THE ASTROPHYSICAL JOURNAL, 361: L23–L27, 1990 September 20

LOW-MASS HELIUM STAR MODELS FOR TYPE Ib SUPERNOVAE: LIGHT CURVES, MIXING, AND NUCLEOSYNTHESIS

TOSHIKAZU SHIGEYAMA, KEN'ICHI NOMOTO, AND TAKUJI TSUJIMOTO
Department of Astronomy, Faculty of Science, University of Tokyo
AND
MASA-AKI HASHIMOTO
Department of Physics, College of General Education, Kyushu University
Received 1990 May 3; accepted 1990 July 6

ABSTRACT

Light curves, Rayleigh-Taylor instability, and nucleosynthesis of exploding helium stars are examined to look for relevant models for Type Ib supernovae, especially for SN 1983N and 1983I whose light curves decline as fast as Type Ia supernovae. The calculated light curves show a systematic dependence on the stellar mass, because smaller mass helium stars undergo more extensive mixing and eject smaller mass, thereby forming light curves with steeper tails. The relatively fast decline of the SN Ib light curves can thus be accounted for by the helium star models if the helium star mass is as low as 3–4 $M_\odot$ and if ^{56}Ni is mixed to the surface layers. Moreover, the 3–4 $M_\odot$ helium stars, having relatively small mass iron cores, can produce ~ 0.15 $M_\odot$ ^{56}Ni as required from the maximum luminosities. In terms of nucleosynthesis, mixing, and light curves, the helium stars of 3–4 $M_\odot$ (which form from stars with $M_{\rm ms} \sim 12$–16 $M_\odot$ in binary systems) are the most relevant progenitors of the Type Ib supernovae 1983N and 1983I.

Subject headings: hydrodynamics — nucleosynthesis — radiative transfer — stars: interiors — stars: supernovae

I. INTRODUCTION

Type I supernovae (SN I), identified from the absence of hydrogen lines in the maximum light spectra, are further subclassified into supernovae of Type Ia (SN Ia) and Type Ib (SN Ib) (see, e.g., Harkness and Wheller 1990 for a review and references). In the maximum light spectra, helium line features are seen in SN Ib but not in SN Ia. In the late time spectra, oxygen emission lines appear in SN Ib, while iron features dominate the SN Ia spectra. The light curves of SN Ib are powered by the decays of ^{56}Ni and ^{56}Co as seen from the exponential tails. The maximum luminosities, being lower than SN Ia by a factor of ~ 4, imply the production of ~ 0.15 $M_\odot$ ^{56}Ni in SN Ib. Most of SN Ib are associated with star-forming regions.

These signatures have led to the currently popular idea that the progenitors of SN Ib are Wolf-Rayet stars. Though white dwarfs could be possible alternative progenitors (Sramek, Panagia, and Weiler 1984; Branch 1988), the light curve of the off-center detonation model (Branch and Nomoto 1986; Nomoto 1982; Woosley, Taam, and Weaver 1986) would decline very fast and look more like SN 1885A (Chevalier and Plait 1988) rather than SN Ib.

Among the Wolf-Rayet star models, a wide range of the progenitor's masses has been proposed (Begelman and Sarazin 1986; Gaskell *et al.* 1986; Schaeffer, Cassé, and Cahen 1987; Uomoto 1987). From the light curve shapes, Wheeler and Levreault (1985) suggest that the mass of SN Ib is as low as 4 $M_\odot$. Ensman and Woosley (1988) showed that the theoretical light curves are basically in agreement with observations if the helium star mass is 4–6 $M_\odot$. Nomoto, Shigeyama, and Hashimoto (1988), Nomoto *et al.* (1988), and Nomoto and Shigeyama (1990) reached similar conclusions and argued that a large-scale mixing of ^{56}Ni is necessary to reproduce the fast decline of the light curves.

However, the previous Wolf-Rayet star models have some difficulties (1) in reproducing the light curves of typical SN Ib (SN 1983N and 1983I) which decline as fast as SN Ia, and (2) in producing enough ^{56}Ni to attain the maximum luminosities of SN Ib in relatively low mass helium star models (Ensman and Woosley 1988).

In the present *Letter*, we examine light curves (§ III), the Rayleigh-Taylor instability (§ IV), and nucleosynthesis (§ V) of exploding helium stars with masses down to 3.3 $M_\odot$ and conclude that the helium stars of 3–4 $M_\odot$ are the most relevant progenitors of SN Ib 1983 N and 1983I (§ VI).

II. HELIUM STAR MODELS

In the helium star models for SN Ib, two scenarios are possible for the presupernova evolution: (1) A fairly massive single star loses its hydrogen-rich envelope in a wind, or (2) a star in a close binary system becomes a helium star by tidal mass loss.

In the present study, we adopt the second scenario and perform hydrodynamical calculations for the explosion of the helium stars of masses $M_\alpha = 3.3$, 4, and 6 $M_\odot$, which are presumed to form from the main-sequence stars of masses $M_{\rm ms} \sim$ 13, 15, and 20 $M_\odot$, respectively. The evolution of these helium stars have been calculated from helium burning through iron core collapse without mass loss (Nomoto and Hashimoto 1988). At the collapse, the radii of helium stars are 3.7, 3.0, and 1.9 $R_\odot$ for $M_\alpha = 3.3$, 4, and 6 $M_\odot$, respectively. In the hydrodynamical calculations, we assume that the ejecta masses are $M_{\rm ej} = 2.1$, 2.7, and 4.4 $M_\odot$ and the masses of the neutron star residue are $M_{\rm ns} = 1.18$, 1.28, and 1.6 $M_\odot$ for $M_\alpha = 3.3$, 4, and 6 $M_\odot$, respectively. We calculate nucleosynthesis and light curves by depositing energy at the bottom of the ejecta to form a strong shock wave and imposing the final kinetic energy of explosion to be $E = 1 \times 10^{51}$ ergs. The same code and input physics are applied as adopted for the study of SN 1987A

(Shigeyama, Nomoto, and Hashimoto 1988; Shigeyama and Nomoto 1990).

III. LIGHT CURVES AND MIXING

Figures 1 and 2 show the calculated bolometric light curves of the exploding helium stars for two cases of the elemental distribution: (1) the original stratified composition structure with ^{56}Ni being confined in the innermost region (Fig. 1) and (2) the mixed distribution (Fig. 2) which is similar to that adopted in simulating the light curves of SN 1987A (Kumagai *et al.* 1989). In order to clarify the dependence of the light curve shape on M_α and mixing, the amount of ^{56}Ni is tentatively assumed to be 0.15 $M_\odot$ for all M_α by modifying the masses of other heavy elements (see § V for the calculated ^{56}Ni mass).

These figures also show three observed light curves of SN Ib with different decline rates: SN 1984L (visual: Wheeler and Levreault 1985), SN 1983N (bolometric: Panagia 1987), and SN 1983I (visual: Tsvetkov 1985). The visual light curve is regarded as close to the bolometric one. The decline rate of SN 1983N is very close to that of an SN Ia (Leibundgut 1988). The maximum luminosities and their dates are arbitrarily shifted for comparison with the calculated curves.

In the calculated bolometric light curves, the early shock heating phase is too brief to be observed because of the small initial radii. The later light curves are powered by the radioactive decays of ^{56}Ni and ^{56}Co and reach maximum around day 7–25 depending on the models, especially on mixing.

After maximum, the optical light curve declines faster than the decay rate of ^{56}Co (shown by the dotted curve) depending on how fast γ-rays escape from the star. The escape probability of γ-rays is determined by the column depth to the ^{56}Ni-^{56}Co layer. Accordingly the optical light curve declines faster, if M_α/E is smaller and the mass above the ^{56}Ni layer is smaller (i.e., ^{56}Ni is mixed closer to the surface).

For the unmixed cases in Figure 1, the calculated light curve tail for $M_\alpha = 6\ M_\odot$ is close to the dotted curve and might be consistent with the slowest SN Ib 1984L. However, these tails (even the fastest decline of $M_\alpha = 3.3\ M_\odot$) are much slower than that of SN 1983N and 1983I after ~day 40.

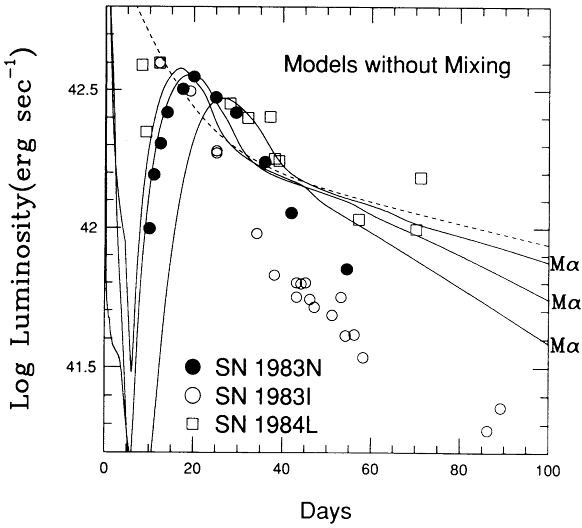

FIG. 1.—Calculated light curves of exploding helium stars of M_α = 3.3, 4, and 6 $M_\odot$. All the models assume the production of 0.15 $M_\odot$ ^{56}Ni, kinetic energy of explosion $E = 1 \times 10^{51}$ ergs, and no mixing (i.e., stratified composition structure). Filled and open circles are the observed light curves of SN Ib 1984L (visual), 1983N (bolometric), and 1983I (visual), where the maximum luminosities and the dates are arbitrarily shifted for comparison. The dotted curve is the energy generation rate of the ^{56}Ni-^{56}Co decays.

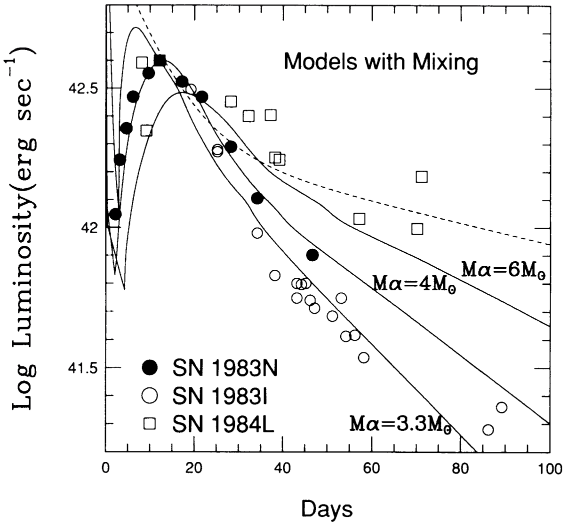

FIG. 2.—Same as Fig. 1 but with *mixed* abundance distribution similar to the model for SN 1987A (Kumagai *et al.* 1989).

For the mixed cases in Figure 2, the light curve shape is significantly different from the unmixed cases:

1. The maximum luminosity is reached ~10 days earlier and thus is higher than in the unmixed cases because of the earlier radioactive heating of the surface layers.

2. The decline of the tail is much faster than the unmixed cases.

Figure 2 shows that the bolometric light curve of the mixed 4 $M_\odot$ model is in excellent agreement with SN 1983N (Panagia 1987) from the premaximum through day 50. The calculated curve for 50–100 days continues to be close to the bolometric light curve obtained by Leibundgut (1988). The light curve of the mixed 3.3 $M_\odot$ model, rising and declining faster than SN 1983N, is in good agreement with SN 1983I. (If mixing occurs, the ejecta would become clumpy and the resultant light curve would decline faster than shown in Fig. 2.)

IV. RAYLEIGH-TAYLOR INSTABILITIES AND MIXING

As shown in the previous section, the helium star models are in good agreement with the observed SN Ib light curves only for the case with extensive mixing of ^{56}Ni. Mixing and clumpiness in SN Ib 1985F are also inferred from the late time emission line features (Fransson and Chevalier 1989; Filippenko and Sargent 1989). Such a mixing has been found in SN 1987A and successfully modeled by the hydrodynamical simulations of the Rayleigh-Taylor instability (Arnett, Fryxell, and Müller 1989; Hachisu *et al.* 1990*a*; Den, Yoshida, and Yamada 1990). To examine whether similar mixing occurs in the exploding helium stars, we have performed a linear stability analysis with the same method as adopted by Ebisuzaki, Shigeyama, and Nomoto (1989; see also Benz and Thielemann 1990).

When the shock wave hits the helium envelope, the expansion of the inner core is largely decelerated, which forms a reverse shock. Then a pressure inversion appears (i.e., the pressure increases outward) in the layer between the forward shock and the reverse shock. The interface between the core and the helium envelope becomes most strongly Rayleigh-Taylor

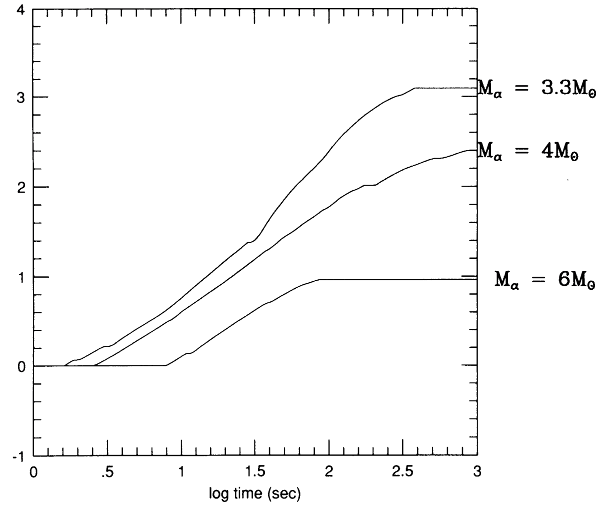

FIG. 3.—Growth of the Rayleigh-Taylor instability (ζ/ζ_0) at the He/C+O interface from the beginning of the explosion for $M_\alpha = 3.3$, 4, and 6 $M_\odot$.

unstable because the density decreases outward most steeply and thus $(dP/dr)(d\rho/dr) < 0$ (see Goodman 1990 for a discussion on the stability criterion in an accelerating compressible fluid).

The instability continues to grow until the forward shock reaches the low-density surface and a rarefaction wave from the surface propagates inward to stabilize the ejecta. Figure 3 shows the time-integrated growth of the initial perturbation ζ_0 at the He/C+O interface

$$\frac{\zeta}{\zeta_0} = \exp\left[\int_0^t \frac{1}{\rho}\left(\sqrt{-\frac{d\rho}{dr}\frac{dP}{dr}}\right)dt'\right] \qquad (1)$$

for $M_\alpha = 3.3$, 4, and 6 $M_\odot$ (see Ebisuzaki, Shigeyama, and Nomoto 1989 for details).

It is seen that the growth of the perturbation is larger for the smaller mass helium star because of the following reasons:

1. For smaller M_α the mass ratio between the helium envelope and the core (excluding the neutron star) is larger (i.e., 2.5, 2.7, 1.0, and 0.45 for $M_\alpha = 3.3$, 4, 6, and 8 $M_\odot$, respectively) so that the deceleration of the core and the pressure inversion are larger.
2. Smaller mass stars have steeper density gradient near the composition interface.
3. The stellar radius is larger for smaller M_α, so that it takes longer for the shock wave to reach the stellar surface and the instability grows for a longer time.

The above linear analysis suggests that a large-scale mixing is more likely to occur for smaller mass helium stars. This has recently been confirmed by the two-dimensional hydrodynamical calculations by Hachisu *et al.* (1990*b*) who have followed the Rayleigh-Taylor instability for $M_\alpha = 3.3$, 4, and 6 $M_\odot$ helium stars (see Nomoto *et al.* 1990 for preliminary results). As expected, the instability leads to only a limited mixing for $M_\alpha = 6$ $M_\odot$, while it does induce a large-scale mixing for $M_\alpha = 3.3$ and 4 $M_\odot$. For $M_\alpha = 3.3$ $M_\odot$, ^{56}Ni is mixed to the layer of 0.4 $M_\odot$ beneath the surface.

V. NUCLEOSYNTHESIS AND THE ^{56}Ni MASS

Nucleosynthesis constraints on the progenitor's mass include the following: (1) SN Ib produce $\sim$0.15 $M_\odot$ ^{56}Ni to attain the observed maximum luminosities, and (2) helium stars with $M_\alpha \sim 6$ $M_\odot$ ($M_{\rm ms} \sim 20$ $M_\odot$) produce $\sim$0.07 $M_\odot$ ^{56}Ni as inferred from SN 1987A. These two constraints imply that possible helium star progenitors of SN Ib must be somewhat more massive or less massive than 6 $M_\odot$. Previous models have shown that smaller mass stars tend to produce smaller ^{56}Ni (Ensman and Woosley 1988), which requires $M_\alpha > 6$ $M_\odot$ for the SN Ib progenitor.

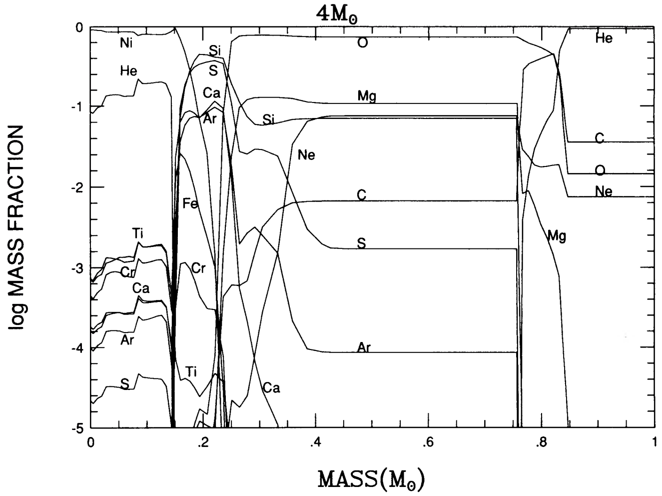

FIG. 4.—Explosive nucleosynthesis in the 4 $M_\odot$ helium star calculated with α-network. Composition of the innermost 1 $M_\odot$ of the ejecta is shown. (The outermost 1.72 $M_\odot$ helium layer and the 1.28 $M_\odot$ neutron star are not included in the figure.) About 0.15 $M_\odot$ ^{56}Ni and 0.43 $M_\odot$ oxygen are produced.

However, our presupernova models have important differences from the previous models, i.e., the iron core masses are as small as 1.18 $M_\odot$ and 1.28 $M_\odot$ for $M_\alpha = 3.3$ $M_\odot$ and 4 $M_\odot$, respectively, so that the Si layers are fairly thick. We have calculated explosive nucleosynthesis in these stars with α-network (see Hashimoto, Nomoto, and Shigeyama 1989 and Thielemann, Hashimoto, and Nomoto 1990 for $M_\alpha = 6$ $M_\odot$). In the hydrodynamical model $M_\alpha = 3.3$ $M_\odot$ (4 $M_\odot$), the layer at $1.18 < M_r/M_\odot < 1.37$ ($1.28 < M_r/M_\odot < 1.44$) undergoes complete Si burning to synthesize mostly ^{56}Ni, and the layer at $1.37 < M_r/M_\odot < 1.45$ ($1.44 < M_r/M_\odot < 1.48$) undergoes incomplete Si burning to produce some ^{56}Ni. The distribution of the nucleosynthesis products for $M_\alpha = 4$ $M_\odot$ is shown in Figure 4. The ^{56}Ni masses are 0.26 and 0.15 $M_\odot$ for $M_\alpha = 3.3$ and 4 $M_\odot$, respectively, which are large enough to account for the SN Ib light curve peak. The oxygen masses are 0.22 and 0.43 $M_\odot$ for $M_\alpha = 3.3$ and 4 $M_\odot$, respectively, and could be consistent with that inferred from the late time spectra because the observed mass is sensitive to the temperature of the ejecta (e.g., Uomoto 1987).

VI. CONCLUSIONS AND DISCUSSION

The main conclusion of the present study is that the observed light curve shape of SN Ib 1983N and 1983I can be well accounted for by the explosions of the 3–4 $M_\odot$ helium stars. The favorite features of this mass range are as follows:

1. Their ejecta masses are 2–3 $M_\odot$ which are small enough to reproduce the relatively fast decline of the light curve if ^{56}Ni is mixed to the surface layers.
2. The large-scale mixing of the ejecta required from the light curves and spectra can be explained by the Rayleigh-

Taylor instability which occurs only for helium stars as small as 3–4 $M_\odot$.

3. Because of the relatively small iron core masses, the 3–4 $M_\odot$ helium stars can produce $\sim$0.15–0.26 $M_\odot$ ^{56}Ni as required from the maximum luminosities.

Our helium star models show a systematic M_α dependence of the light curve shape, the photospheric velocity $v_{\rm ph}$, and the ^{56}Ni mass:

1. Helium stars with smaller M_α undergo more extensive mixing and eject smaller and more clumpy materials, thereby forming light curves with steeper tails.

2. Smaller mass stars produce larger amounts of ^{56}Ni and thus attain higher maximum luminosities.

3. For smaller M_α, the maximum luminosity is reached earlier because of higher expansion velocity and larger radioactive heating. Consequently maximum luminosity is even higher, and $v_{\rm ph}$ near maximum light and its subsequent decrease due to the velocity gradient are larger.

The above mass dependence may correspond to the variation of SN Ib that SN 1983I and 1983V show much weaker helium features than 1983N and 1984L, thereby being called Type Ic supernovae (SN Ic) (Harkness and Wheeler 1990). The light curve models in figure 2 suggest that SN Ic originate from slightly smaller mass helium stars ($M_\alpha \sim 3.3$ $M_\odot$) than SN Ib, thus showing higher maximum luminosities and higher $v_{\rm ph}$. These predictions are consistent with the observations that $v_{\rm ph}$ and its decrease near maximum light is larger in SN 1983V (SN Ic) (Branch 1988; Harkness *et al.* 1987) than in 1983N (SN Ib) (Richtler and Sadler 1983).

For larger M_α, helium stars of $M_\alpha \sim 6$ $M_\odot$ produce too small an amount of ^{56}Ni ($\sim$0.07 $M_\odot$) to be consistent with SN Ib. More massive helium stars might produce a larger amount of ^{56}Ni, but they would not undergo the Rayleigh-Taylor instability. Because of the large ejecta mass and little mixing (and thus little clumpiness), the light curve of such a massive helium star declines slowly; SN 1984L might originate from this mass range (Schlegel and Kirshner 1989).

A single Wolf-Rayet star may reduce its mass by wind down to even $\sim$5 $M_\odot$ (Langer 1989; Maeder 1990). Despite the small mass, however, its light curve may be slower than those of SN 1983N and 1983V because its helium envelope is too thin to induce appreciable mixing or clumpiness is expected. Moreover, its explosion could be faint as suggested to be the case for the progenitor of Cas A.

Since 3–5 $M_\odot$ helium stars form from 12–18 $M_\odot$ stars on the main sequence, our conclusion implies that SN Ib and typical Type II-P supernovae (SN II-P) originate from the similar stellar mass range, where SN Ib are from close binaries while SN II-P are single stars. It is suggestive that the light curve tail of the best observed SN II-P 1969L follows the ^{56}Co decay rate and the inferred ^{56}Ni mass is $\sim$0.13 $M_\odot$ if $H_0 \sim 60$ (Kirshner and Kwan 1974); this is close to the ^{56}Ni mass from SN Ib.

It is interesting to compare SN Ib and SN 1987K which is SN II at early times but later changes into SN Ib, thereby being called SN IIb (Filippenko 1988). The early time spectra of SN 1987K are very similar to SN Ic (1983V and 1987M) except for hydrogen in 1987K (Filippenko 1988; Wheeler and Harkness 1990). The decline of the 1987K light curve is as fast as SN Ia (and thus SN Ic) (Turatto *et al.* 1990). The above similarity suggests that SN 1987K may be the explosion of a low-mass helium star (being probably slightly less massive than SN Ic) formed in a close binary system rather than a massive Wolf-Rayet star. Some hydrogen could be left on the helium star after mass exchange.

In spectroscopic examination of the above hypothesis, non–LTE excitation of hydrogen and helium lines due to mixed radioactive materials would be a key (Branch 1988; Wheeler and Harkness 1990). Differences in relative distribution of H, He, and ^{56}Ni and their amounts after mixing might be related to the spectral differences among SN Ib, Ic, and IIb.

This work has been supported in part by the Japan–US Cooperative Science Program (EPAR-071/88-15999) operated by the JSPS and the NSF. K. N. is grateful to Stan Woosley, Alex Filippenko, Craig Wheeler, Robert Harkness, Doug Swartz, and Dave Branch for stimulating discussion on SN Ib.

REFERENCES

Arnett, W. D., Fryxell, B. A., and Müller, E. 1989, *Ap. J. (Letters)*, **341**, L63.
Begelman, M. C., and Sarazin, C. L. 1986, *Ap. J. (Letters)*, **302**, L59.
Benz, W., and Thielemann, F.-K. 1990, *Ap. J. (Letters)*, **348**, L17.
Branch, D. 1988, in *IAU Colloquium 108, Atmospheric Diagnostics of Stellar Evolution*, ed. K. Nomoto, *Lecture Notes in Physics*, **305**, 281.
Branch, D., and Nomoto, K. 1986, *Astr. Ap.*, **164**, L13.
Chevalier, R. A., and Plait, P. C. 1988, *Ap. J. (Letters)*, **331**, L109.
Den, M., Yoshida, T., and Yamada, Y. 1990, preprint (KUNS1004).
Ebisuzaki, T., Shigeyama, T., and Nomoto, K. 1989, *Ap. J. (Letters)*, **344**, L65.
Ensman, L., and Woosley, S. E. 1988, *Ap. J.*, **333**, 754.
Filippenko, A. V. 1988, *A.J.*, **96**, 1941.
Filippenko, A. V., and Sargent, W. L. W. 1989, *Ap. J. (Letters)*, **345**, L43.
Fransson, C., and Chevalier, R. A. 1989, *Ap. J.*, **343**, 323.
Gaskell, C. M., Cappellaro, E., Dinerstein, H. L., Garnett, D. R., Harkness, R. P., and Wheeler, J. C. 1986, *Ap. J. (Letters)*, **306**, L77.
Goodman, J. 1990, *Ap. J.*, **358**, 214.
Hachisu, I., Matsuda, T., Nomoto, K., and Shigeyama, T. 1990*a*, *Ap. J. (Letters)*, **358**, L57.
———. 1990*b*, *Ap. J. (Letters)*, submitted.
Harkness, R. P., and Wheeler, J. C. 1990, in *Supernovae*, ed. A. Petschek (Springer-Verlag), p. 1.
Harkness, R. P., *et al.* 1987, *Ap. J.*, **317**, 355.
Hashimoto, M., Nomoto, K., and Shigeyama, T. 1989, *Astr. Ap.*, **210**, L5.
Kirshner, R. P., and Kwan, J. 1974, *Ap. J.*, **193**, 27.
Kumagai, S., Shigeyama, T., Nomoto, K. Itoh, M., Nishimura, J., and Tsurita, S. 1989, *Ap. J.*, **345**, 412.
Langer, N. 1989, *Astr. Ap.*, **220**, 135.
Leibundgut, B. 1988, Ph.D. thesis, University of Bäsel.
Maeder, A. 1990, *Astr. Ap. Suppl.*, in press.
Nomoto, K. 1982, *Ap. J.*, **257**, 780.
Nomoto, K., and Hashimoto, M. 1988, *Phys. Rept.*, **163**, 13.
Nomoto, K., and Shigeyama, T. 1990, in *Supernovae*, ed. S. E. Woosley (Springer-Verlag), in press.
Nomoto, K., Shigeyama, T., and Hashimoto, M. 1988, in *IAU Colloquium 108, Atmospheric Diagnostics of Stellar Evolution*, ed. K. Nomoto, *Lecture Notes in Physics*, **305**, 319.
Nomoto, K., Shigeyama, T., Kumagai, S., and Hashimoto, M. 1988, *Proc. Astr. Soc. Australia*, **7**, 490.
Nomoto, K., Shigeyama, T., Yanagita, S., Hayakawa, S., and Yasuda, K. 1990, in *Chemical and Dynamical Evolution of Galaxies*, ed. F. Ferrini, J. Franco, and F. Matteucci (Pisa: Giondini), in press.
Panagia, N. 1987, in *High Energy Phenomena Around Collapsed Stars*, ed. F. Pacini (Dordrecht: Reidel), p. 33.
Richtler, T., and Sadler, E. M. 1983, *Astr. Ap.*, **128**, L3.
Schaeffer, R., Cassé, M., and Cahen, S. 1987, *Ap. J. (Letters)*, **316**, L31.
Schlegel, E. M., and Kirshner, R. P. 1989, *A.J.*, **98**, 577.
Shigeyama, T., and Nomoto, K. 1990, *Ap. J.*, **360**, 242.
Shigeyama, T., Nomoto, K., and Hashimoto, M. 1988, *Astr. Ap.*, **196**, 141.

Sramek, R. A., Panagia, N., and Weiler, K. W. 1984, *Ap. J.* (*Letters*), **285**, L59.
Thielemann, F.-K., Hashimoto, M., and Nomoto, K. 1990, *Ap. J.*, **349**, 222.
Tsvetkov, D. Yu. 1985, *Soviet Astr.*, **29**, 211.
Turatto, M., Cappellaro, E., Barbon, R., Della Valle, M., Ortolani, S., and Rosino, L. 1990, *A.J.*, in press.
Uomoto, A. 1987, *Ap. J.* (*Letters*), **310**, L35.
Wheeler, J. C., and Harkness, R. 1990, *Phys. Rept.*, in press.
Wheeler, J. C., and Levreault, R. 1985, *Ap. J.* (*Letters*), **294**, L17.
Woosley, S. E., Taam, R. E., and Weaver, T. A. 1986, *Ap. J.*, **301**, 601.

KEN'ICHI NOMOTO, TOSHIKAZU SHIGEYAMA, and TAKUJI TSUJIMOTO: Department of Astronomy, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan

MASA-AKI HASHIMOTO: Department of Physics, College of General Education, Kyushu University, Fukuoka 810, Japan