SUPERNOVAE VERSUS NEUTRON STAR MERGERS AS THE MAJOR $r$-PROCESS SOURCES

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ABSTRACT

I show that recent observations of $r$-process abundances in metal-poor stars are difficult to explain if neutron star mergers (NSMs) are the major $r$-process sources. In contrast, such observations and meteoritic data on $^{182}$Hf and $^{129}$I in the early solar system support a self-consistent picture of $r$-process enrichment by supernovae (SNe). While further theoretical studies of $r$-process production and enrichment are needed for both SNe and NSMs, I emphasize two possible direct observational tests of the SN $r$-process model: gamma rays from the decay of $r$-process nuclei in SN remnants and surface contamination of the companion by SN $r$-process ejecta in binaries.

Subject headings: Galaxy; evolution — nuclear reactions, nucleosynthesis, abundances — stars: neutron — supernovae: general

1. INTRODUCTION

All of the actinides and approximately half of the stable nuclei with mass numbers $A \approx 100$ in the solar system were produced by rapid neutron capture, the $r$-process. While the astrophysical site of this process remains a mystery, the main candidate environments are neutrino-heated ejecta from core-collapse supernovae (SNe; Woosley & Hoffman 1992; Meyer et al. 1992; Takahashi, Witti, & Janka 1994; Woosley et al. 1994) and decompressed ejecta from neutron star mergers (NSMs; Lattimer & Schramm 1974, 1976; Symbalisty & Schramm 1982; Freiburghaus, Rosswog, & Thielemann 1999b). To be a major source for the $r$-process, an environment must satisfy two criteria: one on reproducing the solar $r$-process abundance pattern and the other on supplying the total amount of $r$-process material in the present Galaxy. Using more physical parameterizations than the previous approach based on constant neutron number density and temperature (e.g., Kratz et al. 1993), several recent studies (Hoffman, Woosley, & Qian 1997; Meyer & Brown 1997; Freiburghaus et al. 1999a) derived the $r$-process conditions that can produce relative abundance patterns with peaks at $A \approx 130$ and 195 as observed in the solar system. At present, it seems that conditions in models of neutrino-heated ejecta from SNe are deficient (e.g., Qian & Woosley 1996) while those in models of decompressed ejecta from NSMs are promising (e.g., Freiburghaus et al. 1999b) for an $r$-process. However, due to the uncertainties in the theoretical models (e.g., Qian & Woosley 1996; Freiburghaus et al. 1999b), a reliable comparison of the actual conditions in these two environments with the $r$-process conditions cannot be made yet to help establish or discriminate either environment as the $r$-process site. Furthermore, for both environments, the models show that if the ejecta were composed of $r$-process material, then the amount provided by a single event combined with the estimated number of SNe or NSMs over the Galactic history would be adequate to account for the present Galactic $r$-process inventory (e.g., Mathews & Cowan 1990; Qian & Woosley 1996; Rosswog et al. 1999). Therefore, the above two criteria cannot readily identify SNe or NSMs as the major $r$-process sources.

In this Letter, I discuss a phenomenological approach to test SNe and NSMs as the major $r$-process sources. By considering mixing of the ejecta from an individual event with the interstellar medium (ISM), I show that observations of metal-poor stars are difficult to explain if NSMs are the major $r$-process sources (§ 2). I further show that a self-consistent picture of $r$-process enrichment by SNe based on the same consideration is supported by meteoritic data on $^{182}$Hf and $^{129}$I in the early solar system and by observations of metal-poor stars (§ 3). To emphasize the importance of observations in establishing the major $r$-process sources, I conclude with a discussion of two possible direct tests of the SN $r$-process model: gamma rays from the decay of $r$-process nuclei in SN remnants and surface contamination of the companion by SN $r$-process ejecta in binaries (§ 4).

2. $r$-PROCESS ABUNDANCES AND NEUTRON STAR MERGERS

I assume that as far as the $r$-process is concerned, the merging of a neutron star (NS) with a black hole (BH) is similar to that of two neutron stars. These two kinds of events are collectively referred to as NSMs. The rate of such events in the Galaxy is quite uncertain. Here I take an average rate $(f_{\text{NSM}})_{10} \approx (10^3 \text{ yr})^{-1}$ over the Galactic history, which is at the very high end of various estimates (e.g., Phinney 1991; Bethe & Brown 1998; Arzoumanian, Cordes, & Wasserman 1999). Numerical simulations of an NS-NS merger event by Rosswog et al. (1999) show that a total mass from $M_{\text{NSM}}^0 \approx 4 \times 10^{-3}$ to $4 \times 10^{-2} M_\odot$ of decompressed NS material may be ejected. Then the grand total from all the past NSMs over the Galactic history of $t_\odot \approx 10^{10} \text{ yr}$ is $M_{\text{NSM}}^0 \equiv f_{\text{NSM}}(f_{\text{NSM}})_{10} \approx 4 \times (10^3 - 10^4) M_\odot$. This is roughly equal to the present Galactic $r$-process inventory $X_{\odot}^{\text{tot}} M_\odot \approx 10^4 M_\odot$, where $X_{\odot}^{\text{tot}} \approx 10^{-7}$ is the total $r$-process mass fraction of nuclei with $A \approx 100$ in the solar system (Käppeler, Beer, & Wisshak 1989) and $M_\odot \approx 10^{11} M_\odot$ is the total Galactic mass in stars and gas. So it seems that NSMs could be the major $r$-process sources.

However, the amount of ejecta from a single NSM event discussed above is too much to explain the observed $r$-process abundances in metal-poor stars. This can be seen by considering mixing of the ejecta from each event with the ISM. Rosswog et al. (1999) show that the total energy of the NSM ejecta is at most comparable to the SN explosion energy ($\sim 10^{51}$ ergs). Therefore, when its energy/momentum is dispersed in the ISM, this ejecta can mix with at most the same amount of material as swept up by an SN remnant, $M_{\text{mix}} \approx 3 \times 10^4 M_\odot$ (e.g., Thornton et al. 1998). Consequently, if all of this ejecta were $r$-process material, as required to account for the present Galactic $r$-process inventory, an ISM enriched by a single NSM...
that a smaller-than-average fraction of the ISM is oversimplified. For example, one could imagine

\[ X_{\text{NSM}}^{\text{tot}} = 1.3 \times 10^{-7} \left( \frac{M_{\text{NSM}}^{\text{tot}}}{4 \times 10^{-3} M_\odot} \right) \left( \frac{3 \times 10^4 M_\odot}{M_{\text{mix}}} \right). \]  

(1)

The solar r-process mass fractions of elements with 100 ≤ A ≤ 130 and A > 130 are \[ X_{\odot, r}^{100 \leq A \leq 130} = X_{\odot, r}^{A > 130} \approx 4 \times 10^{-8} \] (Käppeler et al. 1989). According to equation (1), \[ X_{\text{NSM}}^{\text{tot}} \] would be approximately equal to \[ X_{\odot, r}^{100 \leq A \leq 130} + \frac{X_{\odot, r}^{A > 130}}{X_{\odot, r}} \] even for the lowest \[ M_{\text{mix}}^{\odot} \] of interest. Therefore, whether the NSM ejecta were composed of r-process elements with 100 ≤ A ≤ 130 or A > 130, or both groups in solar proportion, equation (1) predicts that abundance ratios of, e.g., Ag (A = 107) and/or Eu (A = 153) with respect to hydrogen in an ISM enriched by a single event would be at least comparable to the corresponding solar r-process values (Ag/H)\(\odot, r\) and (Eu/H)\(\odot, r\). This predicted level of r-process enrichment is in disagreement with recent observations of r-process abundances in metal-poor stars since Ag/H in stars with [Fe/H] ~ −1.3 to −2.2 are ~10−10−12 times lower than (Ag/H)\(\odot, r\) (Crawford et al. 1998) while Eu/H in stars with [Fe/H] ~ −3 are ~30−10−13 lower than (Eu/H)\(\odot, r\) (McWilliam et al. 1995; Sneden et al. 1996, 1998).

The following interpretation of equation (1) gives some insights into how NSMs could explain the present Galactic r-process inventory, and it may help us appreciate why this explanation is disfavored by observations. The Galaxy can be divided into ~3 × 10^4 units, each having a mass \[ M_{\text{mix}} \approx 3 \times 10^4 M_\odot \]. This division has a physical meaning since \[ M_{\text{mix}} \] is the maximum mass within which the ejecta from an individual NSM event can be distributed. Due to the rather low rate of NSMs in the Galaxy, on average, at most one NSM event occurred in a unit over the Galactic history. Therefore, in order to account for the present Galactic r-process inventory, each unit would have to be enriched with an approximately solar r-process mass fraction by a single NSM event. As shown above, this picture of r-process enrichment is inconsistent with the observed r-process abundances in metal-poor stars. Furthermore, due to the high rate of SNe in the Galaxy, many SNe occurred in a unit where a single NSM event also occurred at some time in Galactic history (see § 4). Since Fe enrichment of this unit was provided by these SNe, stars formed at different times in this unit would have varying [Fe/H], but they would have either a zero or approximately solar r-process mass fraction if NSMs were the major r-process sources. This is in disagreement with the observed correlation between abundances of r-process elements and Fe at [Fe/H] ≈ −2.5 (Gratton & Sneden 1994; Crawford et al. 1998; see also McWilliam et al. 1995).

Of course, the above discussion of mixing of the NSM ejecta with the ISM is oversimplified. For example, one could imagine that a smaller-than-average fraction of r-process ejecta was mixed into the ISM near the edge of an NSM remnant. In this case, stars formed near the edge of the remnant would have r-process mass fractions smaller than that given by equation (1). However, one would also expect that less-than-average enrichment was not unduly pervasive and that a significant fraction of the metal-poor stars would have the r-process enrichment indicated by equation (1). The fact that no such stars have been observed suggests a difficulty of the NSM r-process model in explaining the observations at low metallicities. Furthermore, even if the observed r-process abundances in metal-poor stars could be attributed to pervasive less-than-average enrichment by NSMs, one would still face the other difficulty in explaining the observed correlation between abundances of r-process elements and Fe at [Fe/H] ≈ −2.5. Since Fe enrichment was controlled by SNe occurring at a much higher rate, widely varying degrees of mixing of the r-process ejecta in an already existing NSM remnant with Fe produced by fresh SNe would result in large scatter in r-process abundances over a broad range of [Fe/H]. This is in disagreement with the rather early onset of the correlation between abundances of r-process elements and Fe at [Fe/H] ≈ −2.5. In summary, observations of metal-poor stars would be difficult to explain if NSMs were the major r-process sources.

3. r-PROCESS ENRICHMENT BY SUPERNOVAE

In contrast to the case of NSMs, observations of metal-poor stars as well as meteoritic data on \(^{182}\text{Hf}\) and \(^{129}\text{I}\) in the early solar system support a self-consistent picture of r-process enrichment by SNe (Qian & Wasserburg 2000, hereafter QW; Wasserburg & Qian 2000, hereafter QW). In this picture, the ejecta from each SN event is mixed with an average mass \[ M_{\text{mix}} = 3 \times 10^4 M_\odot \] of ISM swept up by the SN remnant (e.g., Thornton et al. 1998). It is assumed that the SN rate per unit mass of gas \(f_{\text{SN}}/M_{\text{gas}}\) is approximately constant over Galactic history (this seems reasonable since the star formation rate is proportional to the gas mass). Consequently, an average ISM in the Galaxy is enriched by newly synthesized material from SNe at a frequency

\[ f_{\text{SN}}^{\text{mix}} = f_{\text{SN}}^{\text{SN}} = (10^3 \text{ yr})^{-1} \times \left( \frac{M_{\text{mix}}}{3 \times 10^4 M_\odot} \right) \left( \frac{f_{\text{SN}}^{\text{SN}}}{(30 \text{ yr})^{-1}} \right) \left( \frac{10^{10} M_\odot}{M_{\text{gas}}} \right), \]  

(2)

where \(f_{\text{SN}}^{\text{SN}}/M_{\text{gas}}\) is estimated using quantities for the present Galaxy.

Meteoritic data on \(^{182}\text{Hf}\) (with a lifetime \(\tau_{182} = 1.3 \times 10^7\) yr) and \(^{129}\text{I}\) (\(\tau_{129} = 2.3 \times 10^7\) yr) in the early solar system shed important light on the r-process and its association with SNe. Wasserburg, Busso, & Gallino (1996; see also QW) show that the abundance ratio \(^{182}\text{Hf}/^{180}\text{Hf}\)_{\text{SSF}} = 2.4 \times 10^{-4} \) (Harper & Jacobsen 1996; Lee & Halliday 1995, 1998) is consistent with common SNe injecting \(^{184}\text{Hf}\) into the ISM at a high frequency \(f_{\text{SN}} \approx f_{\text{SN}}^{\text{mix}} \approx 10^7 \text{ yr}^{-1}\) over a uniform production (UP) time \(T_{\text{UP}} \approx 10^9 \text{ yr}\) before solar system formation (SSF). However, the abundance ratio \(^{129}\text{I}/^{127}\text{I}\)_{\text{SSF}} = 10^{-4} \) (Reynolds 1960; see also Brazzle et al. 1999) must be accounted for by a different type of SNe occurring at a low frequency \(f_{\text{SN}} \approx f_{\text{SN}}^{\text{mix}} \approx 10^7 \text{ yr}^{-1}\) (Wasserburg et al. 1996; QW). Therefore, the meteoritic data require at least two distinct types of SN r-process events: the high-frequency \(\gamma\) events producing heavy nuclei with A > 130, including \(^{184}\text{Hf}\), and the low-frequency \(\Lambda\) events producing light nuclei with A ≤ 130, including \(^{129}\text{I}\). The r-process production in the SN environments associated with the \(\gamma\) and \(\Lambda\) events was discussed in some detail by Qian, Vogel, & Wasserburg (1998a).

The above picture of r-process production and enrichment by SNe has clear predictions for r-process abundances resulting from a single event (QW; QW). For example, with an average ISM enriched by the \(\gamma\) events at a frequency \(f_{\text{SN}} \approx 10^7 \text{ yr}^{-1}\), the solar r-process abundances of elements with A > 130 such as Eu were provided by \(f_{\text{SN}} T_{\text{UP}} \approx 10^3 \text{ yr}^{-1}\). This requires that the Eu abundance in an ISM enriched by a single \(\gamma\) event
must be

\[ \log \epsilon_r(\text{Eu}) = \log \epsilon_\odot(\text{Eu}) - \log (f_H T_{\text{up}}) \sim -2.5, \]

(3)

where the log \( \epsilon \) notation is defined as \( \log \epsilon(\text{Eu}) \equiv \log(\text{Eu}/\text{H}) + 12 \), with \( \text{Eu}/\text{H} \) being the abundance ratio of Eu to hydrogen, and \( \log \epsilon_\odot(\text{Eu}) = 0.51 \) is the value for solar r-process Eu (Käppeler et al. 1989). Similarly, the solar r-process abundances of elements with \( A \leq 130 \) such as Ag were provided by \( f_{T_{\text{up}}} \sim 10^2 L \) events. This requires that the Ag abundance in an ISM enriched by a single \( L \) event must be

\[ \log \epsilon_r(\text{Ag}) = \log \epsilon_\odot(\text{Ag}) - \log (f_H T_{\text{up}}) \sim -0.8, \]

(4)

where \( \log \epsilon_\odot(\text{Ag}) = 1.19 \) (Käppeler et al. 1989) is used. The predictions in equations (3) and (4) are in good agreement with observations of very metal-poor stars that were formed when only a small number of SNe had contributed r-process elements to the ISM. The observed log $\epsilon$ values for stars with \( \text{[Fe/H]} \sim -3 \) range from \(-2.5\) to \(-0.9\) (McWilliam et al. 1995; Sneden et al. 1996, 1998), which can be accounted for by \( \sim 1-40 \) $f_H$ events with log $\epsilon_\odot(\text{Eu}) \sim -2.5$ from a single event (QW; WQ). In addition, Ag abundances at the level indicated by equation (4) were observed in HD 2665 and BD +37°14588 with \( \text{[Fe/H]} \sim -2 \) (Crawford et al. 1998) and in CS 22892−052 with \( \text{[Fe/H]} \sim -3 \) (Cowan et al. 1999).

In the above picture of r-process enrichment by SNe, the total mass of r-process elements ejected in an $f_H$ event must be $X^{\gamma_{\odot}}_{\odot} \frac{M_{\text{min}}}{Y} f_H \sim 10^{-4} M_{\odot}$, while that in an $L$ event must be $X^{\gamma_{\odot}}_{\odot} \frac{M_{\text{min}}}{Y} f_H \sim 10^{-5} M_{\odot}$. A total of $\sim 10^{-5}$ to $10^{-4} M_{\odot}$ of material can be naturally provided by the neutrino-heated ejecta from the proto-neutron star in an SN over a period of $\sim 1-10$ s (e.g., Qian & Woosley 1996). However, whether or not this neutrino-heated ejecta is composed of r-process material is yet to be shown. It has been speculated that the difference by a factor of $\sim 10$ in the total amount of r-process ejecta between the $f_H$ and $L$ events is an indication that neutrino emission and, hence, the ejection of r-process material are terminated by the transition of the proto-neutron star into a BH in the $f_H$ events while prolonged ejection is sustained by neutrino emission from a stable NS in the $L$ events (Qian et al. 1998a).

In summary, despite the lack of a complete model for successful r-process production in SNe, there is a self-consistent picture of r-process enrichment by SNe that can account for the meteoritic data on $^{182}$Hf and $^{129}$I in the early solar system and the observed r-process abundances in metal-poor stars. Furthermore, the observed correlation between abundances of r-process elements and Fe at $\text{[Fe/H]} \sim -2.5$ (Gratton & Sneden 1994; Crawford et al. 1998; see also McWilliam et al. 1995) can be understood as the result of sufficient mixing of r-process products and Fe from multiple SN events in this picture. In fact, the same picture was used by WQ as the basic framework to explain the dispersion in abundances of heavy r-process elements such as Eu at $\text{[Fe/H]} \sim -3$.

4. DISCUSSION AND CONCLUSIONS

The amount of the ISM to mix with the ejecta from an individual NSM event is limited by the total energy of the ejecta. On the other hand, due to the very low rate of NSMs in the Galaxy, a large amount of r-process ejecta would be required from each event to account for the present Galactic r-process inventory. When mixed with the ISM, this required amount of ejecta would result in abundances of r-process elements with $A \leq 130$ (such as Ag) and $A > 130$ (such as Eu) that are much too high (by factors of $\sim 10^{-10}$ for Ag and $\sim 10^{-11}$ for Eu) compared with the observed values in metal-poor stars. Furthermore, an average ISM received the ejecta from only $\sim 1$ NSM event over the Galactic history. If r-process enrichment of the ISM was provided by NSMs in this way while Fe enrichment was provided by many SNe, there would be no correlation between abundances of r-process elements and Fe, in disagreement with the observed correlation at $\text{[Fe/H]} \sim -2.5$. While the complexities in mixing of the ejecta with the ISM can affect the above considerations in detail, it is unlikely that they can remove the difficulty of the NSM r-process model in explaining the observations of metal-poor stars (especially the rather early onset of the correlation between abundances of r-process elements and Fe at $\text{[Fe/H]} \sim -2.5$). Nevertheless, future numerical studies of r-process enrichment by NSMs accompanied by Fe enrichment by SNe should be interesting to pursue and may give a more definitive answer.

In contrast, a self-consistent picture of r-process enrichment by SNe can be obtained by considering mixing of the ejecta from an individual event with the ISM. Here an average ISM is enriched in r-process elements with $A > 130$ by the $f_H$ events at a frequency $f_H \sim (10^4 \text{ yr})^{-1}$ and in those with $A \leq 130$ by the $f_L$ events at a frequency $f_L \sim (10^5 \text{ yr})^{-1}$. This picture may explain the meteoritic data on $^{182}$Hf and $^{129}$I in the early solar system and the observed r-process abundances in metal-poor stars. Furthermore, sufficient mixing of r-process products and Fe from multiple SN events in this picture would result in the observed correlation between abundances of r-process elements and Fe at $\text{[Fe/H]} \sim -2.5$. The same picture was also used by WQ as the basic framework to explain the dispersion in abundances of heavy r-process elements such as Eu at $\text{[Fe/H]} \sim -3$. However, a complete model of r-process and Fe production in the $f_H$ and $L$ events is still lacking and should be investigated by future theoretical studies.

In discussing r-process enrichment by NSMs, I have assumed that the maximum amount of the ISM to mix with the ejecta from an individual event is the same as swept up by an SN remnant. This is because the total energy of the NSM ejecta in numerical simulations (Rosswog et al. 1999) is at most comparable to the SN explosion energy ($\sim 10^{51}$ ergs). For given conditions of the ISM, the expansion/evolution of the ejecta is essentially governed by its total energy. The large difference in the amount of ejecta between an NSM and an SN has no significant effect here since, in both cases, the mass of the swept-up ISM soon overwhelms that of the ejecta while the total energy remains more or less the same. I note that a small amount ($\sim 10^{-5} M_{\odot}$) of material might be ejected in highly relativistic jets in an NS-BH merger event (Janka et al. 1999). However, the total energy of these jets is $\sim 10^{50}$ ergs (Janka et al. 1999), and their existence would not increase significantly the amount of the ISM that could mix with the entire ejecta from the event. It takes $\sim 10^5$ yr for the energy ($\sim 10^{51}$ ergs) and the associated momentum of the ejecta to be dispersed in the ISM (e.g., Thronson et al. 1998), where the next NSM or SN would occur on a much longer timescale ($\sim 10^7$ yr for NSMs and $\sim 10^8$ yr for SNe). This leaves substantial time for mixing of the ejecta with the swept-up ISM. However, the details of the mixing process require further studies.

If, as argued here, SNe are the major sources for the r-process, then there are two possible direct observational tests: gamma rays from the decay of r-process nuclei in SN remnants and surface contamination of the companion by SN r-process.
ejecta in binaries. Qian, Vogel, & Wasserburg (1998b, 1999) discussed gamma-ray signals from the decay of long-lived r-process nuclei (with lifetimes of \(\sim 10^3-10^7\) yr) in a nearby SN remnant and from the decay of short-lived r-process nuclei (with lifetimes of \(\sim 1-10\) yr) produced in a Galactic SN that may occur in the future. The nuclide \(^{126}\text{Sn}\) is of particular interest (Qian et al. 1999b) since its lifetime \(\sim 10^7\) yr is much longer than the age \(\sim 10^7\) yr of the Vela SN remnant at a distance of \(\sim 250\) pc. In the picture of r-process enrichment by SNe discussed here (see also QW and WQ), the solar r-process mass fraction of nuclei with \(A\leq 130\) resulted from \(\sim 10^2\) L events (see § 3). So a total mass \(\sum_{A=126}^{128} X_{A}\) of \(\sim 5 \times 10^{-7} M_{\odot}\) of \(^{126}\text{Sn}\) nuclei are produced in each L event, where \(\sum_{A=126}^{128} \approx 1.6 \times 10^{-5}\) (Käppeler et al. 1989) is the solar r-process mass fraction of \(^{126}\text{Te}\), the stable daughter of \(^{126}\text{Sn}\). If the SN associated with the Vela remnant was an L event, then the decay of \(^{126}\text{Sn}\) in this remnant would produce gamma-ray fluxes \(\sim 10^{-7}\gamma\text{ cm}^{-2}\text{s}^{-1}\) at energies \(E_{\gamma} = 415, 666,\) and 695 keV. Detection of these fluxes would require future gamma-ray experiments such as the proposed Advanced Telescope for High Energy Nuclear Astrophysics (ATHENA; Kurfess 1994). Since the Vela remnant contains a pulsar, such detection would also provide evidence for the speculated association between L events and SNe producing neutron stars (Qian et al. 1999a).

The other test mentioned above takes advantage of the occurrence of SNe in binaries. The r-process ejecta from the SN would contaminate the surface of its binary companion. Some binaries would survive the SN explosion and acquire an NS or a BH in place of the SN progenitor. Therefore, an ordinary star observed to be the binary companion of an NS or a BH might show r-process abundance anomalies on the surface. To estimate the plausible level of such anomalies, I assume that a fraction \(\sim 10^{-3}\) of the entire SN ejecta (\(\sim 10 M_{\odot}\), mostly non-r-process material) would be intercepted by a low-mass \((\sim 1 M_{\odot})\) companion and then mixed with \(\sim 10^{-2} M_{\odot}\) of the surface material. If the SN was an H event, \(\sim 10^{-4} M_{\odot}\) of r-process elements with \(A > 130\) would be intercepted, while for an L event, \(\sim 10^{-4} M_{\odot}\) of r-process elements with \(A \leq 130\) would be intercepted (see § 3). These quantities are to be compared with \(\sim 4 \times 10^{-10} M_{\odot}\) of the corresponding r-process elements in \(\sim 10^{-2} M_{\odot}\) of the surface material in a companion star of solar r-process composition. Therefore, an SN in a binary could enhance significantly the surface r-process abundances in the companion star, especially if the SN was an L event. In view of the large overabundance of O, Mg, Si, and S recently observed in the companion star of a probable BH (Israelian et al. 1999), detection of r-process enhancement in similar binary systems seems promising. Such detection may also test directly the speculation by Qian et al. (1999a) that H events are associated with SNe producing BHs while L events are associated with SNe producing neutron stars.

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REFERENCES

Arzoumanian, Z., Cordes, J. M., & Wasserman, I. 1999, ApJ, 520, 696
Bethe, H. A., & Brown, G. E. 1998, ApJ, 506, 780
Brazier, R. H., Pravdivtseva, O. V., Meshik, A. P., & Hohenberg, C. M. 1999, Geochim. Cosmochim. Acta, 63, 739
Cowan, J. J., Sneden, C., Ivans, I., Burles, S., Beers, T. C., & Fuller, G. 1999, BAAS, 31, 930
Crawford, J. L., Sneden, C., King, J. R., Boesgaard, A. M., & Deliyannis, C. P. 1998, AJ, 116, 2489
Freiburghaus, C., Remhges, J.-F., Rauscher, T., Kolbe, E., Thielemann, F.-K., Kranz, K.-L., Pfeiffer, B., & Cowan, J. J. 1999a, ApJ, 516, 381
Freiburghaus, C., Rosswog, S., & Thielemann, F.-K. 1999b, ApJ, 525, L121
Gratton, R. G., & Sneden, C. 1994, A&A, 287, 927
Harper, C. L., & Jacobsen, S. B. 1996, Geochim. Cosmochim. Acta, 60, 1131
Hoffman, R. D., Woosley, S. E., & Qian, Y.-Z. 1997, ApJ, 482, 951
Israelian, G., Rebolo, R., Basri, G., Casares, J., & Martin, E. L. 1999, Nature, 401, 142
Janka, H.-Th., Eberl, Th., Ruffert, M., & Fryer, C. L. 1999, ApJ, 527, L39
Käppeler, F., Beer, H., & Wisshak, K. 1989, Rep. Prog. Phys., 52, 945
Kratz, K.-L., Bitouzet, J.-P., Thielemann, F.-K., Möller, P., & Pfeiffer, B. 1993, ApJ, 403, 216
Kurfess, J. D. 1994, ATHENA Mission Proposal, NASA New Mission Concepts in Astrophysics
Lattimer, J. M., & Schramm, D. N. 1974, ApJ, 192, L145
———, 1976, ApJ, 210, 549
Lee, D.-C., & Halliday, A. N. 1995, Nature, 378, 771
———, 1998, Lunar Planet. Sci., 29, 1416
Mathews, G. J., & Cowan, J. J. 1990, Nature, 345, 491
McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Meyer, B. S., & Brown, J. S. 1997, ApJS, 112, 199
Meyer, B. S., Howard, W. M., Mathews, G. J., Woosley, S. E., & Hoffman, R. D. 1992, ApJ, 399, 656
Phinney, E. S. 1991, ApJ, 380, L17
Qian, Y.-Z., Vogel, P., & Wasserburg, G. J. 1998a, ApJ, 494, 285
———, 1999b, ApJ, 506, 868
———, 1999, ApJ, 524, 213
Qian, Y.-Z., & Wasserburg, G. J. 2000, Phys. Rep., in press (QW)
Qian, Y.-Z., & Woosley, S. E. 1996, ApJ, 471, 331
Reynolds, J. H. 1960, Phys. Rev. Lett., 4, 8
Rosswog, S., Liebendorfer, M., Thielemann, F.-K., Davies, M. B., Benz, W., & Piran, T. 1999, A&A, 341, 499
Sneden, C., Cowan, J. J., Burrus, D. L., & Truran, J. W. 1998, ApJ, 496, 235
Sneden, C., McWilliam, A., Preston, G. W., Cowan, J. J., Burrus, D. L., & Armowski, B. J. 1996, ApJ, 467, 819
Symbalistyi, E., & Schramm, D. N. 1982, Astrophys. Lett., 22, 143
Takahashi, K., Witti, J., & Janka, H.-Th. 1994, A&A, 286, 857
Thornton, K., Gaudlitz, M., Janka, H.-Th., & Steinmetz, M. 1998, ApJ, 500, 95
Wasserburg, G. J., Busso, M., & Gallino, R. 1996, ApJ, 466, L109
Wasserburg, G. J., & Qian, Y.-Z. 2000, ApJ, 529, L21 (WQ)
Woosley, S. E., & Hoffman, R. D. 1992, ApJ, 395, 202
Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, ApJ, 433, 229