ENRICHMENT OF s-PROCESS ELEMENTS IN THE PROGENITOR OF SN 1987A

by

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Abstract: Existing calculations of s-process nucleosynthesis in massive stars such as Sk -69° 202 show enhancements in the He-burning shells which, when mixed to the surface, lead to Sc, Sr, and Ba enrichments of factors of 2 to 15. Abundances derived from the supernova absorption lines using a simple scattering model yield enhancements of this magnitude. Thus, the observed and predicted s-process abundances are roughly in accord, although the Ba/Sr ratio derived for the supernova may be higher than the s-process can account for.

The early development of the optical spectrum of SN 1987A has been presented by Danziger et al. (1987), Blanco et al. (1987), and Menzies et al. (1987). After an initial high-excitation phase which lasted less than a week and featured strong absorption from the Balmer lines and helium, the excitation and color temperature dropped. Numerous lines rapidly appeared during this subsequent phase of low-excitation, after which the spectrum underwent little change for four months until the low-excitation lines gradually weakened and the spectrum began to develop stronger emission lines.

An interpretation of the absorption spectrum in the low-excitation phase has been made by Williams (1987), based on line identifications of scandium, strontium, and barium---elements which are selectively enriched from nucleosynthesis by the slow capture of neutrons (Clayton 1968). Since Sr and Ba are enhanced much more by the s-process than by the r-process, these elements must have been present in the progenitor star. Furthermore, since they appeared in the spectrum within two weeks after the outburst, they were present in the outer part of the ejected envelope. They were either formed with the progenitor from the interstellar medium, or they were created in it as an adjunct to helium-burning and mixed to the surface. In the latter event, some enrichment of the elements would be expected, although calculations of the evolution of massive stars have indicated that no products from the helium burning core should be convected to the surface (Lamb et al. 1977).

The extent to which the s-process may have operated in the supernova progenitor is an important source of information concerning its structure and evolutionary history, as well as the origin of s-process elements in the galaxy. Standard procedures of spectral analysis can be used to determine the relative element abundances from the strengths of the spectral lines. A rigorous analysis would involve constructing a curve of growth from unblended and unsaturated lines. In SN 1987A this is not possible since each of the ions has at best only one or two usable lines. However, each of the ions Sc II, Fe II, Sr II, and Ba II does have

https://doi.org/10.1017/S0252921100094021 Published online by Cambridge University Press

one line of moderate strength, not strongly saturated, that can be used to derive relative abundances. Fortunately, the lines all have similar absorption depths and so uncertainties caused by saturation partly cancel out.

Ion abundances can be obtained either from the equivalent widths W_λ of the absorption lines, or from their residual intensity at line center, r_{λ_0}. The two parameters are basically equivalent in that they are directly related to each other, although the use of W_λ is preferable because it is directly proportional to abundance in a model-independent way when the lines are unsaturated, e.g., finite spectral resolution increases the observed residual line intensity, but not the equivalent width. In the supernova the lines are all easily resolved, and the residual intensity at the bottom of the lines is more readily measured than W_λ, hence we use r_{λ_0} to obtain the abundances.

Many of the absorption lines in SN 1987A are quite deep, and are therefore produced largely by scattering rather than true absorption. This is consistent with the large deviations from LTE that must exist in the rapidly expanding, tenuous envelope. In this situation the line formation can be approximately represented by the Schuster-Schwarzschild model of a reversing layer superposed on top of a continuum, in which case the residual intensity of a line r_{λ_0} is related to the optical depth at line center τ_0 by the relation (Mihalas 1969)

$$r_{\lambda_0} = \frac{1}{1 + \tau_0} . \tag{1}$$

The optical depth,

$$\tau_0 = N_\ell \frac{\sqrt{\pi} e^2}{m_e c^2} \frac{f_\ell \lambda_\ell}{V_0}, \tag{2}$$

where N_ℓ is the column density of absorbers in the lower level of the transition, and f_ℓ and λ_ℓ are the oscillator strength and wavelength. The Doppler velocities V_0 of the lines are all roughly the same because they are dominated by the large-scale velocity structure of the envelope. The abundance of the ion N_i producing each absorption line can be related to N_ℓ by the Boltzmann equation,

$$N_\ell = N_i \frac{g_\ell}{Z_i} e^{-\chi_\ell/kT_{exc}} , \tag{3}$$

where $Z_i = g_1$ is the partition function of the ion, and χ_ℓ is the excitation potential. Thus, the ion abundance

$$N_i = \frac{m_e c^2}{\sqrt{\pi} e^2} \frac{g_1}{g_\ell} \frac{V_0}{f_\ell \lambda_\ell} e^{\chi_\ell/kT_{exc}} \left(\frac{1}{r_{\lambda_0}} - 1\right). \tag{4}$$

We have selected the most appropriate lines suitable for use for the ions observed in SN 1987A, and they are listed in Table 1 together with the relevant atomic data for the transitions and the observed absorption depths. The f-values have been taken from the sources referenced.

The optical Sr II lines are all strongly blended and saturated, so we have used

https://doi.org/10.1017/S0252921100094021 Published online by Cambridge University Press

the IR line at 1.03μ from a scan obtained on 9 May 1987. The nearest date for which a good signal-to-noise optical scan was obtained is 14 May, and so all of the optical data pertain to this date, although neither the IR nor the optical spectrum was changing appreciably near this time. The largest uncertainties in the determination of the abundances derive from the poorly defined continuum flux levels and the unknown excitation temperature. It is not likely that the continuum flux is uncertain by more than 40 percent, and it should be in error by similar amounts for all the optical lines. In addition, although the excitation temperature is not well known, the lines being considered all have similar excitation potentials and so the relative Boltzmann factors between the various lines are not sensitive to temperature.

The spectral line identifications for SN 1987A indicate that the heavy elements are predominantly singly ionized. Limits to the amount of neutral material can be obtained from the absence of the neutral lines Fe I λ5269 and Ba I λ5535, both of which should be quite strong for any substantial fraction of neutral species because of their low excitation potentials and high f-values. The limits to the absorption strengths of these lines listed in Table 1 require the amount of neutral iron and barium to be Fe I/Fe II $\leq$ 0.004 and Ba I/Ba II $\leq$ 0.01, thus the heavy elements may be considered to be singly ionized. The possibility does exist that a non-negligible fraction of doubly ionized species could be present, yet undetected, since none of those ions have low-excitation transitions in the optical or IR, although we believe this to be unlikely.

TABLE 1

ABSORPTION LINE PROPERTIES OF SN 1987A
(MAY 1987)

Line	r_{λ_0}	log $g_\ell f_\ell$	χ_ℓ(eV)	g_1	Ref.
H I λ4861	0.37	-0.02	10.19	2	a
Sc II λ5527	0.73	+0.13	1.76	15	b
Fe I λ5269	>0.5	-1.32	0.86	25	c
Fe II λ5018	0.42	-1.40	2.88	30	d
Sr II λ1.033μ	0.48	-0.25	1.83	2	e
Ba I λ5535	>0.75	+0.20	0.00	1	b
Ba II λ6142	0.39	-0.08	0.70	2	b

(a) Wiese, Smith, and Glennon (1966); (b) Reader, Corliss, Wiese, and Martin (1980); (c) Fuhr, Martin, Wiese, and Younger (1981); (d) Phillips (1979); (e) Lindgard and Nielsen (1977).

Using the line strengths and parameters given in Table 1, and the solar abundances for Sc, Fe, Sr, and Ba listed by Cameron (1982), we have computed the relative abundances of these elements with respect to their solar values as a function of excitation temperature from eqn. (4), and the results are shown in Figure 1. The corresponding color temperature for the supernova at this time has

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been computed by Hamuy et al. (1987) from optical and IR photometry to be $T_c = 5,600$ K. By analogy with supergiant atmospheres, the excitation temperature should be less, in the vicinity of $T_{exc} = 5,000$ K, since it is coupled to the lower kinetic temperature higher in the envelope than the region where the continuum is formed.

It should be emphasized that solar abundance ratios are used here only as a convenient reference point. The LMC is known to have a total heavy element abundance that is approximately two to three times less than solar (van Genderen, van Driel, and Greidanus 1986; Dufour 1984). The abundances of Sc, Sr, and Ba in the LMC are not known because of the difficulty in detecting lines of these elements in objects. They are probably not solar; however, unless the history of nucleosynthesis in the Large Cloud is completely different from that in our Galaxy, the relative abundances of the s-process elements with respect to each other and to Fe should not differ greatly from those of the sun.

The Fe II lines have the highest excitation potentials of the heavy elements we are considering, therefore a lower assumed temperature leads to a higher derived abundance for Fe relative to Sc, Sr, and Ba, as is seen in Figure 1. For temperatures exceeding $T_{exc} = 4,000$ K, all of the s-process elements are enriched relative to Fe. At lower temperatures, the Sc and Sr are increasingly enhanced relative to Ba. The uncertainties in the logarithmic abundances relative to each other are of the order of ±0.3, independent of the uncertainties associated with knowing T_{exc}. For $T_{exc} = 5,000$ K, the s-process elements have enrichments of factors of 3 to 8 with respect to iron.

In mid-May on the dates of the present observations the highest Balmer lines were visible in the spectrum, and their existence helps immeasurably in the determination of T_{exc}. Because of the much higher excitation potential of the Balmer lines ($\chi = 10.2$ eV) in comparison with the other lines under consideration, the strengths of the hydrogen lines relative to those of Fe II are very sensitive to temperature for $T_{exc} \leq 10^4$ K. There is no a priori reason to suspect that the Balmer lines are formed under conditions much different from those of the heavy elements since their strengths are comparable, although their formation is selectively favored in higher temperature regions of the envelope. Since $H\alpha$ is more saturated than $H\beta$, we have used the strength of $H\beta$ to determine the relative abundance of H with respect to Fe from eqn. (4) in the same manner as the other elements, and that result is also plotted in Figure 1. The curve represents a lower limit to [H/Fe] since some hydrogen could be ionized. An abundance of [H/Fe] = 0.4 in the progenitor is expected on the basis of the lower metallicity of the LMC. This value occurs for a temperature $T_{exc} = 5,100$ K, which is essentially the same T_{exc} inferred from the color temperature. Thus, we take as the derived abundances for the supernova envelope the following values based on the observed absorption line strengths [Sc/Fe] = 0.90, [Sr/Fe] = 0.75, and [Ba/Fe] = 0.55.

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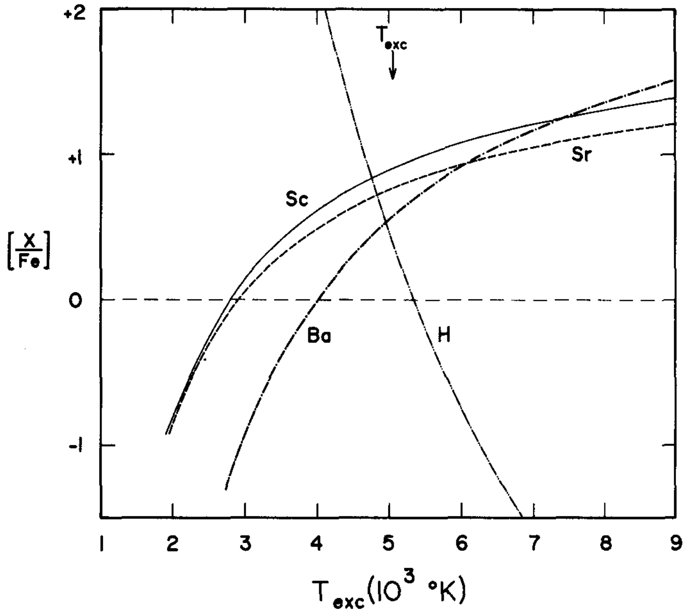

FIG. 1-- The logarithmic abundances of H, Sc, Sr, and Ba with respect to Fe in SN 1987A relative to their solar system values, as a function of the envelope excitation temperature T_{exc}. The abundances are derived from the absorption lines in May 1987, and the vertical arrow shows the appropriate temperature at that time.

The calculations confirm what the spectral scans suggest, i.e., the unusual strengths of absorption from Sc, Sr, and Ba are due in part to enhancements of these elements. The enrichments are not very large, partly a result of dilution caused by mixing of the processed gas from the He-burning zone with the outer hydrogen envelope of the star. One of the predictions of individual s-process episodes in stars is a greater enrichment of Sc and Sr compared to that of Ba. The calculations of Lamb et al. (1977) and Prantzos, Arnould, and Arcoragi (1987) have shown that the enhancement factors for Sr are roughly 6 times that for Ba from the s-process in stars with initial masses in the range $15 < M < 60\ M_\odot$. Repeated episodes in which a larger fraction of the star is subjected to He-shell burning with multiple pulses over a long time-scale can eventually lead to an equilibrium situation which gives similar enhancement factors for Sr and Ba, as occurs in Ba II stars, however this situation is not expected to pertain to massive stars such as Sk -69° 202.

Models of the supernova progenitor have indicated that SN 1987A possessed a helium-core mass of $M_{He} \approx 6\ M_\odot$, with a total mass at the time of outburst in the range of 10-20 $M_\odot$, and a carbon-core mass of 4 $M_\odot$ (Woosley et al. 1987). If the s-process enhancements produced in the carbon core are approximately those computed by Lamb et al. (1977) for this mass regime, and if these are subsequently mixed via

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convection or the outburst itself with the outer hydrogen envelope of the star, the resulting abundance ratios would, assuming an initial solar distribution, be given by

$$[\frac{X_A}{X_B}] = \log [\frac{E_A M_C + M_T}{E_B M_C + M_T}] , \tag{5}$$

where E_A and E_B are the enrichment factors of elements X_A and X_B, and M_C and M_T are the C-core and total mass of the progenitor. For an initial mass of around 18 $M_\odot$, interpolation of the results of Lamb et al. gives $E_{Sc} = 20$, $E_{Sr} = 25$, and $E_{Ba} = 3.5$. We have used these over-production factors to compute the expected s-process enhancements in SN 1987A on the basis of complete core/envelope mixing. Since the helium-core (and therefore carbon-core) mass is fairly well fixed by the supernova models, with $M_C \sim 4\ M_\odot$ (Woosley et al. 1987), the primary variable in the calculations is the uncertain envelope mass. We have assumed several values of M_T for the calculations, and have computed the resulting abundance ratios of Sc, Sr, and Ba with respect to Fe, as given in Table 2. For homogeneous mixing in the progenitor, which is indicated from the absence of appreciable spectral evolution during the first four months following outburst, the calculations demonstrate that enhancements of the order of factors of 2 to 20 should be present in the supernova. This is roughly what the observations of the absorption line strengths yield.

TABLE 2

EXPECTED s-PROCESS ENRICHMENTS IN THE PROGENITOR

		$M_C = 4\ M_\odot$	
Elements	$M_T = 7\ M_\odot$	$M_T = 10\ M_\odot$	$M_T = 15\ M_\odot$
[Sc/Fe]	1.1	0.9	0.8
[Sr/Fe]	1.2	1.0	0.9
[Ba/Fe]	0.5	0.4	0.3

The extent of the s-process enrichments in SN 1987A could enable limits to be placed on the mass of the hydrogen envelope if the uncertainties in the observed abundances can be improved upon. The over-all enrichments deduced from the present scattering-atmosphere analysis are consistent with total progenitor masses in the range of 7 - 15 $M_\odot$. Also, it is worth noting that the enhancement of Ba with respect to Sr and Fe is observed to be larger than it is predicted to be from the s-process calculations. The differences are near the limits of the uncertainty of the analysis, so they may not be significant. On the other hand, they may signify that the initial abundance distribution of the elements was not solar, or that the r-process also operated to modify the distribution.

The present calculations show that the Sc, Sr, and Ba abundances are higher with respect to Fe than found in the sun. Since these elements are secondary nucleosynthesis products, synthesized from CNO and the iron-peak nuclei by the

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s-process, we expect from the lower metallicity of the LMC that their normal abundances with respect to Fe in the Cloud are lower than the solar values. Their enhancements in SN 1987A may therefore be taken as evidence for the s-process in the progenitor, as is indeed expected to occur in massive stars. The extent of the observed enrichments is in rough agreement with that computed from the models of the progenitor if mixing occurs, however the Ba/Sr ratio in the supernova does appear to be higher than that expected. This could be due to the fact that the Ba/Sr abundance is generally higher in the LMC than in our Galaxy, having been produced in the ISM of the two galaxies by different classes of objects.

As an adjunct to the s-process enrichments, carbon should also be enhanced since the s-process occurs in the helium burning zone. At low temperatures no absorption lines of the lower ionization stages of carbon are expected in the optical. However, when the spectrum evolves to an emission spectrum, emission from C II λ4267 (or C IV λ1549 and C III] λ1909 in the UV) should be detected to test this expectation. Further refinements to the abundance analysis and the s-process calculations applied to the progenitor should ultimately allow more detailed statements to be made concerning the nature of the progenitor and its evolution.

The author wishes to thank D. Dearborn and I. Iben for informative discussions, A. McWilliam for assistance with the atomic data, and acknowledges the stimulating atmosphere of the Aspen Center for Physics where part of this work was done. Most important, great credit must be given to the entire CTIO staff who have gone to such lengths to secure and reduce the photometric and spectroscopic data each clear night, making it readily available to every interested scientist. Their tremendous attitude and spirit of inquiry is a pleasure to be associated with.

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