The origin of HE0107-5240 and the production of O and Na in extremely metal-poor stars

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We elaborate the binary scenario for the origin of HE0107-5240, the most metal-poor star yet observed ([Fe/H] = −5.3), using current knowledge of the evolution of extremely metal-poor stars. From the observed C/N value, we estimate the binary separation and period. Nucleosynthesis in a helium convective zone into which hydrogen has been injected allows us to discuss the origin of surface O and Na as well as the abundance distribution of s-process elements. We can explain the observed abundances of $^{12}$C, $^{13}$C, N, O, and Na and predict future observations to validate the Pop III nature of HE0107-5240.

1. Introduction

The existence of a star with [Fe/H] = −5.3 has had a great impact on our understanding of circumstances in the early universe. In spite of its very small metallicity, HE0107-5240 shows large enhancements of CNO elements, ([C/Fe] = 4.0, [N/Fe] = 2.3, and [O/Fe] = 2.4±0.2), a mild enhancement of Na ([Na/Fe] = 2.3), but no enhancement of main s-process elements ([Ba/Fe] < 0.8)\cite{1,2}. The observed ratio of C to N ($\sim 150$) cannot be accounted for by the evolution of an isolated star of mass $M = 0.8M_\odot$ \cite{3,4,5}.

Several attempts to explain the abundance pattern of HE0107-5240 rely on supernova (SN) nucleosynthesis \cite{6,7} and the evolution of a second generation star born from Big Bang matter polluted by the supernova ejectum \cite{4,5,8}. The detailed analysis of low mass and extremely metal poor models \cite{4,5} are consistent with a case I scenario \cite{8}.

In this paper we describe a first generation binary scenario for explaining the observed properties of HE0107-5240. We pay particular attention to neutron capture reactions that play a key role in systems which consist initially of an $0.8M_\odot$ secondary and a 1-4 $M_\odot$ primary.

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2. Binary Scenario for HE0107-5240

The binary scenario for our Pop. III model is illustrated in Fig. 1. We postulate that only after it has been formed out of primordial matter does the binary accrete gas from interstellar matter that has been polluted by the ejecta of Pop. III SNe (a). After the primordial cloud disperses, accretion of interstellar matter by the binary as it travels through the Galaxy is negligible [8]. The primary experiences a helium-flash driven deep mixing (He-FDDM) episode as an EAGB star (b) and products of the nucleosynthesis in the deep interior are dredged up into surface layers [8]. During the TPAGB phase, additional carbon is dredged to the surface and the primary emits a wind. The amount of matter accreted from this wind by the secondary is a function of the assumed orbital characteristics (c). By requiring that, when the secondary becomes a red giant, the abundances at its surface match those of HE0107-5240, we estimate that a total mass of \( \sim 0.01 M_\odot \) is accreted by the secondary and that the primary experienced of the order of 30 third dredge-up episodes. This translates into an initial orbital separation of 18 AU and period of 76 yr. Consideration of angular momentum loss from the binary system suggests final values of 34 AU and 150 yr. From the amount of mass transferred and the number of dredge-up episodes experienced, we infer that that the primary emitted mass at the rate \( \dot{M}_{\text{loss}} \sim 10^{-5} M_\odot/\text{yr} \), typical of the superwind sustained by ordinary AGB stars.

![Figure 1](image)

Figure 1. (a) Wide binary (secondary = 0.8\( M_\odot \) star, primary = 1.2 – 3\( M_\odot \) star) forms from primordial cloud. SNe pollute cloud and binary stars acquire surface layers of enhanced Fe by accreting from polluted cloud. (b) Primary experiences He-FDDM on the early AGB. (c) Primary experiences 3rd Dredge-up episodes which produce required abundance ratios in its envelope, and develops superwind. Some of the wind matter is accreted by the secondary and orbital separation increases due to angular momentum loss. (d) MS star evolves into red giant and is observed as HE0107-5240. Secondary has become WD.

3. Progress of He-FDDM and Nucleosynthesis in the helium convective zone

The character of mixing during a He-FDDM event is illustrated schematically in Fig. 2. As the helium shell flash develops, the helium convective zone grows in mass until, near the peak of the flash, its outer edge extends into the hydrogen-rich layer. Hydrogen is carried downward by convection until it reaches a point where the lifetime of a proton becomes less
than the convective mixing timescale; then, hydrogen burns via the $^{12}\text{C}(p, \gamma)^{13}\text{N}$ reaction. The energy flux due to this reaction causes the convective zone to split into two parts, the outer one driven by the energy flux due to hydrogen burning and the inner one driven by the energy flux due to helium burning. The convective shell engendered by hydrogen burning transports C- and N-rich matter outwards where it can ultimately be dredged up and incorporated into the surface convective zone. In models with large core masses, the convective shell sustained by helium burning persists even after the hydrogen-driven convective zone has disappeared [3, 9].

Before the split into two convective zones, some of the mixed-in hydrogen is captured by $^{12}\text{C}$; the product is carried inward and, after the split, is trapped in the surviving helium convective zone as $^{13}\text{N}$ and/or as its daughter $^{13}\text{C}$. At the high temperatures in the surviving helium convective shell, the reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$ occurs, with interesting consequences, as demonstrated by [9] for a $2M_\odot$ star with $[\text{Fe}/\text{H}] = -2.7$.

To explore the ensuing neutron-capture nucleosynthesis in the helium convective shell, we adopt the same one-zone approximation used by [10]. We treat the amount of mixed $^{13}\text{C}$ as a parameter since this amount varies with the strength of the helium shell flash, which depends on stellar mass, and, also, is a function of the treatment of convection. The mixing is assumed to occur at the peak of the shell flash.

Fig. 3 illustrates the progress of nucleosynthesis in the helium convective zone in a Pop. III model star, when the amount of $^{13}\text{C}$ mixed into this zone is chosen in such a way that $^{13}\text{C}/^{12}\text{C} = 10^{-3}$. As soon as $^{13}\text{C}$ is mixed into the convective zone, it rapidly reacts with helium to produce neutrons. The neutrons so produced are captured primarily by $^{12}\text{C}$ to form $^{13}\text{C}$ and then reappear in consequence of additional $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reactions. This neutron cycling process continues until the $^{16}\text{O}(n, \gamma)^{17}\text{O}$ reaction has converted most of the initially injected $^{13}\text{C}$ into $^{17}\text{O}$. Then, $\alpha$ capture on $^{17}\text{O}$, which occurs $\sim 10^4$ times more slowly than capture on $^{13}\text{C}$ at the relevant temperatures, starts to produce neutrons via the reaction $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$. The newly formed $^{20}\text{Ne}$ consumes neutrons to yield heavier isotopes of Ne and isotopes of Na and Mg. If the iron-group elements exist in the helium convective zone, most of them are converted into heavy s-process elements. Therefore, in the case of stars formed from a polluted cloud or stars with helium convective zones that were polluted by accreted metals during He-FDDM, the upper limit of the surface lead enhancement for HE0107-5240 becomes $[\text{Pb}/\text{Fe}] = 1 - 2$. We emphasize that the appearance of $^{13}\text{C}$ in a convective shell occurs only once. During subsequent thermal pulses, any $^{13}\text{C}$ that might be formed because of extra-mixing would be burned radiatively between pulses [11]. However, the observed sharp decrease in the $[\text{Pb}/\text{Ba}]$ ratio for $[\text{Fe}/\text{H}] < -2.5$ suggests that this mechanism does not operate in extremely metal-poor stars.

4. Conclusions

We can explain C, N, O, Na, and $^{12}\text{C}/^{13}\text{C}$ quantitatively by the binary scenario. The scenario predicts a current orbital period of $\sim 150$ yr and continuous observations over an extended period (>10 years) may reveal the predicted variations in radial velocity. It also predicts the enhancement of $^{25}\text{Mg}$ and $^{26}\text{Mg}$ relative to $^{24}\text{Mg}$. A deficiency of Pb by $[\text{Pb}/\text{H}] \sim -3$ is needed to establish conclusively that HE0107-5240 is a Pop.III star.
Figure 2. Schematic representation of the time dependence of (1) convective zones associated with helium-shell flashes and (2) sites for the nucleosynthesis and/or storage of s-process elements associated with these flashes. He-FDDM begins when hydrogen is ingested by a convective zone driven by the energy flux from a unique helium-burning flash in an extremely metal-poor ([Fe/H] ≤ −2.5) model star of low or intermediate mass at the beginning of the TPAGB phase.

Figure 3. The lower panel shows the variation with time of isotopic abundances in a helium-flash driven convective zone after $^{13}$C has been mixed into the zone. The top panel shows the variations in the temperature (solid line) and in the density (broken line) during the helium flash. Abundances relative to carbon observed for HE0107-5240 are plotted at the right-hand side of the lower panel for O (open circle), Na (filled circle), and Mg (cross).

REFERENCES

1. Christlieb, N. et al., Nature, 419, 904 (2002)
2. Bessell, M. S. Christlieb, N. & Gustafsson, B, (2004), astro-ph/0401450
3. Fujimoto, M. Y., Ikeda, Y., & Iben, I. Jr., Astrophys. J. Letters, 529, L25 (2000)
4. Picardi, I. et al. ApJ, 609, 1044 (2004)
5. Weiss, A., Schlattl, H., Salaris, M., & Cassisi, S., A&A, 422, 217 (2004)
6. Umeda, H. & Nomoto, K., Nature, 412, 793 (2003)
7. Limongi, M., Chieffi, A., & Bonifacio, P. 2003, ApJ, 594, L123
8. Suda, T., Aikawa, M., Machida, M. N., Fujimoto, M. Y., & Iben, I. Jr., ApJ, 611, 476 (2004)
9. Iwamoto, N., Kajino, T., Mathews, G.J., Fujimoto, M.Y., Aoki, W. 2004, ApJ, 602, 377 (2004)
10. Aikawa, M., Fujimoto, M. Y., & Kato, K., ApJ, 560, 937 (2001)
11. Straniero, O., et. al.,ApJ, 440, L85 (1995)