SN 1987A REVISITED AS A MAJOR PRODUCTION SITE FOR r-PROCESS ELEMENTS
TAKUJI TSUJIMOTO¹ AND TOSHIKAZU SHIGEYAMA²
Received 2001 August 9; accepted 2001 September 19; published 2001 October 9

ABSTRACT

The origin of nucleosynthesis products of rapid neutron capture reactions (the r-process) is a long-standing astrophysical problem. Recent analyses of elemental abundances for extremely metal-poor stars shed light on the elemental abundances of individual supernovae. Comparison of the abundance distributions of some extremely metal-poor stars with those of the best-observed supernova SN 1987A clearly indicates that the overabundances of barium and strontium found in SN 1987A that have been ascribed to the slow neutron capture process must be results of r-process nucleosynthesis. The mass of freshly synthesized barium in SN 1987A is estimated to be \(6 \times 10^{-6} M_\odot\), based on the observed surface abundance and detailed hydrodynamical models for this supernova. These new findings lead to the conclusion that 20 \(M_\odot\) stars, one of which is the progenitor star of SN 1987A, are the predominant production sites for r-process elements in the Galaxy and the r-process element donors for notable neutron capture–rich giant stars, CS 22892-052 and CS 31082-001.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II — supernovae: general — supernovae: individual (SN 1987A) — supernova remnants

1 INTRODUCTION

The existence of astrophysical r-process elements (elements synthesized by the rapid neutron capture process) in old metal-poor stars indicates that these elements are synthesized in the preceding supernovae (SNe) originating in massive stars (Truran 1981). The elemental abundance determination of numerous Galactic halo stars with extremely low metal abundances has opened the door to much more detailed investigations of r-process production from SNe in the early Galaxy (McWilliam et al. 1995; Ryan, Norris, & Beers 1996). However, which SNe produce the r-process elements has not yet been agreed upon in spite of many authors’ attempts (Mathews, Bazen, & Cowan 1992; Ishimaru & Wanajo 1999; Tsujimoto, Shigeyama, & Yoshii 2000; Qian 2001; Truran, Cowan, & Fields 2001).

Direct information about the production site for r-process elements should come from abundance determination of the elements in the ejecta of individual SNe. Absorption lines due to barium (Ba) and strontium (Sr), \(\sim 10\%\) of which are of r-process origin in the solar elemental abundance, were detected in the spectra of SN 1987A (Williams 1987). A remarkable feature found by Mazzali, Lucy, & Butler (1992) was that the shape of the Ba absorption line indicated the lack of this element at the very surface of the ejecta. Thus, the observed Ba must have been synthesized inside the star and did not exist in the interstellar matter (ISM) from which the star formed. The abundances of Ba and Sr were derived by taking into account non-LTE effects. The result showed that these elements are overabundant in comparison with the abundance of the Large Magellanic Cloud (Höflich 1988; Mazzali et al. 1992; Mazzali & Chugai 1995). The overabundances of Ba and Sr in SN 1987A have led a few authors to argue that these elements were synthesized by a slow neutron capture process (weak s-process) operating in the core helium (He) burning stage of the progenitor star (e.g., Prantzos, Arnould, & Cassé 1988). However, the derived abundance ratio of these two elements in SN 1987A was larger than the corresponding solar ratio, i.e., \(\text{Ba/Sr} \sim 2.5(\text{Ba/Sr})_\odot\). This value is clearly inconsistent with the results of weak s-process calculations (Prantzos et al. 1988), which predict a ratio significantly smaller than the solar ratio such as \(0.1(\text{Ba/Sr})_\odot \leq \text{Ba/Sr} \leq 0.6(\text{Ba/Sr})_\odot\) (Fig. 1). Another fact casts doubt on s-process origin: other Type II-P SNe such as SN 1985P, SN 1990E, and SN 1990H did not show any sign of the overabundance of Ba (Chalabaev & Cristiani 1987; Mazzali & Chugai 1995), although s-process calculations predict the overabundance of Ba irrespective of the He core mass (Prantzos et al. 1988). Together, these facts strongly suggest that these elements in SN 1987A are not of s-process origin.

On the other hand, the derived Ba/Sr ratio can be reconciled with the ratios of the same elements in two extremely metal-poor stars CS 22892-052 and CS 31082-001 (Fig. 1). Since these elements in such metal-poor stars must be results of r-process nucleosynthesis (McWilliam 1998), the derived ratio suggests that these elements in SN 1987A might also be of r-process origin. If this is the case, it is expected that the observed Ba/Sr is synthesized during the explosion in the deepest layers of the ejecta where the matter is exposed to an intense flux of neutrons. At the same place, a radioactive element, nickel 56 (\(^{56}\text{Ni}\)), which is one of the major seed elements for r-process nucleosynthesis, is also synthesized. The detection of \(\gamma\)-ray lines emitted from \(^{56}\text{Co}\) at unexpectedly early times (Matz et al. 1988) and multidimensional hydrodynamical calculations (e.g., Fryxell, Müller, & Arnett 1991; Hachisu et al. 1990) suggest that the Rayleigh-Taylor instabilities occurring at each composition interface in the progenitor star after the passage of the blast wave have brought the matter in the deep region near the mass cut out to the surface regions expanding at a few thousand kilometers per second. This mixing process finishes soon after the blast wave hits the stellar surface. The hydrodynamical evolution would not change the relative abundances of these elements inside each fluid element. Therefore, it is likely that the spatial distributions of these three elements are...
similar throughout the explosion. With this in mind, we will discuss the amount of Ba synthesized in SN 1987A with the support of detailed observations and modeling for this SN in the next section.

2. SYNTHESIZED BARIUM MASS IN SN 1987A

The progenitor star of SN 1987A was identified as a B3 I star, Sk $-69^\circ202$ (Sonneborn, Altner, & Kirshner 1987). Thus, the initial mass is estimated as $\sim 20 M_\odot$ and the radius as $\sim 40 R_\odot$. To estimate the stellar mass at explosion, one needs to consider the evolutionary path to the B3 I star, because this type of star undergoes mass loss due to the effects of stellar wind. Numerical calculations (Saiio, Nomoto, & Kato 1988) suggest that the stellar mass at explosion is about $16 M_\odot$.

Multiband photometric observations for SN 1987A have been used to construct so-called bolometric light curves during the first 400 days after the explosion (Menzies 1988). Comparison of hydrodynamical models for this B3 I progenitor star explosion with the bolometric light curve enables us to estimate the explosion energy, the amount of synthesized $^{56}$Ni, and the neutron star mass left behind (e.g., Shigeyama & Nomoto 1990). Furthermore, X- and $\gamma$-rays from this SN were detected. These emissions originate in $^{56}$Ni decays and the subsequent $^{56}$Co decays. The spectra and light curves of these emissions give us information about the distribution of $^{56}$Ni. Monte Carlo simulations of $\gamma$-ray transfer in the ejecta derived the $^{56}$Ni distribution as a function of the enclosed mass (Kumagai et al. 1989) based on hydrodynamical model 14E1 (Shigeyama & Nomoto 1990) as shown in Figure 2. If the distribution of Ba is similar to that of $^{56}$Ni (i.e., the ratio Ba/$^{56}$Ni is uniform in the ejecta), the total amount of Ba can be estimated from the mass fraction at the photosphere because both the total mass and distribution of $^{56}$Ni are known. The measurement of the mass fraction of Ba was performed based on the spectrum obtained at day 20, and the mass fraction was found to be $\sim 2.4 \times 10^{-5}$ (Mazzali et al. 1992; Mazzali & Chugai 1995). According to the above model 14E1, the photosphere at day 20 is located at the enclosed mass of $\sim 12 M_\odot$ (Fig. 2). Thus, the mass of Ba is estimated to be about $6 \times 10^{-6} M_\odot$. A similar amount of Ba is obtained based on another hydrodynamical model, W10 (Pinto & Woosley 1988a, 1988b; Pinto, Woosley, & Ensmann 1988), which also derived the distribution of elements in the ejecta from comparison with observations. The, Burrows, & Bussard (1990) also arrived at a similar distribution to obtain the light curves consistent with the observed X-ray and $\gamma$-ray line emissions at early phases based on hydrodynamical model 14E1.

3. IMPLICATIONS FROM THE DERIVED BARIUM YIELD

From two different angles, we could say that the inferred amount of Ba, $\sim 6 \times 10^{-6} M_\odot$, in SN 1987A is significantly high. First of all, this mass results in a large enhancement of Ba in comparison with iron (Fe) in the ejecta. The mass of Fe contained in SN 1987A is known with fairly good accuracy, because $^{56}$Ni eventually decays to $^{56}$Fe. As a result, the mass ratio of Ba to Fe in SN 1987A is found to be a factor of $\sim 8$ larger than the corresponding solar abundance ratio.

Recent studies on the chemical compositions of metal-poor halo stars claim that these stars might inherit the abundance pattern of the ejecta of the preceding few SNe (Audouze & Silk 1995) or a single SN (Shigeyama & Tsujimoto 1998). To put it another way, stars are likely to be formed from the ISM comprising the ejecta of a single SN. Have we already found the very star that has a large enhancement of Ba as inferred in the ejecta of SN 1987A? The answer is yes. The stars are notable neutron capture–rich giant stars CS 22892-052 and CS 31082-001, whose abundance distributions of elements have been precisely determined up to $Z = 90–92$ (Sneden et al. 2000; Hill et
al. 2001) and in which the neutron capture elements are found to be overabundant: +0.3 < [neutron capture/Fe] < +1.8 ([X/Y] denotes the logarithmic value of the number ratio of element X to element Y divided by the corresponding solar ratio). The Ba/Fe ratios in these stars are a factor of ~8–12 larger than the corresponding solar ratio. This coincidence of a large enhancement of Ba between SN 1987A and these two stars might imply that these stars are descendants of SNe whose progenitor masses were ~20 $M_\odot$. Here we compare the abundance distribution of some elements in CS 22892-052 with that in the ejecta of SN 1987A (Fig. 1). The masses of a few elements (Si, Ca, Ni) in SN 1987A have been obtained from its nebular spectra (Dunziger et al. 1991). For deducing the mass of Sr, we use the same procedure as for Ba. The masses thus obtained have been converted to the abundance ratios of element X to Fe ([X/Fe]). We also show in this figure the abundance curve between Mg and Ni predicted by recent nucleosynthesis calculations for 20 and 13 $M_\odot$ models (Umeda & Nomoto 2001). The abundance distribution of CS 22892-052 is very similar to that of SN 1987A and also to the theoretical curve of a 20 $M_\odot$ nucleosynthesis model for lighter elements.

Second, the estimated mass of Ba implies that 20 $M_\odot$ SNe are the predominant sites for r-process nucleosynthesis. This can be illustrated by the following argument: suppose that stars in the mass range of 20 $\pm$ $\Delta M$ $M_\odot$ yield the same amount of Ba as that from SN 1987A; then what $\Delta M$ suffices to supply Ba to reach the observed solar r-process abundance? Since current theoretical SN models can predict the yields of oxygen as a function of the progenitor mass with fairly good accuracy (Woosley & Weaver 1995), one can estimate the mass ratio of these two elements ejected from all SNe as Ba/O ~ 3 $\times$ 10$^{-3}\Delta M/M_\odot$, adopting the Salpeter initial mass function. To explain the corresponding solar abundance ratio by this SN yield, we deduce $\Delta M = 0.7$ $M_\odot$. Therefore, the number of stars populating the derived mass range is only ~4% of all SN progenitor stars. This narrow mass range suggests that the abundance distributions of r-process elements in any star including the Sun must be similar. This uniformity in the abundance distributions of r-process elements has already been pointed out by Cowan et al. (1999) in abundance analyses of four stars—CS 22892-052, HD 115444, HD 122563, and HD 126238 (in the latter three stars, Ba is not so enhanced; i.e., [Ba/Fe] < +0.2)—which led to the conclusion that there is only one r-process site in the Galaxy, at least for $Z \geq 56$. Our finding is that the unique r-process site is 20 $\pm$ 0.7 $M_\odot$ SNe, as represented by SN 1987A.

4. CONNECTION BETWEEN SN 1987A AND NEUTRON CAPTURE–RICH STARS

A noteworthy point is that two stars—CS 22892-052 and CS 31082-001—with a large enhancement of Ba such as [Ba/Fe] ~ +1.0 have similar metallicities, i.e., [Fe/H] = −3.1, −2.9, respectively. This also leads to the same conclusion as discussed above—that these stars inherit the abundance pattern of the 20 $M_\odot$ SN belonging to the first few generations in the Galaxy. For a given SN in the early galaxy, metallicities of the descendant stars can be estimated from the ratio of the mass of a certain heavy element, conventionally Fe, ejected from the SN, to the mass of hydrogen eventually swept up by the explosion (Shigeyama & Tsujimoto 1998). Neutron capture–rich stars must be the first few generation stars, because in later generation stars, such a large enhancement of r-process elements would be reduced due to a gradual increase in the contribution from the ISM with low [r-process/Fe] ratios to the stellar abundance. Since each SN with a different progenitor mass yields different amounts of heavy elements, we obtain the stellar metallicity (or the Fe/H ratio) as a function of the progenitor mass of a SN from which the star was born. Taking a ratio of the Fe yield $\sim$0.07 $M_\odot$ to the swept-up mass of hydrogen $\sim$6.5 $\times$ 10$^2$ $M_\odot$ for a 20 $M_\odot$ SN, we obtain [Fe/H] ~ −3. The metallicities of CS 22892-052 and CS 31082-001 indeed suggest that their progenitor masses were ~20 $M_\odot$.

Once the progenitor mass for these stars has been determined, we can estimate the mass of Ba ejected by a 20 $M_\odot$ SN, combining the observed [Ba/Fe] ratios in these stars with the Fe yield from the SN. In fact, it has been already found (Tsujimoto et al. 2000) that CS 22892-052 was born from a 20 $M_\odot$ SN that had produced 8 $\times$ 10$^6$ $M_\odot$ of Ba. Thus, there is a fairly good agreement in the Ba mass ejected from a 20 $M_\odot$ SN independently predicted by both SN 1987A and CS 22892-052. It is a natural result of their similar elemental abundance distributions.

Finally, we need to examine Sr. The overabundance of Sr in comparison with Fe in SN 1987A is relatively small, compared with the prediction by the theoretical r-process line (Käppeler, Beer, & Wisshak 1989) in Figure 1. This might imply that Sr has other production sites besides 20 SNe. This consideration is compatible with the observed breakdown of the concordance between the solar abundances and the CS 22892-052 abundances for the lighter r-process elements (Sneden et al. 2000). One possible candidate for other sites may be a wider mass range for the production site of Sr, e.g., 20 $\pm$ 3 $M_\odot$. This range is obtained from the same procedure for estimating the value of $\Delta M$ as was performed for Ba. The obtained $\Delta M$ for Sr approximately corresponds to the metallicity range −3.3 ≤ [Fe/H] ≤ −2.7. It implies that among stars in this metallicity range, there exist stars in which Sr is much enhanced compared with Ba. As a matter of fact, HD 122563 ([Fe/H] = −2.74) has a very large enhancement of Sr, such as [Sr/Ba] = +1.1 (Westin et al. 2000).

5. CONCLUSIONS

We have shown that r-process nucleosynthesis is certainly evident in SN 1987A. Our study clarifies that the observed overabundance of Ba in the outer layer of the ejecta of SN 1987A is part of the r-process production synthesized during explosion in the deepest layers of the ejecta, although this overabundance was ascribed to the result of the s-process operating in the core He-burning stage. We presented three strong arguments for this.

First, we should pay attention to the observed fact that the overabundance of Sr was also found at the same time in SN 1987A and that the abundance of Sr is less enhanced than that of Ba, which makes it unlikely that these elements are of s-process origin. In addition, the derived Ba/Sr ratio in SN 1987A is rather similar to those observed from metal-poor stars in which Ba has been shown to be of r-process origin from the observed Ba/Eu ratios.

Second, the absence of an overabundance of Ba in other Type II-P SNe contradicts the prediction from theoretical models that the s-process operates irrespective of He core masses. Alternatively, this fact implies that the r-process occurs in SNe whose progenitor masses are limited to a narrow range. Such a unique production site for the r-process is fully consistent with the uniformity in the abundance distributions of r-process elements among several stars including the Sun.

Finally, the total amount of Ba inferred from the Ba abun-
dance in the outer layer of the ejecta from the standpoint of the $r$-process origin reveals that 20 $M_\odot$ SNe, one of which is SN 1987A, are the prominent production sites for $r$-process elements. This is consistent with the second point above, i.e., no overabundances of Ba in type II-P SNe other than SN 1987A and the uniformity in the stellar abundance distributions of $r$-process elements.

We have further shown that the elemental abundance distributions of neutron capture–rich giant stars—CS 22892-052 and CS 31082-001—are very similar to that of SN 1987A, which suggests that these stars are born from the ejecta of 20 $M_\odot$ SNe like SN 1987A in the early Galaxy. The high abundances of Ba observed in these stars also imply that the major production sites for the $r$-process are $\sim 20 M_\odot$ SNe.

This work has been partly supported by COE research (07CE2002) and a Grant-in-Aid for Scientific Research (12640242) of the Ministry of Education, Science, Culture, and Sports in Japan.

REFERENCES

Audouze, J., & Silk, J. 1995, ApJ, 451, L49
Chalabaev, A. A., & Cristiani, S. 1987, in ESO Workshop on the SN 1987A, ed. I. J. Danziger (Garching: ESO), 655
Cowan, J. J., Pfeiffer, B., Kratz, K.-L., Thielemann, F.-K., Sneden, C., Burles, S., Tytler, D., & Beers, T. C. 1999, ApJ, 521, 194
Danziger, I. J., Lucy, L. J., Bouchet, P., & Gouiffes, C. 1991, in Supernovae: The 10th Santa Cruz Workshop in Astronomy and Astrophysics, ed. S. E. Woosley (New York: Springer), 69
Fryxell, B., Müller, E., & Arnett, D. 1991, ApJ, 367, 619
Hachisu, I., Matsuda, T., Nomoto, K., & Shigeyama, T. 1990, ApJ, 358, L57
Hill, V., Plez, B., Cayrel, R., & Beers, T. C. 2001, in Astrophysical Ages and Timescales, ed. T. Von Hippel, N. Manset, & C. Simpson (San Francisco: ASP), in press (astro-ph/0104172)
Höflich, P. 1988, Proc. Astron. Soc. Australia, 7, 434
Ishimaru, Y., & Wanajo, S. 1999, ApJ, 511, L33
Käppeler, F., Beer, H., & Wisshak, K. 1989, Rep. Prog. Phys., 52, 945
Kumagai, S., Shigeyama, T., Nomoto, K., Itoh, M., Nishimura, J., & Tsuruta, S. 1989, ApJ, 345, 412
Mathews, G. J., Bazan, G., & Cowan, J. J. 1992, ApJ, 391, 719
Matz, S. M., Share, G. H., Leising, M. D., Chupp, E. L., Vestrand, W. T., Purcell, W. R., Strickman, M. S., & Reppin, C. 1988, Nature, 331, 416
Mazzali, P. A., & Chugai, N. N. 1995, A&A, 303, 118
Mazzali, P. A., Lucy, L. B., & Butler, K. 1992, A&A, 258, 399
McWilliam, A. 1998, AJ, 115, 1640
McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
McWilliam, A., & Sneden, C. 1995, ApJS, 109, 2757
Menzies, J. W. 1988, Proc. Astron. Soc. Australia, 7, 401
Pinto, P. A., & Woosley, S. E. 1988a, ApJ, 329, 820
———. 1988b, Nature, 333, 534
Pinto, P. A., Woosley, S. E., & Ensmann, L. 1988, ApJ, 331, L101
Prantzos, N., Arnould, M., & Cassé, M. 1988, ApJ, 331, L15
Qian, Y.-Z. 2001, ApJ, 552, L55
Ryan, S. G., Norris, J. E., & Beers, T. C. 1996, ApJ, 471, 254
Saio, H., Nomoto, K., & Kato, M. 1988, ApJ, 331, 388
Shigeyama, T., Nomoto, K., 1990, ApJ, 360, 242
Shigeyama, T., & Tsujimoto, T. 1998, ApJ, 507, L135
Sneden, C., Cowan, J. J., Evans, I. N., Fuller, G. M., Burles, S., Beers, T. C., & Lawler, J. E. 2000, ApJ, 533, L139
Sonneborn, G., Altner, B., & Kirshner, R. P. 1987, ApJ, 323, L35
The, L.-S., Burrows, A., & Bussard, R. 1990, ApJ, 352, 731
Truran, J. W. 1981, A&A, 97, 391
Truran, J. W., Cowan, J. J., & Fields, B. D. 2001, Nucl. Phys. A, in press (astro-ph/0101440)
Tsujimoto, T., Nomoto, K., Hashimoto, M., Yanagida, S., & Thielemann, F.-K. 1995, MNRAS, 277, 945
Tsujimoto, T., Shigeyama, T., & Yoshii, Y. 2000, ApJ, 531, L33
Umeda, H., & Nomoto, K. 2001, ApJ, in press (astro-ph/0103241)
Williams, R. E. 1987, ApJ, 320, L117
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181