Enrichment of Very Metal-Poor Stars with Both r-Process and s-Process Elements from $8 - 10M_\odot$ Stars

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ABSTRACT

Recent spectroscopic studies have revealed the presence of numerous carbon-enhanced, metal-poor stars with [Fe/H] < -2.0 that exhibit strong enhancements of s-process elements. These stars are believed to be the result of a binary mass-transfer episode from a former asymptotic giant-branch (AGB) companion that underwent s-process nucleosynthesis. However, several such stars exhibit significantly lower Ba/Eu ratios than solar s-process abundances. This might be explained if there were an additional contribution from the r-process, thereby diluting the Ba/Eu ratio by extra production of Eu. We propose a model in which the double enhancements of r-process and s-process elements originate from a former $8 - 10M_\odot$ companion in a wide binary system, which may undergo s-processing during an AGB phase, followed by r-processing during its subsequent supernova explosion. The mass of Eu (as representative of r-process elements) captured by the secondary through the wind from the supernova is estimated, which is assumed to be proportional to the geometric fraction of the secondary (low-mass, main-sequence) star with respect to the primary (exploding) star. We find that the estimated mass is in good agreement with a constraint on the Eu yield per supernova event obtained from a Galactic chemical evolution study, when the initial orbital separation is taken to be ~ 1 year. If one assumes an orbital period on the order of five years, the efficiency of wind pollution from the supernova must be enhanced by a factor of ~ 10. This may, in fact, be realized if the expansion velocity of the supernova's innermost ejecta, in which the r-process has taken place, is significantly slow, resulting in an enhancement of accretion efficiency by gravitational focusing.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II — supernovae: general — Galaxy: evolution — Galaxy: halo

1. Introduction

Recent spectroscopic studies have demonstrated the existence of numerous carbon-enhanced, metal-poor (CEMP) stars that exhibit strong enhancements of their neutron-capture elements, in particular at metallicities [Fe/H]< -2.0. This is believed to be due to mass transfer in binary systems from former asymptotic giant-branch (AGB) companions that underwent s-process nucleosynthesis during their lifetimes (McClure & Woodsworth 1990). However, a significant fraction of these stars appear to exhibit large deviations from the scaled solar s-process distribution of elemental abundance ratios, especially with re-

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gard to their enhanced Eu (e.g., Sivarani et al. 2004).

This observed discrepancy in Eu for some CEMP stars prompted Hill et al. (2000), Cohen et al. (2003), Nomoto et al. (2004), and Barbuy et al. (2005) to suggest that the large excess of Eu in these stars might be due to an additional contribution from the *r*-process. Beers & Christlieb (2005), in their suggested taxonomy of CEMP stars, refer to this class as CEMP-r/s. Qian & Wasserburg (2003) proposed an accretion-induced collapse (AIC) of a white dwarf into a neutron star in a binary system as one astrophysical scenario for enrichment of the surviving companion with both *r*-process and *s*-process elements. As an alternative, Zijlstra (2004) suggested that these double enhancements might be due to the explosions of degenerate cores in AGB stars ("type 1.5 supernova"; Iben & Renzini 1983). Previously, Nomoto et al. (2004) and Barbuy et al. (2005) suggested massive AGB stars ($\approx 8-10 M_\odot$)[1] to be the origin of these double enhancements.

In this paper we explore the astrophysical scenario suggested by Nomoto et al. (2004) and Barbuy et al. (2005). Specifically, we consider the available constraints on a model in which $8-10 M_\odot$ stars in wide binary systems may be invoked to explain the double enhancements of *r*-process and *s*-process elements that results in the creation of CEMP-r/s stars. In § 2 the observed abundances of CEMP-r/s stars are compared to the abundances from a low-metallicity AGB model (Goriely & Mowlavi 2000), which implies additional contributions of *r*-processed material to these stars. In § 3, the wind pollution model is examined to explain the double enhancements with *r*-process and *s*-process elements in these stars. The efficiency of wind pollution by a supernova required to be consistent with the Galactic chemical evolution of *r*-process elements is then discussed. A brief summary of our conclusions and a discussion of future areas for theoretical and observational investigation of the CEMP-r/s phenomenon is presented in §4.

2. CEMP-r/s Stars

Table 1 lists seven CEMP-r/s stars with large enhancements of neutron-capture elements reported in the recent literature (Aoki et al. 2002; Cohen et al. 2003; Barbuy et al. 2005; Ivans et al. 2005), all of which were further selected to have the lowest observed [Ba/Eu][2] ratios (< 0.4). Note that the highly *r*-process-enhanced star CS 22892-052 (Sneden et al. 2003a), which marginally qualifies as a CEMP star, is added on the last line of Table 1 for comparison purposes. With the exception of this star, which exhibits a nearly solar *r*-process ratio of [Ba/Eu], all of the CEMP-r/s stars listed in Table 1 lie between the solar *r*-process and *s*-process values of [Ba/Eu] (-0.69 and $+1.15$, respectively, Arlandini et al. 1999).

These stars have similar metallicities ($-2.9 \leq$ [Fe/H] ≤ -2.3) and excesses in their C and Ba abundances ([C/Fe] $\sim$ [Ba/Fe] $\sim +2$). These stars also exhibit very high Pb abundances ([Pb/Fe] $\sim +3$), and hence belong to the class of "lead stars" (Aoki et al. 2002; Van Eck et al. 2003). The overproduction of Pb is believed to be a consequence of the operation of an *s*-process with a high neutron-to-seed ratio in an AGB star, owing to its low metallicity (Gallino et al. 1998; Goriely & Mowlavi 2000). The similarity of the abundance patterns amongst these stars implies that all the CEMP-r/s stars may have been formed in similar astrophysical environments.

2.1. Comparison with a Low-Metallicity AGB Model

Figure 1 compares the observed abundances of two representative stars from Table 1, HE 2148-1247 and CS 29497-030, to the abundances of elements predicted to be found in the dredge-up material of a low-metallicity AGB model taken from Goriely & Mowlavi (2000), as shown by the thin-solid line. The metallicity of this model, [Fe/H] $= -1.3$, is clearly not as low as to be completely relevant for the stars presented here. Nevertheless, we employ this comparison, since a zero-metal AGB model by Goriely & Siess (2001) appears to show a similar abundance trend. The Goriely & Mowlavi (2000) result predicts a slightly lower [Ba/Eu] ratio ($+1.08$) than the solar *s*-process value ($+1.15$),

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[1] The suggested mass range by Barbuy et al. (2005), $\approx 10-12 M_\odot$, is likely to be too high for stars that undergo AGB evolution. The low metallicity of the CEMP-r/s stars pushes the appropriate mass range to even lower values ($\approx 7-9 M_\odot$, e.g., Umeda et al. 1999).

[2] $[\mathrm{A/B}] = \log(N_\mathrm{A}/N_\mathrm{B}) - \log(N_\mathrm{A}/N_\mathrm{B})_\odot$

but still significantly higher than applies to the measured stellar abundances ($< +0.4$) listed in Table 1. As can be seen in Figure 1, the abundance curve from the low-metallicity AGB model (scaled to match the Ba abundances) does not appear to account for any of the stellar abundances of Eu, Gd, and Dy (as well as Ho, Er, Yb, and Hf for CS 29497-030), although the highly enhanced Pb (and Bi for CS 29497-030) can be reasonably explained.

It should be noted that the [Ba/Eu] ratio in the atmosphere of the observed stars could be expected to be lower than the dredge-up value taken here, after this material is mixed with the envelopes of the primary (former AGB) and secondary (post-accretion) stars. For example, these envelopes might already have contained r-process matter at the time of their formation (e.g., from supernova-induced star formation with production of r-process nuclei; Ishimaru & Wanajo 1999). It is unlikely, however, that the mixture of envelope material will result in such low [Ba/Eu] values ($< +0.4$) for all the stars considered here. In fact, the CEMP-r/s stars account for about 30% of all the CEMP stars with the enhancements of s-process elements (e.g., Sivarani et al. 2004). On the other hand, non-CEMP-r/s stars with a high [Eu/Fe] ratio, relevant to those considered here (Table 1, $+1.6 \leq$ [Eu/Fe] $\leq +2.0$) are extremely rare – CS 22892-052 ([Eu/Fe] $= +1.64$, Sneden et al. 2003a) and CS 31082-001 ([Eu/Fe] $= +1.63$, Hill et al. 2002) are the only two such stars with published high-quality abundance analyses. Such stars account for only a few percent of the stars near [Fe/H] $= -3.0$ (Barklem et al. 2005).

2.2. Are There Additional r-Process Contributions?

There exists the possibility that, under conditions of extremely high neutron density ($\sim 10^{12}\mathrm{cm}^{-3}$), with a sufficiently large exposure in an AGB star, one might obtain a low [Ba/Eu] value by an "sr-process" (e.g., Goriely & Mowlavi 2000), a model that must be investigated more thoroughly in the future. With currently available data, however, the possibility of r-process contributions cannot be excluded. As an exercise, the abundances of HE 2148-1247 and CS 29497-030 are further compared with a simple mixture of the abundances of the low-metallicity AGB model and the solar r-process abundances (Käppeler et al. 1989), which is normalized to match the [Ba/Eu] ratio in the star. This result is shown in Figure 1 by a thick-solid line, together with the solar r-process (thick-dotted) and s-process (thin-dotted) abundance curves, scaled to match the Ba abundance. Good agreement can be seen for both stars, including the boosted Pb abundances.

The non-detection of Th in these stars (see also Johnson & Bolte 2004) may not be crucial, since theoretical studies show that the Th abundance can be significantly lower than the scaled solar r-process curve, even when good agreement is observed up to the third r-process-peak elements (Wanajo et al. 2002, 2003). In addition, the upper limit on Th for HE 2148-1247 (Figure 1a) still does not conflict with the mixture of the solar r-process and s-process (assuming the Th abundance at the birth of the star may be ~ 0.3 dex higher). Nevertheless, future detection of Th (which cannot be synthesized by the s-process) would strongly support a contribution from the r-process, although it presents an observational challenge because of severe blending with CH lines (Norris, Ryan, & Beers 1997; Cohen et al. 2003; Johnson & Bolte 2004). Alternatively, measurements (or solid upper limits) on the abundances of elements near the third r-process peak (Os, Ir, and Pt), which are also not produced by the s-process, would be of particular importance to support a contribution from the r-process (see Figure 1b).

Another way to check for possible contamination by the r-process may be the (accurate) determination of isotopic ratios of, e.g., Eu. For instance, the ratio $^{151}\mathrm{Eu}/(^{151}\mathrm{Eu} + ^{153}\mathrm{Eu})$ would be ≈ 0.5 if there were a substantial contribution from the r-process (Sneden et al. 2002; Wanajo et al. 2002; Aoki et al. 2003a). In contrast, the ratio would be ~ 0.6 if the s-process dominated, as is found for some of the CEMP stars with large enhancements of s-process elements, such as LP 625-44 and CS 31062-050 (Aoki et al. 2003b). Future accurate measurements of the isotopic ratio of Eu (or other elements, if possible) for the stars listed in Table 1 would be of special importance to test for r-process contributions to their abundances.

3. Double Enhancements by $8 - 10M_\odot$ Stars

The presence of *s*-process elements, along with large enhancements of carbon ([C/Fe] $\sim +2$, Table 1) suggests that a mass-transfer episode from a former AGB companion in a binary system took place (McClure & Woodsworth 1990). Thus, one major goal is to find an astrophysical scenario, associated with an AGB star in a binary system, in which the *r*-process might also occur. Recent nucleosynthesis studies suggest that core-collapse supernovae, which include "neutrino winds" (Woosley et al. 1994; Wanajo et al. 2001) and "prompt explosions" (Sumiyoshi et al. 2001; Wanajo et al. 2003) may be responsible for the production of the *r*-process elements. It should be emphasized that all of these models suffer from severe problems that remain to be solved (e.g., Wanajo et al. 2001, 2003; Janka et al. 2005), and no consensus has yet been achieved. Nevertheless, remarkable agreements of the neutron-capture elements in some extremely metal-poor stars, e.g., CS 22892-052 (Sneden et al. 2003a) and CS 31082-001 (Hill et al. 2002), with the scaled solar *r*-process curve strongly support the idea that *r*-process elements originate from short-lived, massive stars.

3.1. Scenarios for Double Enhancements

Qian & Wasserburg (2003) suggested that the double enhancement in the CEMP-r/s star HE 2148-1247 is due to the *s*-process occurring in an AGB star member of a binary system, followed by the *r*-process taking place in a subsequent AIC of the white dwarf remnant of the former AGB. The nucleosynthetic outcome from an AIC event, *if it occurs*, can be similar to that arising from a core-collapse supernova, although the absence of an outer envelope in the former case may cause some differences. The rate of the occurrence of the AIC process in the Galaxy is highly uncertain, and perhaps no more than $\sim 10^{-4}$ yr^{-1} (e.g., Bailyn & Grindlay 1990) (but see Qian & Wasserburg 2003). This rarity seems to be in conflict with the substantial fraction of CEMP-r/s stars ($\sim 30\%$) among all the CEMP-*s* stars currently observed. In addition, this scenario involves *three* separate mass-transfer episodes – transfer of *s*-process elements from a former AGB companion, mass accretion onto the white dwarf remnant, and subsequent pollution of the presently observed member of the system by *r*-process elements formed during an AIC event of the white dwarf. This may make such an event extremely rare, although the possibility cannot be excluded. Furthermore, an AIC is thought to only occur in close binary systems, which is in conflict with the long periods observed for some of the stars listed in Table 1 (see below). Note, however, that it remains possible that the explosion may change the orbital period of the binary, or even fractionate the pair into single stars.

Compared to the above model, the scenario suggested by Zijlstra (2004) has the advantage that it involves only two mass-transfer steps – transfer of *s*-process elements from an AGB companion followed by pollution with *r*-process elements by a "Type 1.5" supernova event. The nucleosynthetic outcome from a "Type 1.5" supernova may be very similar to that of a Type Ia supernova, in which *r*-processing is not expected to be significant. Nomoto et al. (2004) and Barbuy et al. (2005) suggested an alternative scenario, in which the double enhancements are due to a massive AGB star that may eventually collapse to be an electron-capture supernova rather than a "Type 1.5" supernova.

Below we further examine the possibilities suggested by Nomoto et al. (2004) and Barbuy et al. (2005), by investigation of a scenario in which an $8 - 10M_\odot$ star with a low-mass companion ($\sim 0.8M_\odot$) in a wide binary system is responsible for the double enhancements of *r*-process and *s*-process elements, resulting in CEMP-r/s stars. A star in this mass range is likely to undergo *s*-processing during its AGB phase (Nomoto 1984), although the amount of the *s*-processed material produced and its expected abundance distribution is uncertain. Subsequently, the degenerate O-Ne-Mg core of this star may collapse by electron capture and explode (Nomoto 1984, 1987; Hillebrandt, Nomoto, & Wolff 1984; Nomoto & Hashimoto 1988; Hashimoto, Iwamoto, & Nomoto 1993; Janka et al. 2005); in such a scenario the *r*-process is expected to take place (Wanajo et al. 2003). This model also involves only two mass-transfer episodes, as in Zijlstra (2004).

The possibility of *s*-processing occurring in a $10M_\odot$ star with an O-Ne-Mg core has been suggested recently by Ritossa, García, & Iben (1996) (see also N. Iwamoto et al. 2005, in preparation, for a similar result with a $9M_{\odot}$ star). These authors demonstrate that the reaction $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ is efficient in such high-mass stars, owing to the high temperature ($\gtrsim 3\times10^8$ K) reached at the base of the He convective shell, suggesting that the likely occurrence of the *s*-process for stars in this mass range. It is clear that a more quantitative study of the *s*-process nucleosynthesis in this mass range is needed in the future, but the results to date are certainly encouraging.

3.2. Fate of an $8 - 10M_{\odot}$ Star

Nomoto (1984) pointed out that the final fate of $8-10M_{\odot}$ stars could be divided into the following two cases, depending on the highly uncertain mass-loss rate. (i) For stars in the mass range from 8 $M_{\odot}$ to M_{up}, mass loss results in the ejection of the entire envelope before the core mass reaches the Chandrasekhar limit, thereby leaving an O-Ne-Mg white dwarf. (ii) Stars in the mass range from M_{up} to $10M_{\odot}$ undergo electron-capture supernovae. Here M_{up} denotes the upper bound mass of the white dwarf progenitors; if only the C+O white dwarfs are considered, $M_{\mathrm{up}} \sim 8M_{\odot}$ (see, e.g., Umeda et al. 1999, for the metallicity dependence of M_{up}), while $8M_{\odot} \leq M_{\mathrm{up}} \leq 10M_{\odot}$ applies to the progenitors of O-Ne-Mg white dwarfs (see also the more recent studies of Ritossa, García, & Iben 1996; Iben, Ritossa, & García 1997; Ritossa, García, & Iben 1999; Eldridge & Tout 2004).

Stars in the mass range $8-10M_{\odot}$ that are found in close binary systems, on the other hand, become helium stars that expand to red giants. Subsequently, their helium envelope is lost by Roche-lobe overflow and O-Ne-Mg dwarfs are formed (Nomoto 1984; Habets 1986). Hence, these stars do not undergo electron-capture supernovae (but they can undergo AICs; Nomoto & Kondo 1991)[3].

3.3. The Binarity of CEMP-*r*/*s* Stars

Currently, HE 2148-1247, CS 22948-027, CS 29497-034, CS 29526-110, and CS 29497-030 (Table 1) have been found to be radial-velocity variables, indicating their binarity. For CS 22948-027, CS 29497-034 (Barbuy et al. 2005), and CS 29497-030 (Sneden et al. 2003b), the orbital periods are estimated to be 426.5, 4130, and 342 days, respectively. These stars may belong to the class of CH-star binaries with orbital periods of $\sim 1 - 10$ years, as found by McClure & Woodsworth (1990), although no clear evidence of binarity for the other two CEMP-*r*/*s* stars in Table 1 has been obtained to date.

This high binary frequency (see also Lucatello et al. 2005) implies that, *if the current scenario is correct*, an electron-capture supernova must only rarely, if ever, fractionate the pair into single stars. This is in contrast to the neutrino-driven supernova from a more massive progenitor that may obtain a large recoil velocity (~ 500 km s^{-1}; Sheck et al. 2004). The lack of fractionation might result if the shock arising from an O-Ne-Mg core is lifted too early after bounce ($\sim$ 80 ms, Janka et al. 2005) to obtain a large recoil by convective instability ($\sim$ 1 s, Sheck et al. 2004), owing to the steep density gradient of the outer edge of the core (Nomoto 1984).

3.4. Wind Pollution from an AGB Star

For wide binary systems mass transfer operates through stellar winds, rather than by Roche-Lobe overflow (Boffin & Jorissen 1988). Theuns et al. (1996) estimated the fraction of the mass captured by its companion ($1.5M_{\odot}$) to be $\sim 1 - 2$ % of the mass lost by the wind (15 km s^{-1}) from the AGB star ($3M_{\odot}$) with a period of 895 days and an orbital velocity of 36 km s^{-1}, using a three-dimensional, smoothed particle hydrodynamic simulation.

Note that most of the CEMP-*r*/*s* stars under consideration here (five stars in Table 1) have relatively high effective temperatures ($6000 - 7000$ K, Aoki et al. 2002; Cohen et al. 2003; Ivans et al. 2005), which suggests that these stars are main-sequence turn-off stars. For main-sequence stars of $\approx 0.8M_{\odot}$ with [Fe/H] < -2, the mass of the convective envelope, M_c, is smaller by a factor of ~ 10 than that for a stars with solar metallicity (a

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[3] Podsiadlowski et al. (2004) concluded that such stars in close binary systems result in electron-capture supernova because the helium core mass is larger than the Chandrasekhar mass. However, these stars would eventually leave O-Ne-Mg white dwarfs, when considering the later evolutionary phases as described here. We thus consider a wide binary system in this study.

few $10^{-3}M_{\odot}$, e.g., see Table 1 in Yoshii 1981). As a result, the dilution of the accreted material is relatively small. Here we assume $M_c = 2 \times 10^{-3}M_{\odot}$, which is one order of magnitude smaller than that of the Sun ($\sim 0.02M_{\odot}$, Bahcall, Pinsonneault, & Wasserburg 1995). If we take [C/Fe] = [Ba/Fe] = +2 and [Fe/H] = −2.5 as representative of the CEMP-r/s stars in Table 1, the accreted masses of C and Ba from the AGB onto its companion are estimated to be $\sim 2\times10^{-5}M_{\odot}$ and $\sim 1\times10^{-10}M_{\odot}$, respectively.

Assuming the mass accretion rate to be 1%, according to Theuns et al. (1996, although the binary system in their simulation is not completely relevant to this study), the masses of C and Ba ejected from the AGB are estimated to be $\sim 2 \times 10^{-4}M_{\odot}$ and $\sim 1 \times 10^{-9}M_{\odot}$. The former is in good agreement with the result from the stellar evolution calculation of a $9M_{\odot}$ star by N. Iwamoto et al. (2005, in preparation). For the abundance of Ba, a future study of the s-process nucleosynthesis in an $8 - 10M_{\odot}$ model is needed to confirm the current hypothesis. Note that the amount of C added by the subsequent supernova wind is negligible, owing to its far less efficient accretion onto the secondary compared to that from an AGB star (§ 3.6).

3.5. Wind Pollution from a Supernova

There is no currently available hydrodynamic study of the efficiency of wind pollution by a supernova in a binary system. Hence, we now estimate the fraction of the ejected mass from a subsequent supernova explosion which is captured by the companion star simply to be $(R_2/2a_0)^2 f$, as in Podsiadlowski et al. (2002). Here, $(R_2/2a_0)^2$ is the geometric fraction of the companion, R_2 is the radius of the secondary, a_0 is the initial orbital separation, and f is the enhancement (or reduction) factor. The value of f can be larger than unity as the result of "gravitational focusing", if the ejecta velocity is decelerated below the escape velocity from the surface of the secondary. On the other hand, f can be smaller than unity if the ejecta velocity is large enough to strip the surface material from the secondary.

Assuming the masses of the primary and secondary to be $9M_{\odot}$ and $1M_{\odot}$, respectively, with $R_2 = 1R_{\odot}$ and an initial orbital period of one year, we obtain $(R_2/2a_0)^2 \sim 1 \times 10^{-6}$ (which reduces to $\sim 1\times10^{-7}$, if we change the initial orbital period to five years). Note that the orbital period would become as twice as large as its initial value after the explosion of the primary, owing to the reduction of its mass to $\sim 1.3M_{\odot}$, even if the orbital separation were unchanged. The accreted material is further diluted with the mass of the convective zone of the secondary, e.g., $M_c = 2 \times 10^{-3}M_{\odot}$ (see § 3.4). This results in the required mass of Eu produced per supernova event (from a star of initial mass $9M_{\odot}$) is $M_{\rm Eu} \sim 3 \times 10^{-7}f^{-1}M_{\odot}$, to obtain [Eu/Fe] $\sim +2$ for the secondary star with [Fe/H] ~ -2.5.

3.6. Consistency with Galactic Chemical Evolution

A Galactic chemical evolution study shows that the required mass of Eu per supernova event in order to account for its solar value is $\sim 1 \times 10^{-7}M_{\odot}$ (e.g., Wanajo & Ishimaru 2005), if *all* core-collapse supernovae equally contribute to its enrichment. Ishimaru & Wanajo (1999) have suggested, however, that the supernova progenitors that contribute to the chemical evolution of Eu (as representative of r-process elements) must be limited to a small range ($\sim$ 10% of all supernova events, e.g., $8 - 10M_{\odot}$ or $20 - 25M_{\odot}$, see also Tsujimoto, Shigeyama, & Yoshii 2000; Ishimaru et al. 2004; Wanajo & Ishimaru 2005). This leads to a natural explanation of the large star-to-star scatter of the r-process elements (e.g., Eu) relative to iron (by more than two orders of magnitude) that can be seen in extremely metal-poor halo stars.

If one assumes that the stars of $8 - 10M_{\odot}$ (i.e., $M_{up} = 8M_{\odot}$, see § 3.2) are the dominant source of Eu, the mass of Eu ejected per explosive event estimated from a Galactic chemical evolution study should be increased to $\sim 3\times10^{-7}M_{\odot}$ (Ishimaru & Wanajo 1999; Ishimaru et al. 2004). This follows because the mass range $8 - 10M_{\odot}$ accounts for about 30% of all supernova events, when assuming a Salpeter initial mass function. The mass of Eu per event would be $\sim 1\times10^{-6}M_{\odot}$ if $M_{\rm up}$ were, e.g., $9.5M_{\odot}$, since the mass range of $9.5-10M_{\odot}$ accounts for only about 10% of all supernova events. Note that further restriction of the mass range (e.g., $M_{up} = 9.9M_{\odot}$) would lead to larger star-to-star scatter of [Eu/Fe] values than those observed in extremely metal-poor stars. It should be also noted that the amount of Eu from a supernova event estimated here seems reasonable from a nucleosynthetic point of view (e.g., from the neutrino wind scenario as a possible explanation, Wanajo et al. 2001, 2002).

Thus, the estimate from the wind model (§ 3.5) and the constraint from Galactic chemical evolution above are in good agreement when assuming $f \sim 1$. However, an enhancement of the accretion by gravitational focusing is needed ($f \sim 10$), if we assume an initial orbital period of five years pertains. This shows that wind pollution by a supernova explosion is far less effective than that by an AGB star. In fact, the efficiency of accretion for the AGB star is more than four orders of magnitude larger than that estimated by the simple geometric fraction (i.e., $f > 10^4$), owing to its small expansion velocity (comparable to the orbital period of the system).

It should be noted that the contribution of *s*-processed material (e.g., Ba) produced for stars of $8 - 10 M_\odot$ (which are short-lived stars) must be a negligible contributor to the Galactic chemical evolution of neutron-capture elements. This is required in order to be consistent with observations of non-CEMP stars having [Ba/Eu] values very close to the solar *r*-process ratio, with no sign of an increase owing to the *s*-process for [Fe/H] < -2.5 (Johnson & Bolte 2001). The mass of Ba per supernova event (from a star of initial mass $9 M_\odot$) due to the *r*-process can be estimated to be $\sim 3 \times 10^{-6} M_\odot f^{-1}$, assuming $M_{\rm Eu} \sim 3 \times 10^{-7} M_\odot f^{-1}$ applied above (§ 3.5) and the solar *r*-process ratio of Ba/Eu (= 9.29, Arlandini et al. 1999). On the other hand, the estimated mass of Ba from the *s*-process during the AGB phase (for a star with an initial mass of $9 M_\odot$) is $\sim 1 \times 10^{-9} M_\odot$ (§ 3.4). This is negligible compared to the *r*-process contribution considered here, when assuming $f \sim 1 - 10$.

3.7. Enhancement of the Accretion Efficiency

The discussion above demonstrates that the accretion efficiency onto the secondary should not be reduced with respect to its geometric fraction, leading to $f \gtrsim 1$. For supernova explosions with a typical explosion energy ($\sim 10^{51}$ ergs), the velocity of the inner ejecta is expected to be a few thousand km s^{-1} (e.g., Shigeyama et al. 1994). This is larger than the escape velocity from the secondary (e.g, 618 km s^{-1} for the Sun), which may result in $f < 1$. However, a collapsing O-Ne-Mg core is expected to lead to a neutrino-powered explosion with a rather low explosion energy (a few times 10^{50} ergs; Janka et al. 2005). Furthermore, its innermost ejecta, in which the *r*-process is expected to operate, may expand rather slowly. In fact, the core-collapse supernova from a more massive progenitor ($> 20 M_\odot$) is considered to suffer from fallback onto the remnant (Umeda & Nomoto 2002, 2003), in which the expansion velocity of the inner ejecta becomes zero at some point. If the innermost ejecta from a collapsing O-Ne-Mg core expands slowly (e.g., $\lesssim$ a few hundred km s^{-1}) without substantial fallback, the accretion can be significantly enhanced by gravitational focusing. This may result in f becoming larger than unity. It is obvious, however, that a detailed hydrodynamic study will be needed in the future to estimate quantitatively the efficiency of the wind-pollution model discussed here.

4. Conclusions

The abundances of CEMP stars with large enhancements of *s*-process elements, but with the lowest [Ba/Eu] ratios ($< +0.4$), disagree with the predicted elemental abundance patterns from contemporary low-metallicity AGB models, and seem to require an additional *r*-process contribution. We have investigated a model in which these CEMP-*r*/*s* stars could be accounted for by an $8 - 10 M_\odot$ star in a wide binary system that is responsible for enrichment with *s*-process elements during its AGB phase, and with *r*-process elements by the subsequent supernova explosion of its collapsing O-Ne-Mg core. It should be cautioned, however, that the expected *s*-process signature resulting from the AGB stage in stars in this mass range, as well as the *r*-process abundance signature of the subsequent core collapse of stars of this mass, are still not well known.

The estimated mass of Eu (as representative of *r*-process elements) captured by the secondary, through the wind from the supernova, is in good agreement with the constraint obtained from a Galactic chemical evolution study, at least when the initial orbital separation is taken to be ~ 1 year. However, the efficiency of wind pollution from the supernova must be enhanced by a factor of ~ 10 when assuming an initial orbital separation to be ~ 5 years. It is suggested that the expansion velocity of the supernova's innermost ejecta, in which the *r*-process has taken place, must be significantly slow, resulting in an enhancement of accretion efficiency by gravitational focusing.

Future theoretical studies of *s*-process and *r*-process nucleosynthesis in $8 - 10 M_\odot$ stars, as well as a full hydrodynamic study of wind pollution during the supernova explosion in a wide binary system, are needed before one can draw firm conclusions. Future comprehensive spectroscopic studies of CEMP-r/s stars, in particular measurements of their Pt-peak (Os, Ir, and Pt) and Th abundances, and/or isotopic Eu measurements, are also of special importance to confirm the *r*-process contribution to these stars.

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Table 1
Abundance Ratios

Star	[Fe/H]	[C/Fe]	[Ba/Fe]	[Eu/Fe]	[Ba/Eu]	[Pb/Fe]	Reference
HE 2148-1247	−2.3	+1.91	+2.36	+1.98	+0.38	+3.12	1
CS 22948-027	−2.47	+2.43	+2.26	+1.88	+0.38	+2.72	2
CS 29497-034	−2.90	+2.63	+2.03	+1.80	+0.23	+2.95	2
CS 29526-110	−2.38	+2.2	+2.11	+1.73	+0.38	+3.3	3
CS 22898-027	−2.25	+2.2	+2.23	+1.88	+0.35	+2.84	3
CS 31062-012	−2.55	+2.1	+1.98	+1.62	+0.36	+2.4	3
CS 29497-030	−2.57	+2.30	+2.32	+1.99	+0.33	+3.65	4
CS 22892-052	−3.10	+0.95	+0.99	+1.64	−0.65	+1.20	5

References.— 1 Cohen et al. (2003); 2 Barbuy et al. (2005); 3 Aoki et al. (2002); 4 Ivans et al. (2005); 5 Sneden et al. (2003a)

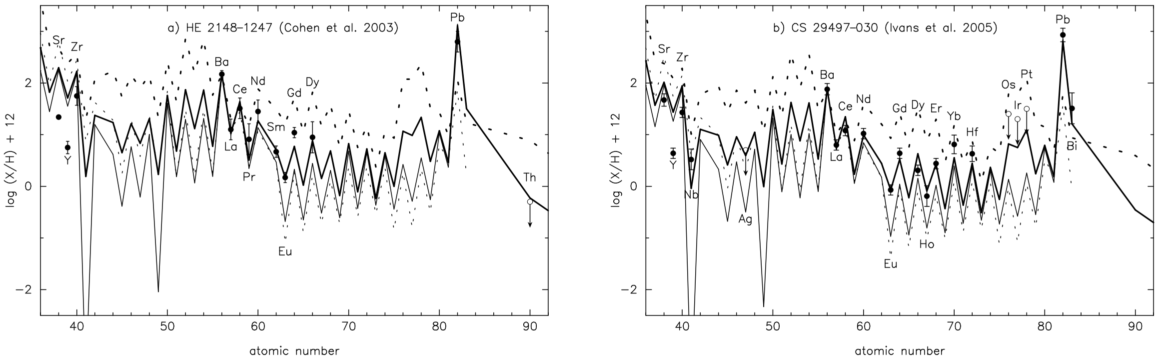

Fig. 1.— Abundances in (a) HE 2148-1247 and (b) CS 29497-030, compared with the solar *s*-process (thin-dotted line), *r*-process (thick-dotted line), a low-metallicity AGB model (thin-solid line, Goriely & Mowlavi 2000), and a mixture of the latter two (thick-solid line, see the text). The abundances are vertically scaled to match the Ba abundance. For some elements (Os, Ir, Pt, and Th), only an upper limit is shown (open circle with down arrow).