THE ASTROPHYSICAL JOURNAL, 414:L105–L108, 1993 September 10

TYPE II SUPERNOVAE FROM 8–10 $M_\odot$ ASYMPTOTIC GIANT BRANCH STARS

MASAAKI HASHIMOTO
Department of Physics, College of General Education, Kyushu University, Fukuoka 810, Japan
AND
KOHICHI IWAMOTO AND KEN'ICHI NOMOTO
Department of Astronomy, School of Science, University of Tokyo, Tokyo 113, Japan
Received 1993 April 19; accepted 1993 May 11

ABSTRACT

The final evolution of 8–10 $M_\odot$ stars in the AGB phase is recalculated to clarify whether these stars undergo collapse or thermonuclear explosion. New electron capture rates based on the shell model wave functions are employed for the evolution of the degenerate O + Ne + Mg core. It is found that the difference between the old and new rates are too small to alter the earlier conclusion that the O + Ne + Mg core collapses. The optical appearance of the resultant supernova explosion of AGB stars are discussed for observational diagnostics. In particular, a possible connection of the AGB star model with SN 1993J is examined.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: evolution — stars: interiors — supernovae: general — supernovae: individual (SN 1993J)

1. INTRODUCTION

The evolution of AGB stars has been studied mostly for stars less massive than $\sim 8\ M_\odot$ which develop degenerate C + O cores. If the C + O core mass reaches the Chandrasekhar limit, the star undergoes carbon deflagration as in Type Ia supernovae (SNs) (Nomoto, Thielemann, & Yokoi 1984) but to be observed as Type II SNs (Woosley 1990; Swartz, Wheeler, & Harkness 1991); this could be the case for a narrow mass range such as 7–8 $M_\odot$ (Branch, Nomoto, & Filippenko 1991) as also constrained from the galactic chemical evolution model (Nomoto, Shigeyama, & Tsujimoto 1991b).

The stars of 8–10 $M_\odot$ undergo nondegenerate carbon burning and form degenerate O + Ne + Mg cores (Nomoto 1984c, 1987). The O + Ne + Mg core mass at the carbon exhaustion already exceeds 1.1 $M_\odot$ but is smaller than the critical mass of 1.37 $M_\odot$ for neon ignition. Hence neon burning is never ignited. These stars become AGB stars as demonstrated in Nomoto (1984c, 1987), and the further evolution is brought about by the growth of the O + Ne + Mg core mass through H/He double shell burning toward the Chandrasekhar limit (Nomoto 1987). A fraction of the 8–10 $M_\odot$ stars could become O + Ne + Mg white dwarfs due to mass loss, but the majority of these stars are more likely to reach the supernova stage than less massive stars because of their relatively short lifetime after entering the AGB phase, which could be as short as $\sim 4 \times 10^4$ yr for the 9 $M_\odot$ star and shorter for more massive stars (Nomoto 1984c).

Miyaji et al. (1980) have shown that the degenerate O + Ne + Mg core eventually undergoes collapse due to electron capture on ^{24}Mg and ^{20}Ne (see also Miyaji & Nomoto 1987; Nomoto & Kondo 1991). Recently, Canal, Isern, & Labay (1992) claimed that the 8–10 $M_\odot$ stars undergo thermonuclear explosion if the new electron capture rates (Takahara et al. 1989) are applied. To examine this controversial issue is important, since the explosion of 8–10 $M_\odot$ stars could constitute a significant fraction of SNs II and thus make a substantial contribution to the chemical evolution of galaxies.

The optical appearance of the resultant supernova explosion must be very different between the above two scenarios, so that its study is important in establishing the supernova type–progenitor connection (Branch, Nomoto, & Filippenko 1992). It is also an interesting possibility that the recent SN II 1993J in M81 might be the explosion of the AGB star in view of its peculiar behavior. If it turns out to be the case, it could provide a critical test to distinguish the explosion models.

To clarify whether 8–10 $M_\odot$ stars undergo collapse or thermonuclear explosion, we recalculate the evolution of the O + Ne + Mg core by applying the new electron capture rates (Takahara et al. 1989) and conclude that the difference in the new and old capture rates alone is too small to alter our earlier conclusion of collapse (§ 2). To distinguish the explosion models, we examine possible observable features of the AGB star models of SNs II (§ 3). We then discuss a possible connection with SN 1993J (§ 4).

2. ELECTRON CAPTURE AND QUASI-DYNAMIC COLLAPSE OF THE O + Ne + Mg CORE

In the final stages of the evolution of 8–10 $M_\odot$ stars, the growth of the O + Ne + Mg core mass leads to the increase in the central density ρ_c and the Fermi energy of degenerate electrons. When the core mass grows to 1.38 $M_\odot$, the central density gets close to $\sim 4 \times 10^9$ g cm^{-3}, the threshold for the electron capture reaction ^{24}Mg$(e^-, \nu)^{24}$Na$(e^-, \nu)^{24}$Ne for zero temperature. Near $\rho_c \sim 1 \times 10^{10}$ g cm^{-3} also electron capture on ^{20}Ne via ^{20}Ne$(e^-, \nu)^{20}$F$(e^-, \nu)^{20}$O takes place (Miyaji et al. 1980).

Electron capture that reduces the electron mole number Y_e has the following competing effects on the final evolution of the degenerate O + Ne + Mg core (Miyaji et al. 1980):

1. The effective Chandrasekhar mass is reduced as Y_e^2, which rapidly accelerates a *quasi-dynamic* contraction of the core.

2. Entropy is produced by γ-ray emission from the excited states of daughter nuclei and the distortion of the electron distribution function. The electron capture region becomes semiconvective because of the formation of steep gradients of temperature and the electron mean molecular weight (Nomoto 1984a, b; Mochkovitch 1984; Miyaji & Nomoto 1987). If semiconvective mixing is negligible, the electron capture region is heated locally. This is likely the case because the electron capture time scale is shorter than the diffusion time scale. Electron capture eventually ignites explosive oxygen burning at the central density of $\rho_c \sim 9.5 \times 10^9$ g cm^{-3} (Miyaji & Nomoto 1987). The resulting oxygen deflagration processes the material into nuclear statistical equilibrium (NSE).

3. Whether the oxygen deflagration will lead to collapse or explosion depends on the relative time scales of nuclear energy release and electron capture in NSE behind the deflagration wave. The energy generation rate is determined mainly by the propagation velocity of the deflagration wave, while the electron capture rate depends on the density.

Nomoto & Kondo (1991) have shown that the convective oxygen deflagration starting at $\rho_c \sim 9.5 \times 10^9$ g cm^{-3} induces collapse, although it depends on the propagation velocity of deflagration (Isern, Canal, & Labay 1991). Timmes & Woosley (1992) have argued that if the ignition density is higher than $\sim 9 \times 10^9$ g cm^{-3}, rapid electron capture behind the deflagration front may prevent convection from developing, thus inducing collapse.

The above result is based on the electron capture rates using the gross theory of β-decay (Miyaji et al. 1980, hereafter case G). Takahara et al. (1989) calculated the electron capture rates using the shell model wave functions (hereafter case S). Canal et al. (1992) have claimed that the ignition density of oxygen burning depends rather strongly on the adopted electron capture rates, being as low as 8.5×10^9 g cm^{-3} for case S, while it is slightly higher than 1×10^{10} g cm^{-3} for case G. Since the critical central density which discriminates between collapse and explosion is $\sim 9 \times 10^9$ g cm^{-3}, such a difference is important.

In the present calculations, we have found that the difference in the electron capture rates between case G and case S is too small to significantly change the ignition density. We start from the degenerate O + Ne + Mg core formed in the 2.6 $M_\odot$ helium core of the ~ 9 $M_\odot$ star. Input physics and the method of calculation are the same as in Nomoto & Hashimoto (1988) except for the use of the nuclear reaction rates by Caughlan & Fowler (1988). The initial compositions of the core are $X_{\rm O} = 0.34$, $X_{\rm Ne} = 0.49$, $X_{\rm Mg} = 0.12$, and other trace elements. The core grows at a rate determined by H/He double shell burning (Nomoto 1987), which increases the central density.

In Figure 1, the solid and the dashed lines show the evolutionary paths of the central density and temperature for cases S and G, respectively. Because of the finite temperature effect, electron capture starts below the threshold density for zero temperature. When electron capture on ^{24}Mg starts, the heating rate first sharply increases but drops as the ^{24}Mg and ^{24}Na abundances decrease. Accordingly the central temperature in Figure 1 increases sharply and then decreases as the bremsstrahlung neutrino cooling overcomes electron capture effects. Although the start of electron capture for case S is slightly earlier than in case G, the difference is too small to affect the later evolutionary path.

When the central density gets close to $\sim 9 \times 10^9$ g cm^{-3}, heating due to electron capture on ^{20}Ne exceeds the bremsstrahlung neutrino cooling. Afterward, the evolution in the central density and temperature plane is determined by the competition between the heating rate and the core contraction rate. The contraction becomes faster and faster as the electron capture region grows in mass with increasing densities, which also contributes to increase the temperature and heating. Eventually the sharp increase in the central temperature starts when the heating time scale becomes much shorter than the *quasi-dynamic* time scale of contraction. It leads to the explosive ignition of oxygen burning.

The oxygen ignition density depends very weakly on the electron capture rate on ^{20}Ne, i.e., 9.3×10^9 g cm^{-3} for case S being slightly lower than 9.4×10^9 g cm^{-3} for case G (Fig. 1); the dependence on the capture rate is practically negligible. The reason for such a small difference in the ignition density between the two cases can be seen in Figure 2. It shows the net heating rate due to electron capture ^{20}Ne$(e^-, \nu)^{20}$F$(e^-, \nu)^{20}$O at log T (K) = 8.6, 8.65, and 8.7 as a function of the density. Here the solid and the dashed lines show cases S and G, respectively, and the upper lines correspond to the higher temperature. Since the ignition takes place at densities below the zero temperature threshold, the heating rate is very sensitive to the density. Therefore, even though the electron capture rate is higher in case S than case G at a given density around log T (K) = 8.65, the resulting difference in the ignition density is minor.

Our result is consistent with Miyaji & Nomoto (1987) and the difference between cases S and G is much smaller than that reported by Canal et al. (1992). In this connection, we note the importance of the *quasi-dynamic* nature of the core contraction which gets faster and faster with the decreasing effective Chandrasekhar limit. It should also be noted that careful interpolation is necessary in using the electron capture tables.

Since the ignition density is close to that found in Miyaji & Nomoto (1987), it is likely that the oxygen deflagration would lead to collapse (Nomoto & Kondo 1991) rather than explosion of the O + Ne + Mg core. As far as the difference between

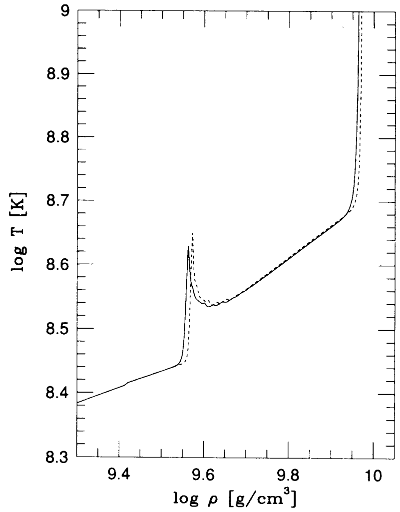

FIG. 1.—Evolutionary paths of the central density and temperature of the O + Ne + Mg core for cases S (*solid curve*) and G (*dashed curve*).

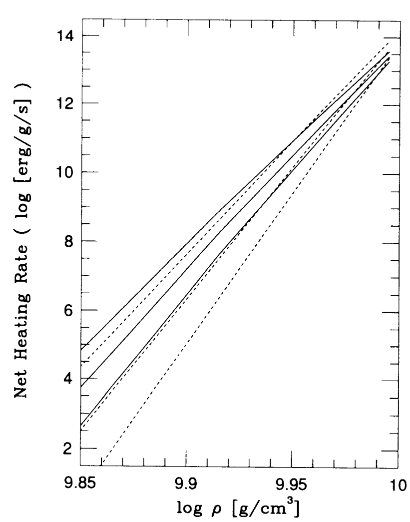

FIG. 2.—Net heating rate due to electron capture ^{20}Ne$(e^-, \nu)^{20}$F$(e^-, \nu)^{20}$O at log T (K) = 8.6, 8.65, and 8.7 as a function of the density. The solid and dashed lines show cases S and G, respectively, and the upper lines correspond to the higher temperature.

the two rates is concerned, therefore, it would not affect the final fate of 8–10 $M_\odot$ stars.

3. SUPERNOVA EXPLOSIONS OF AGB STARS

In § 2, we have shown that the difference between the new and old electron capture rates alone is too small to significantly alter the earlier conclusion that the 8–10 $M_\odot$ stars would undergo collapse. However, some other effects such as semiconvective mixing and the stellar mass dependence need further investigation. In view of these uncertainties, it is useful to describe the differences of the model predictions to be compared with supernova observations. We also describe some observable features expected from the AGB star explosions to distinguish them from more massive star explosions.

The shape of the optical light curve of SNs II depends sensitively on the luminosity, radius, and the H-rich envelope mass of the progenitor. Thus we first examine possible ranges of these quantities of the AGB progenitors. The luminosity of the AGB star near the Chandrasekhar limit ranges from $6 \times 10^4\ L_\odot$ to $1 \times 10^5\ L_\odot$, depending on the H/He ratio in the envelope (Paczyński 1970; Uus 1970). The effective temperature depends also on the H/He ratio, metallicity, and the mixing length adopted for the surface convection zone (e.g., Nomoto & Sugimoto 1972). A He-rich envelope of the AGB star can be formed as a result of mass loss and the dredge-up of the He layer by the surface convection zone as has been suggested for the progenitor of the Crab Nebula (Nomoto et al. 1982; Nomoto 1985). For a relatively small mass He-rich envelope, the luminosity and the color at the top of the AGB can be consistent with a K0 supergiant (Saio 1993), which might be relevant to the progenitor of SN 1993J as described in § 4.

We note also that the AGB star undergoes a large amplitude pulsation as a Mira variable, thereby changing its luminosity and color. The pulsation is likely to form a shock wave that would induce a series of unsteady mass ejection from the AGB star rather than a steady wind. Therefore the structure of the circumstellar materials could be quite complex, which might be revealed from the X-ray and radio light curves.

The explosion of AGB stars is observed as SNs II because of H-rich envelope. Based on our explosion models, there exist two possible subclasses of SNs II from the AGB stars (1 and 2 below):

1. Carbon deflagration of the $\sim$7–8 $M_\odot$ star, which yields the explosion energy of $E \sim 1.3 \times 10^{51}$ ergs s^{-1}, the ^{56}Ni mass of $M_{\rm Ni} \sim 0.6\ M_\odot$, and the ejected core mass of $M_{\rm core} = 1.38\ M_\odot$ (Nomoto et al. 1984).
2. Gravitational collapse of the 8–10 $M_\odot$ star, whose outcome depends on the very uncertain explosion mechanism and the mass cut (Hillebrandt, Nomoto, & Wolff 1984; Burrows & Lattimer 1985; Baron, Cooperstein, & Kahana 1987; Mayle & Wilson 1988); some amount of core materials including ^{56}Ni would be ejected, although being much less than in the above case.
3. If instead oxygen deflagration would occur at $\rho_c \sim 8.5 \times 10^{10}$ g cm^{-3} in the 8–10 $M_\odot$ star, the explosion would be relatively weak as $E \sim 0.4$–0.6×10^{51} ergs s^{-1}, $M_{\rm Ni} \sim 0.3$–$0.4\ M_\odot$, and $M_{\rm core} = 1.38\ M_\odot$ (Isern et al. 1991). Also the ejecta would contain very neutron-rich iron peak elements compared with the above two scenarios (Sutherland & Wheeler 1984; Nomoto & Kondo 1991).

These differences can be distinguished in the supernova light curve and spectra. The shape of the optical light curve has been found to depend on the mass of the hydrogen-rich envelope (e.g., Swartz, Wheeler, & Harkness 1991; Blinnikov & Bartunov 1993). More specifically, the duration $t_{\rm pl}$ of the light curve plateau due to hydrogen recombination is determined by the lowest expansion velocity of hydrogen $v_{\rm H}$ as (Shigeyama & Nomoto 1990)

$$t_{\rm pl} \sim 110^{\rm d} \left(\frac{L_{\rm pl}}{10^{42}\ {\rm ergs\ s^{-1}}}\right)^{1/2} \left(\frac{v_{\rm H}}{10^3\ {\rm km\ s^{-1}}}\right)^{-1} . \quad (1)$$

Here $L_{\rm pl}$ is the luminosity around $t = t_{\rm pl}$, which depends on the progenitor's radius and E; $v_{\rm H}$ depends on the envelope mass $M_{\rm env}$, the kinetic energy of explosion E, and mixing of hydrogen. The plateau period is longer for smaller $E/M_{\rm env}$ and more extensive mixing of hydrogen into the core if the mixing occurs. The AGB stars tend to have smaller $M_{\rm env}$ than more massive stars, so that the explosions tend to have shorter plateau.

Later the heating effect due to the ^{56}Ni–^{56}Co decays will gradually appear as in SN 1987A. Eventually the ^{56}Ni mass can be known from the exponential tail, which is the best way to distinguish the models. For larger $M_{\rm env}/M_{\rm core}$ (as in the above case 2), the Rayleigh-Taylor instability at the core-envelope interface grows more strongly (Hachisu et al. 1991) so that the radioactive heating effect would appear earlier.

Other characteristics of the AGB star models are the peculiar abundances of the surface layer and circumstellar materials, since the 8–10 $M_\odot$ stars undergo dredge-up of the He layer and thermal pulses of He shell burning (Nomoto 1984c) as in the smaller mass AGB stars (e.g., Becker & Iben 1980). These abundances are sensitive to the stellar mass.

For example, the evolutionary scenario of the 9 $M_\odot$ star for the Crab Nebula's progenitor predicts the overabundances of N and He in the convective envelope, while larger mass stars undergo convective He shell burning before the dredge-up, thus containing more C and Ne in the convective envelope (Nomoto et al. 1982). The abundances of He, C, N, and O may be estimated from the UV observations as was done for SN 1979C (Fransson et al. 1984).

4. DISCUSSION

SN 1993J in M81 was discovered in the very early rising phase (Garcia 1993) and is providing a wealth of new information to test the stellar evolution and explosion theories as in SN 1987A. Therefore, it is quite relevant to examine if there is any indication of a connection between the AGB star and SN 1993J.

A K0 supergiant has been suggested for a possible progenitor of SN 1993J (Perelmuter 1993; Filippenko 1993b). The early detections of X-rays (Zimmerman et al. 1993; Tanaka 1993) and radio (Weiler 1993; Pooley & Green 1993) from SN 1993J are consistent with the red supergiant progenitor which had a significant amount of circumstellar materials in contrast to SN 1987A which was the blue supergiant explosion.

However, the mass of the progenitor is not certain. The bolometric luminosity of the K0 supergiant may be estimated as $\sim 1 \times 10^5\ L_\odot$ (Yamaoka 1993) for the distance modulus 27.5, V magnitude $\sim$20.8 (Salzer, Herbst, & Vinton 1993; Blakeslee & Tonry 1993), extinction $A_v \sim 0.3$ and the bolometric correction of 0.7 mag (Allen 1973). However, this estimate is subject to large uncertainties. Possible variation is also pointed out (Humphreys et al. 1993). For the moment, diverse progenitor models should be explored and compared with SN 1993J in view of the uncertainty of the progenitor identification.

1. The straightforward progenitor model would be a massive star with a main sequence mass of $M_{\rm ms} \sim 15$–$20\ M_\odot$ whose presupernova luminosity (see, e.g., Nomoto & Hashimoto 1988; Shigeyama, Nomoto, & Hashimoto 1988) is consistent with the observed estimate; however, a more massive progenitor model may not be precluded in view of uncertain extinction and color. The supernova explosion of this class of

stars, whose envelope mass is typically $\sim 10\ M_\odot$, would form a plateau in the light curve (SN II-P), which will be described in a separate paper (Suzuki et al. 1993).

2. Alternative possibility is the AGB star with $M_{ms} \sim$ 7–10 $M_\odot$. As discussed in § 3, the K0 supergiant progenitor is consistent with the AGB star if its H-rich envelope is relatively less massive and somewhat He-rich.

SN 1993J is identified as an SN II (Filippenko 1993a; Taniguchi et al. 1993), but its visual light curve is not typical, i.e., a rapid increase to the first peak, fast decline, a steady rise to the second peak, and a gradual decline. The light curve has not shown a clear plateau as in Type II-P SNs, but its decline is not monotonic as in the linear decline type (II-L) either. Certainly further observations are necessary to identify the exact type of SN 1993J. It is important to infer the H-rich envelope mass from the expansion velocities, light curve shape, etc. If the H-rich envelope mass turns out to be rather small, then the progenitor would be more likely the AGB star or a star more massive than $\sim 40\ M_\odot$ because of their large wind mass loss, or could be a binary member that lost large mass by tidal interaction.

If SN 1993J turns out to be the explosion of stars more massive than $\sim 10\ M_\odot$, some of the discussion applied to the AGB star models (§ 3) may also be relevant to those massive stars. The duration of the plateau of the optical light curve is given by equation (1), thereby depending also on the supernova brightness, E/M_{env}, and mixing of ^{56}Ni and hydrogen. Compared with SN 1987A, the development of Rayleigh-Taylor instabilities in the explosion of a red supergiant is somewhat different. Because of the lower envelope density and thus the larger density contrast at the H/He interface, the instability grows faster and mix hydrogen well down to the velocity as low as ~ 1000 km s^{-1} for all the 13–20 $M_\odot$ stars. On the other hand, the propagation of the reverse shock is slower, so that the mixing of ^{56}Ni depends on the stellar mass, i.e., it is much less for the 20 $M_\odot$ star but substantial for stars of less massive than $\sim 15\ M_\odot$ (Hachisu et al. 1993).

The light curve tail will provide the ^{56}Ni mass, whose dependence on the progenitor mass is crucial for the models of the Type Ib/Ic SNs and the chemical evolution of galaxies. If less massive stars produce larger amount of ^{56}Ni and undergo more extensive mixing (Shigeyama et al. 1990; Nomoto, Filippenko, & Shigeyama 1990), the effect of radioactive heating would appear earlier.

The ^{56}Ni mass and the H-rich envelope mass are also related to the intensities of line γ-rays from the ^{56}Ni–^{56}Co decays. At the distance of 3.2 Mpc, *CGRO* could detect the γ-ray lines from Type Ia/Ib/Ic SNs but not from ordinary Type II-P SNs (e.g., Kumagai, Shigeyama, & Nomoto 1991; Nomoto, Kumagai, & Shigeyama 1991). Therefore, if SN 1993J has a rather small mass H-rich envelope and produced more than $\sim 0.2\ M_\odot$ ^{56}Ni, the observations of line γ-rays from SN 1993J with *CGRO* could be marginally possible.

We would like to thank H. Yamaoka, H. Saio, T. Suzuki, T. Shigeyama, S. Kumagai, and F.-K. Thielemann for useful discussion. This work has been supported in part by the Grant-in-Aid for Scientific Research (04234203, 04640265, 05242102, 05242207) of the Ministry of Education, Science, and Culture in Japan.

REFERENCES

Allen, C. W. 1973, Astrophysical Quantities (London: Athlone)
Baron, E., Cooperstein, J., & Kahana, S. 1987, ApJ, 320, 300
Becker, S. A., & Iben, I., Jr. 1980, ApJ, 237, 111
Blakeslee, J., & Tonry, J. 1993, IAU Circ., No. 5758
Blinnikov, S. I., & Bartunov, O S. 1993, A&A, in press
Branch, D., Nomoto, K., & Filippenko, A. V. 1991, Comm. Ap., 15, 221
Burrows, H., & Lattimer, J. M. 1985, ApJ, 299, L19
Canal, R., Isern, J., & Labay, J. 1992, ApJ, 398, L49
Caughlan, G. R., & Fowler, W. A. 1988, Atomic Data Nucl. Data, 40, 283
Filippenko, A. V. 1983a, IAU Circ., No. 5731
———. 1993b, IAU Circ., No. 5737
Fransson, C., Benvenuti, P., Gordon, C., Hempe, K., Palumbo, G. G. C., Panagia, N., Reimers, D., & Wamstecker, W. 1984, A&A, 132, 1
Garcia, F. 1993, IAU Circ., No. 5731
Hachisu, I., Iwamoto, K., Matsuda, T., Nomoto, K., & Shigeyama, T. 1993, in preparation
Hachisu, I., Matsuda, T., Nomoto, K., & Shigeyama, T. 1991, ApJ, 368, L27
Hillebrandt, W., Nomoto, K., & Wolff, R. G. 1984, A&A, 133, 175
Humphreys, R. M., Aldering, G. S., Bryja, C. O., & Thurmes, P. M. 1993, IAU Circ., No. 5739
Isern, J., Canal, R., & Labay, J. 1991, ApJ, 372, L83
Kumagai, S., Shigeyama, T., & Nomoto, K. 1991, in SN 1987A and Other Supernovae, ed. I. J. Danziger (Garching: ESO), 203
Mayle, R., & Wilson, J. R. 1988, ApJ, 334, 909
Miyaji, S., & Nomoto, K. 1987, ApJ, 318, 307
Miyaji, S., Nomoto, K., Yokoi, K., & Sugimoto, D. 1980, PASJ, 32, 303
Mochkovitch, R. 1984, in Problems of Collapse and Numerical Relativity, ed. D. Bancel & M. Signore (Dordrecht: Reidel), 125
Nomoto, K. 1984a, in Stellar Nucleosynthesis, ed. C. Chiosi & A. Renzini (Dordrecht: Reidel), 239
———. 1984b, in Problems of Collapse and Numerical Relativity, ed. D. Bancel & M. Signore (Dordrecht: Reidel), 125
———. 1984c, ApJ, 277, 791
———. 1985, in The Crab Nebula and Related Supernova Remnants, ed. M. C. Kafatos & R. B. C. Henry (Cambridge Univ. Press), 97
———. 1987, ApJ, 322, 206
Nomoto, K., Filippenko, A. V., & Shigeyama, T. 1990, A&A, 240, L1
Nomoto, K., & Hashimoto, M. 1988, Phys. Rep., 163, 13
Nomoto, K., & Kondo, Y. 1991, ApJ, 367, L19
Nomoto, K., Kumagai, S., & Shigeyama, T. 1991a, in AIP Conf., Proc. 232, Gamma-Ray Line Astrophysics, ed. P. Durouchoux & N. Prantzos (New York: AIP), 236
Nomoto, K., Shigeyama, T., & Tsujimoto, T. 1991b, in IAU Symp. 145, Evolution of Stars: The Photospheric Abundance Connection, ed. G. Michaud (Dordrecht: Kluwer), 21
Nomoto, K., Sparks, W. M., Fesen, R. A., Gull, T. R., Miyaji, S., & Sugimoto, D. 1982, Nature, 299, 803
Nomoto, K., & Sugimoto, D. 1972, Prog. Theor. Phys., 48, 46
Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, ApJ, 286, 644
Paczyński, B. 1970, Acta Astr., 20, 47
Perelmuter, J.-M. 1993, IAU Circ., No. 5736
Pooley, G. G., & Green, D. A. 1993, IAU Circ., No. 5751
Saio, H. 1993, private communication
Salzer, J., Herbst, W., & Vinton, G. 1993, IAU Circ., No. 5741
Shigeyama, T., & Nomoto, K. 1990, ApJ, 360, 242
Shigeyama, T., Nomoto, K., & Hashimoto, M. 1990, ApJ, 361, L23
Sutherland, P. G., & Wheeler, J. C. 1984, ApJ, 280, 282
Suzuki, T., Kumagai, S., Shigeyama, T., Nomoto, K., Yamaoka, H., & Saio, H. 1993, ApJ, submitted
Swartz, D. A., Wheeler, J. C., & Harkness, R. P. 1991, ApJ, 374, 266
Takahara, M., Hino, M., Oda, T., Muto, K., Wolters, A. A., Glaudemans, P. W. M., & Sato, K. 1989, Nucl. Phys., A504, 167
Tanaka, Y. 1993, IAU Circ., No. 5753
Taniguchi, Y., Murayama, T., Sato, Y., Yadoumaru, Y., Ohyama, Y., Kosugi, J., Yoshida, M., & Kurakami, T. 1993, PASJ, submitted
Timmes, F. X., & Woosley, S. E. 1992, ApJ, 397, 220
Uus, U. 1970, Nauch. Inf. Akad. Nauk USSR, 17, 25
Weiler, W. 1993, IAU Circ., No. 5743
Woosley, S. E. 1990, in Supernovae, ed. A. G. Petschek (Berlin: Springer), 182
Yamaoka, H. 1993, private communication
Zimmerman, H. U., et al. 1993, IAU Circ., No. 5748

Note added in proof.—According to Canal (1993), the calculation by Canal et al. (1992) did not take into account the effect of Coulomb interactions correctly in electron capture on ^{20}Ne. After the correction, R. Canal (talk presented at IAU Colloq. 145, Supernovae and Supernovae Remnants [1993]) found the ignition density of $9. \times 10^9$ g cm^{-3}, which is in agreement with our result. As for SN 1993J, recent developments of the light curve and spectra have led Nomoto et al. (Nomoto, K., Suzuki, T., Shigeyama, T., Kumagai, S., Yamaoka, H., & Saio, H., Nature, submitted [1993]) and A. V. Filippenko & T. Matheson (IAU Circ., No. 5787 [1993]) to suggest that SN 1993J was the explosion of a star that had lost more than 90% of its hydrogen-rich envelope due to the Roche lobe overflow in the close binary system.