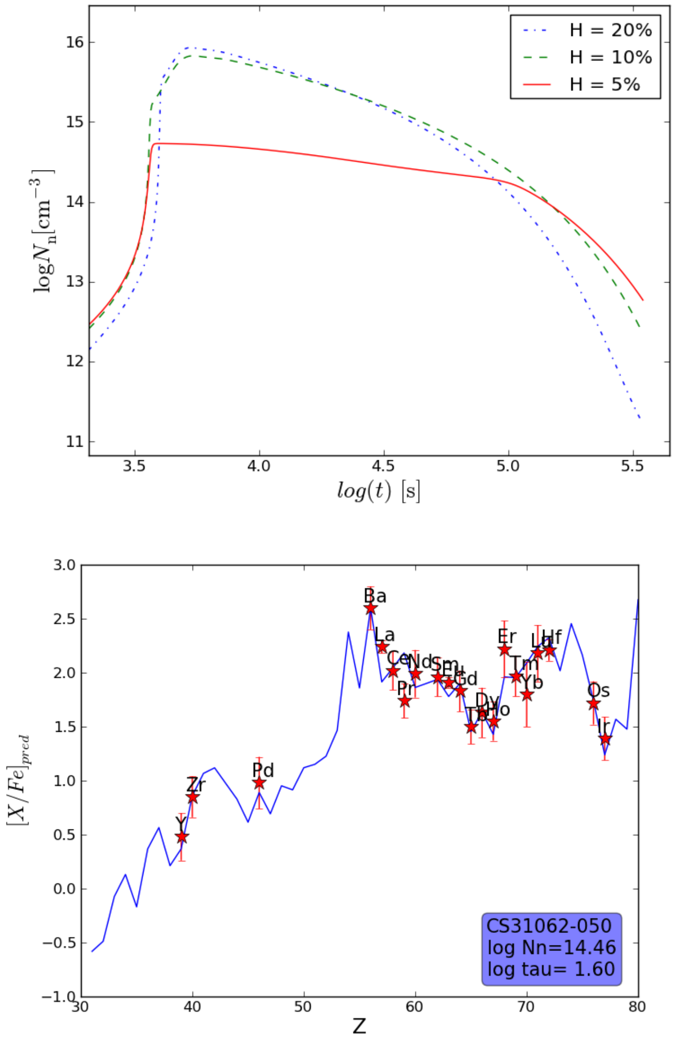

Figure 1: The evolution of the neutron density $N_{\rm n}$ with time for the initial H mass fractions 0.2, 0.1 and 0.05 (upper panel). The best fit of the abundance pattern in the CEMP-r/s star CS 31062-050 with the i-process model (lower panel, with observational data from [16]). Shown in the bottom-right corner are the fitted values of the neutron density $N_{\rm n}$ and exposure (tau).

scaled down to the metallicity $Z = 10^{-3}$. The abundances of C and O are additionally modified, so that they are close to those found in the He PDCZ, i.e. $X(^{12}{\rm C}) = 0.5$ and $X(^{16}{\rm O}) = 0.05$. A specified fraction of H, assumed to be ingested from the H-rich envelope, is added to the mixture, with the combined mass fraction of C+H being always set to 0.7. The i-process nucleosynthesis is followed with the NuGrid single-zone PPN code [12].

During the first second, ^{12}C is almost all transformed into ^{13}N which then decays into ^{13}C on the timescale of 9.97 min. After the decay of ^{13}N, the reaction $^{13}{\rm C}(\alpha,{\rm n})^{16}{\rm O}$ releases neutrons with a high neutron density. The upper panel of Fig. 1 shows the evolution of the neutron density $N_{\rm n}$ with time for different initial mass fractions of H. As the simulation proceeds, the neutron exposure $\tau = \int_0^t N_{\rm n} v_T \, dt'$ (v_T is the neutron thermal velocity) increases with time, and the abundance

distribution is shifted to heavier elements. The model results shown in the lower panel of Fig. 1 give the best representation of the abundance pattern in CS 31062-050. Its corresponding neutron density and exposure are indicated in the panel's bottom-right corner.
Hydrodynamic simulations suggest that the i-process nucleosynthesis in the stellar environment is terminated when the energy released through the combustion of ingested H leads to a significant perturbation of the spherically symmetric convective shell structure. This self-quenching will depend on the exact configuration of the convective shells at the time of H-ingestion and can be expected to vary. Therefore, a range of the termination time is expected for the i-process, which motivates us to consider it as a free parameter in this simple model. However, in spite of its simplicity, our one-zone i-process model reproduces surprisingly well the entire heavy-element abundance distribution from Y to Ir within the observational errors in CS 31062-050 (Fig. 1). Specifically, this includes the large ratio of [hs/ls] ≈ 1, the [La/Eu] ratios between 0.0 and 0.5, which are between the ratios predicted for the s- and r-processes, as well as high abundances in the Er-W region compared to those in the Os-Ir region, which are characteristic signatures of the i-process nucleosynthesis at high neutron density, and which are all present in the abundance pattern of CS 31062-050. On the other hand, the one-zone model is not suited to correctly describe the evolution of the Fe group elements and Pb, because of its unrealistic depletion of the n-capture seed elements. The observed abundance distributions in the CEMP-r/s stars HE 0338-3945 [17] and CS 22898-027 [2] are also well reproduced by the one-zone i-process model (Fig. 2).

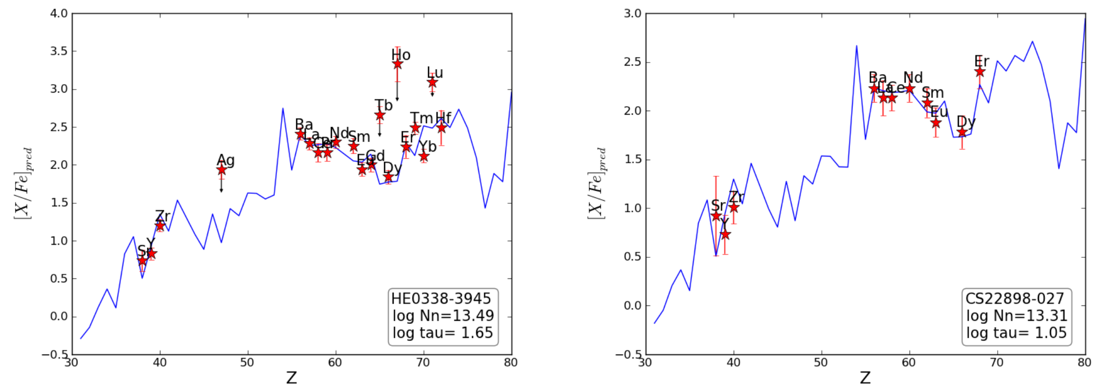

Figure 2: Fit of the results of the one-zone i-process model to the abundance distributions in the CEMP-r/s stars HE 0338-3945 (left panel, with data from [17]) and CS 22898-027 (right panel, with data from [2]) for the indicated neutron densities (N_n) and exposures (tau).

3. Nuclear physics uncertainties relevant to the i-process

When comparing predicted nucleosynthesis yields from the i-process with observations, it is important to understand what and how strongly nuclear physics uncertainties can affect the calculated abundances of isotopes along the i-process nucleosynthesis path, that goes four to five species off the valley of stability, as shown in Fig. 3. The first i-process uncertainty analysis was done in

[4], where propagating systematic uncertainties of nuclear reaction cross sections from different theoretical models were investigated for elements of the second s-process peak. The analysis considered Ba, La and Eu. The same i-process one-zone model described in Section 2 was used. Fig. 6 in [4] shows changes of the [La/Eu] versus [Ba/La] ratio for cases when nuclear reaction rates are estimated using three different theoretical Hauser-Feshbach codes: NON-SMOKER [23] (with rates from JINA REACLIB [8]), CoH 3.3 [18] and TALYS 1.4 [19]. The changes were found to be strongly model-dependent. The resulting [Ba/La] and [La/Eu] ratios varied, at least, by factors of ~ 0.7 dex and ~ 0.3 dex, respectively, between the models. The conclusions are that the nuclear physics uncertainties strongly limit, at present, the predictive power of i-process simulations [4] and that it would be very important to further study the impact of nuclear physics uncertainties on the i-process element production at various sites.

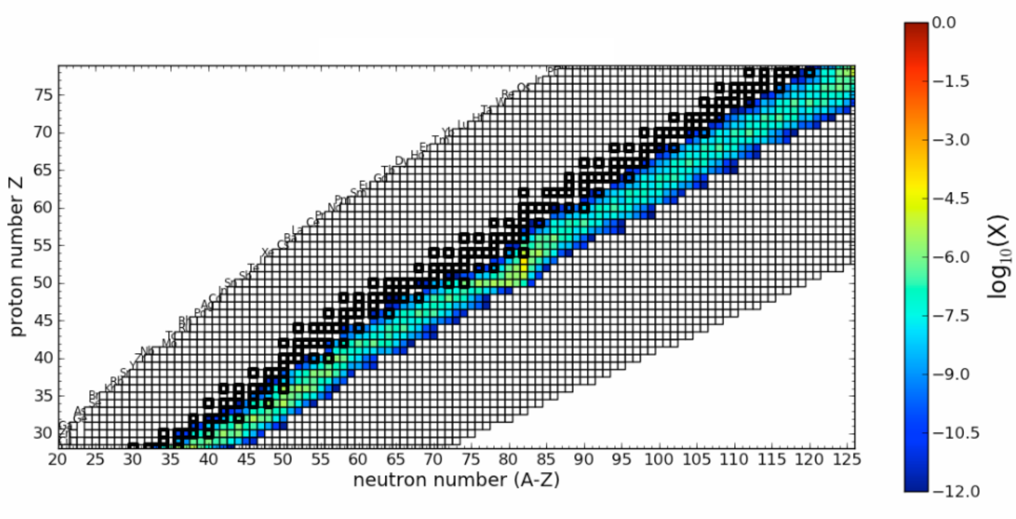

Figure 3: The i-process nucleosynthesis path in the chart of isotopes with the color-coded mass fraction (X) of each species from our one-zone simulations.

4. The i-process conditions in Sakurai's object

3D hydrodynamic simulations of mixing and H entrainment in the He PDCZ of the post-AGB star Sakurai's object are now possible at fine enough grids, so that the entrainment process is numerically converged [24]. Combustion of ingested protons in the reaction ^{12}C(p,γ)^{13}N and its energy feedback on mixing was taken into account [14]. Two runs with 768^3 and 1536^3 grid resolutions were performed and showed quantitatively quite similar behaviour. The continued H ingestion led to its accumulation in the upper part of the convective zone. At some point, a large amount of H fuel ignited there and a resulting burning pocket rose and collided with the stiff convective boundary. The mass-conservation law then made the pocket to spread and move along the boundary to the antipode, where the two fronts collided causing a strong downdraft of the material, and the process repeated several times. That new mode of non-radial instabilities, coined by the authors "The Global Oscillation of Shell H-ingestion (GOSH)", first appeared after nearly 850 min in the 1536^3 run. It is shown in Fig. 4 at 1149 min [14, 24]. Such a GOSH event becomes

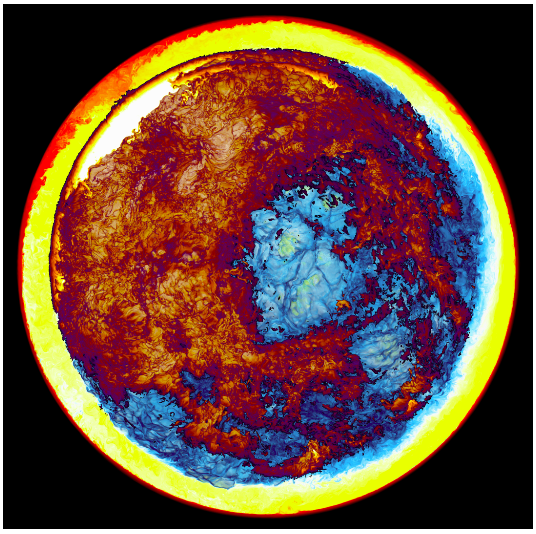

Figure 4: A hemisphere with mixtures of entrained H-rich gas and He+C-rich gas of the He PDCZ. The energy release rate from the burning of ingested H is shown in very dark blue, yellow, and white.

more and more violent as it is repeated for about a dozen times in a row, leading to entrainment of entropy from the stable layer. In the run with 768^3 grid resolution, a new upper convective boundary forms, while the run with 1536^3 cells has not been followed to this point yet. It is not clear yet how the GOSH can be taken into account in 1D stellar evolution calculations.

5. Conclusion

Simple one-zone simulations of i-process nucleosynthesis give yields that can fit almost all of the observed heavy-element abundances from Y to Ir, within their observational errors, in some of the CEMP-r/s stars. The observed high enrichments with s- and r-process material in these stars cannot be explained by the currently prevailing model that assumes a superposition of yields from different s- and r-process sources. These CEMP-r/s stars could therefore represent an i-process site. Nuclear physics uncertainties are a main obstacle to obtaining reliable yields from the i-process nucleosynthesis calculations, as found by [4]. Mixing and H entrainment relevant to the i-process in the post-AGB star Sakurai's object have recently been investigated, which has revealed a new mode of non-radial instabilities, the GOSH [14].
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