The Astrophysical Origin of Neutron-Capture Elements in the CEMP Star HE 1005-1439: A Postprint

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Abstract

HE 1005-1439 is an extremely metal-poor ([Fe/H] ~ -3.0) Carbon-Enhanced Metal-Poor (CEMP) star, whose s-process elements are significantly overabundant ([Ba/Fe] = 1.16 ± 0.31, [Pb/Fe] = 1.98 ± 0.19), while its r-process elements are moderately overabundant ([Eu/Fe] = 0.46 ± 0.22). Neither a pure s-process model nor an i-process model can reproduce the star's neutron-capture abundance distribution. Adopting an abundance decomposition approach to investigate the astrophysical origins of this star's chemical elements can aid in understanding the formation and chemical evolution of CEMP stars. By employing a mixed s-process and r-process model to fit the abundance distribution of its neutron-capture elements, we find that the star's neutron-capture elements primarily originate from s-process nucleosynthesis in a low-mass, low-metallicity AGB companion star, with r-process nucleosynthesis also contributing.

Full Text

Preamble

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The Astrophysical Origins of Neutron-capture Elements in CEMP Star HE 1005-1439

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Abstract

HE 1005-1439 is a Carbon Enhanced Metal-Poor (CEMP) star with [Fe/H] -3.0, which is significantly enhanced in elements produced by the slow neutron-capture process (s-process; e.g., $[\mathrm{Ba/Fe}] = 1.16 \pm 0.31$, $[\mathrm{Pb/Fe}] = 1.98 \pm 0.19$) and mildly enhanced in elements produced by the rapid neutron-capture process (r-process; e.g., $[\mathrm{Eu/Fe}] = 0.46 \pm 0.22$). The neutron-capture element patterns of this star cannot be fitted by either a pure s-process model or an intermediate (i-) process model. Studying the astrophysical origins of chemical elements in this star based on the method of abundance decomposition can help us understand the formation and chemical evolution of CEMP stars. By fitting the abundance patterns of neutron-capture elements with a mixed s- and r-process model, we find that the neutron-capture elements in this star are mainly produced by s-process nucleosynthesis in a low-mass, low-metallicity AGB companion star, while r-process nucleosynthesis also contributes.

Keywords: stars: abundances, stars: formation, stars: chemically peculiar

1 Introduction

Due to Coulomb barrier effects, heavier nuclides become increasingly difficult to produce through thermonuclear fusion reactions. Since ^{56}Fe has the largest binding energy per nucleon, elements heavier than the iron group cannot be produced via charged-particle capture reactions because of their lower binding energies and higher Coulomb barriers. Instead, they must be synthesized through neutron-capture reactions, which are not hindered by Coulomb barriers [1]. Researchers classify neutron-capture processes that are slower than β-decay as the slow neutron-capture process (s-process) and those faster than β-decay as the rapid neutron-capture process (r-process). Together, these two processes each contribute nearly half of the heavy elements in the universe.

The s-process is typically divided into the weak s-process and the main s-process. The weak s-process occurs primarily during the late stages of central helium burning and carbon shell burning in massive stars, producing lighter neutron-capture elements such as Sr and Y [2–3]. Travaglio et al. [4] suggested that the contribution from the weak s-process decreases with metallicity, with only about 10% of Sr in the solar system originating from this process. However, considering rotational effects, Frischknecht et al. [5] proposed that rapidly rotating massive metal-poor stars can efficiently produce weak s-process elements. The main s-process occurs during the asymptotic giant branch (AGB) phase of low- to intermediate-mass stars and can effectively produce all neutron-capture elements [6].

Similarly, the r-process can be divided into weak and main components. The weak r-process may occur in core-collapse supernovae of massive stars [7] and primarily produces lighter neutron-capture elements. The main r-process can produce all neutron-capture elements. Recent observations and studies of the gravitational wave candidate GW 170817 [8–9] indicate that main r-process elements are produced in neutron star merger events, though neutron star mergers are not the only possible site. Yong et al. [10] studied the elemental abundance pattern of the red giant SMSS J200322.54–114203.3 and found that neutron star mergers alone cannot reproduce the abundance pattern of ultra-metal-poor stars, suggesting that other r-process sites must exist, such as black hole accretion disks [11] and magnetorotational supernovae [12].

Metal-poor stars are particularly valuable because their natal interstellar medium was polluted by only a few nucleosynthetic events, preserving the chemical signatures of the early Galaxy. Consequently, these stars serve as probes for investigating the early chemical evolution of the Milky Way [13]. CS 22892-052 ([Fe/H] = -3.1) and CS 31082-001 ([Fe/H] = -2.9) are two extremely metal-poor stars with enhanced r-process elements ([Eu/Fe] > 1.6) and are typically regarded as archetypal main r-process stars [14]. Here we define [A/B] = log(N /N)* − log(N /N) , where N and N are the number densities of elements A and B, the subscript "*" represents a particular star, and “ ” represents the Sun. The abundance of element A in a star is expressed as log (A) = log(N /N) + 12.0. Likewise, the metal-poor stars HD 122563 ([Fe/H] = -2.77) and HD 88609 ([Fe/H] = -3.07) show overabundances of light neutron-capture elements (Sr, Y, etc.) relative to heavy neutron-capture elements (Ba, Eu, etc.) and are considered typical weak r-process stars [15–16]. Li et al. [17] and Hansen et al. [18] used iterative methods to derive the abundance patterns of main and weak r-process components.

Carbon Enhanced Metal-Poor (CEMP) stars are generally defined as metal-poor stars with [C/Fe] > 1.0. They constitute a large fraction of metal-poor stars, particularly at the extremely metal-poor end. The diversity of elemental abundances and the unclear formation mechanisms of CEMP stars make them a major research focus [19]. Beers et al. [20] classified CEMP stars into several categories: CEMP-s stars ([Ba/Fe] > 1, [Ba/Eu] > 0.5), CEMP-r stars ([Eu/Fe] > 1, [Ba/Eu] < 0), CEMP-r/s stars ($0 <$ [Ba/Eu] < 0.5), and CEMP-no stars ([Ba/Fe] < 0).

HE 1005-1439 is a CEMP star with enhancements in both s- and r-process elements ([Ba/Fe] = 1.16 ± 0.31, [Eu/Fe] = 0.46 ± 0.22, [C/Fe] = 2.25 ± 0.27, [Fe/H] = -3.04 ± 0.15). Based on the classification according to neutron-capture element abundances, it should belong to the CEMP-s class. Goswami et al. [21] could not fit the neutron-capture element abundances of this star using an s-process model alone; they achieved a satisfactory fit only after superimposing an intermediate (i-) process component. However, Pb was not well fitted, with the observed Pb abundance being 0.3–0.6 dex lower than the model predictions. They concluded that there was no contribution from the r-process to the heavy element abundances of this star. Since the astrophysical site of i-process nucleosynthesis has not been definitively identified [22], Karinkuzhi et al. [23] suggested that low-mass, low-metallicity AGB stars are effective sites for i-process production and used the i-process to explain the abundance patterns of neutron-capture elements in several CEMP-r/s stars. Clearly, the neutron-capture element abundances of HE 1005-1439 require further investigation. In this paper, we analyze the abundances of neutron-capture elements in this star using a parametric method based on a four-component model (main r-, weak r-, main s-, and weak s-process). Section 2 describes the models and fitting calculations, Section 3 presents the analysis and discussion of the abundance characteristics, and we conclude in Section 4.

2 Models and Calculations

To investigate the astrophysical origins of neutron-capture elements in HE 1005-1439, we assume that the elemental abundances in this star originate from four neutron-capture nucleosynthesis processes [24]:

$$N\ = (C , N , ,\ + C , N , ,\ + C , N , ,\ + C , N , ,) \times 10$$[1]

where N , , , N , , , N , , , and N , , represent the component abundance templates of element i for the main r-process, weak r-process, main s-process, and weak s-process, respectively, while C , , C , , C , , and C , are the fitting coefficients for the four corresponding components.

Since s-process-enhanced metal-poor stars show large dispersion in [Pb/hs] (where hs denotes heavy s-process elements such as Ba and La) [25], Straniero et al. [26] argued that this requires explanation through variations in the efficiency of the ^{13}C pocket. Bisterzo et al. [27] calculated yields of low-mass AGB stars with various metallicities and different ^{13}C-pocket efficiencies, including the standard case (ST), ST/12, ST/18, and ST/30. The “ST” case, proposed by Gallino et al. [28], indicates that the solar system main s-process abundance distribution can be explained by the s-process yields of an AGB star with half the solar metallicity [29]. In this work, N , , adopts the AGB model calculated by Bisterzo et al. [27] ([Fe/H] = −2.6, M = 2.0 M , where M denotes solar mass), using the ST/12 case and normalized to the solar system s-process abundance of Ba [29]. These models have been adopted in several studies [24, 30–34] and are reliable. We use all the main s-process theoretical abundances provided by [27] for fitting and compare the results with those obtained using other models. The ST/12 case provides the best fit, and compared to other models, its [Sr/Ba] = −0.84 and [Ba/Pb] = −0.64 ratios are closest to the observed abundance ratios of the sample star.

The normalization method is: log N ,mod = log N , + [X /Fe]mod + [Fe/H]mod, where N ,mod and N , represent the abundance of element i in the

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[1] Fe/H

model and in the Sun, respectively, and [X /Fe]mod and [Fe/H]mod denote the yields and metallicity given by the model.

N , , = N ,mod × N(Ba) , , / N(Ba)mod, where N(Ba) , , and N(Ba)mod are the main s-process abundance of Ba in the solar system and the abundance of Ba in the model, respectively.

Goswami et al. [21] calculated that the mass of this star is 0.8 M , implying that its companion star should be more massive than 0.8 M . In their model fitting the neutron-capture element abundances of this star, they found that a combination of a 2.0 M AGB model and an i-process model provided the best fit. In our fitting calculations, when we superimposed r-process components with yield models from low-mass, low-metallicity AGB stars of different masses to fit the observed abundances, we found that the 1.3 M model produced theoretical Sr abundances that were too low (0.3 dex) and Pb abundances that were too high (0.3 dex) compared to observations. For the 1.5 M model, the theoretical Sr abundance was too high (0.4 dex), while Eu and Pb abundances were too low (0.3 dex). The 2.0 M AGB model, however, provided good fits to the observed abundances of Sr, Ba, Eu, and Pb, so we selected this model. The abundances of Ba and La used in our calculations are those marked with asterisks in Table 2 of [21], as abundances obtained through spectral synthesis methods are more reliable. N , , and N , , adopt the results calculated by Li et al. [17], while the weak s-process abundances of Sr, Y, and Zr (N , ,) use the yields given by Raiteri et al. [2]. Since weak s-process nucleosynthesis is generally considered to contribute mainly to light neutron-capture elements [2–3], we set the weak s-process component of heavy neutron-capture elements (Ba, Eu, and Pb) to zero. This component model has been adopted in several studies [24, 30–32, 35]. The specific component values for each element are listed in Table 1 , where Z is the atomic number and solar system elemental abundances are taken from [36].

By iteratively comparing the observed stellar elemental abundances with calculated values, we determine the best-fit component coefficients in Equation (1) by minimizing ^{2}, which is defined as:

$$^2 = \Sigma\ (\log N\ ,\mathrm{obs} - \log N\ ,\mathrm{cal})^2\ /\ (\Delta \log N\ ,\mathrm{obs})^2\ (K - K\_\{free\})$$

where N ,cal represents the calculated abundance of element i in the sample star from Equation (1), N ,obs is the observed abundance, Δ log N ,obs is the observational uncertainty, K is the number of observed neutron-capture elements, and K_{free} is the number of free component coefficients (four in this case). The observed elemental abundances and their uncertainties are taken from [21]. The best-fit results are $^2 = 1.29$, C , = 1.4, C , = 0, C , = 20.3, C , = 0. Figure 1 [Figure 1: see original paper] compares the calculated results with observations. The neutron-capture element abundances of this star are dominated by the s-process, with a small contribution from the r-process, while the weak r- and weak s-processes from massive stars contribute essentially nothing to its chemical abundances. The fitting results are consistent with the observational data within the error bars. The Pb abundance is well fitted by the combination of r- and s-processes, indicating that the Pb abundance in this star originates mainly from low-mass, low-metallicity AGB stars, with a minor contribution from the r-process.

3 Analysis and Discussion

Goswami et al. [21] proposed that a combination of main s-process and i-process could fit the abundance pattern of neutron-capture elements in this star. However, both the main s-process and i-process are associated with AGB stars [23, 37–38], so using these two processes together might double-count the contribution from AGB stars. To further investigate the influence of each nucleosynthetic process on the stellar abundances, we calculated the component abundance ratios of neutron-capture elements in this star and present them in Figure 2 [Figure 2: see original paper]. In the figure, $[X/H] = \log(C N ,) - \log N , + [Fe/H]$, where k represents a particular neutron-capture process (e.g., main r-, weak r-, main s-, or weak s-process), C is the fitting coefficient for that process, and N , is the component abundance template of element i for that process. We find that the main s-process from low-mass AGB stars provides the dominant contribution to neutron-capture element abundances, particularly for Ba and Pb. Approximately 98.3% of the Ba abundance comes from the main s-process, with its s-process component abundance being about 1.8 dex higher than its r-process component. For Pb, the s-process component abundance is about 2.4 dex higher than the r-process component. For Eu, however, the r-process contributes 38.1% while the s-process contributes 61.9%, with the r-process component abundance being about 0.25 dex lower than the s-process component.

Straniero et al. [26] pointed out that the large dispersion in the efficiency of the ^{13}C pocket leads to significant observational scatter in [Pb/hs] for s-process-enhanced metal-poor stars, and that $[Pb/hs] > 1.0$ when $[Fe/H] \leq -1.3$. In Figure 3 [Figure 3: see original paper], we compare the relationship between [Pb/Ba] and [Fe/H] for HE 1005-1439 and several CEMP stars. We find that the dispersion in [Pb/Ba] decreases with increasing metallicity, indicating that Pb production is favored at extremely low metallicities, while Ba and other neutron-capture elements are more readily produced at higher metallicities. HE 1005-1439 lies near the linear fit trend line, suggesting that its [Pb/Ba] ratio follows the general enrichment trend. Figure 4 [Figure 4: see original paper] shows the comparison between [Pb/Eu] and [Ba/Eu], revealing an overall linear increasing trend. Normally, Eu is considered a typical r-process element originating mainly from r-process contributions. However, since HE 1005-1439 is a CEMP-s star in a binary system, its Ba and Eu may originate primarily from mass transfer in the binary system. Its companion star has undergone AGB evolution and violent thermal pulses, and the neutron-capture elements (including Eu) produced were accreted onto the surface of HE 1005-1439. According to our calculations, the companion star contributed approximately 62% of the Eu in this star. The remaining 38% of Eu comes from the r-process, likely from the parental gas cloud where the star formed. This parental gas cloud had a history of r-process pollution, and during subsequent evolution, the star accreted s-process material ejected by its companion, leading to gradually increasing abundances of Ba, Pb, and other elements, resulting in the observed abundance pattern.

In this work, we fitted the abundance distribution of neutron-capture elements in the CEMP star HE 1005-1439 using a mixed s- and r-process model, obtaining the following results: $^{2} = 1.29$, C , $= 1.4$, and C , $= 20.3$. Goswami et al. [21] used a parametric method based on theoretical models with s- and i-process components to fit most neutron-capture elements in this star, but they concluded that the Pb abundance ([Pb/Fe] = 1.98) was 0.3–0.6 dex lower than their model predictions and could not be well fitted. In contrast, our parametric approach using different theoretical models shows that the observed Pb abundance is consistent with our calculations within the error bars, demonstrating that the Pb abundance can be reproduced by a combination of AGB nucleosynthesis and r-process contributions. Our component calculations reveal that the s-process contribution to Pb reaches 99.6%, indicating that AGB nucleosynthesis dominates Pb production in this star, meaning that most of its Pb originates from its companion star. Goswami et al. [21] observed significant radial velocity variations in HE 1005-1439 during 2002–2003, providing dynamical evidence that it is a binary system. Additionally, the carbon isotope ratio ^{12}C/^{13}C is a useful probe for studying AGB nucleosynthesis. Karakas et al. [41] found that the ^{12}C/^{13}C value from AGB nucleosynthesis depends on the initial stellar mass and the number of third dredge-up episodes. For low-mass stars, the ^{12}C/^{13}C ratio can exceed 100, and even surpass 1000 at low metallicities. The ^{12}C/^{13}C ratio (5) of this star is far smaller than the intrinsic AGB value, again confirming that it belongs to a binary system and has not yet evolved to the AGB stage. Its s-process elements likely originate mainly from its white dwarf companion that has already passed through the AGB phase. Therefore, the neutron-capture elements in HE 1005-1439 are primarily produced by s-process nucleosynthesis in a low-mass, low-metallicity AGB companion star.

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Note: Figure translations are in progress. See original paper for figures.