THE ORIGIN OF TYPE IB-IC-IIB-IIL SUPERNOVAE AND BINARY STAR EVOLUTION

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Abstract. Supernovae are classified as type I and type II and further subdivided into Ia, Ib, Ic, II-P, II-L, and IIb. The origin of this observational diversity has not been well understood. The recent nearby supernovae SN 1993J and SN 1994I have provided particularly useful material to clarify the supernova - progenitor connection. For a progenitor of type IIb supernova 1993J, we propose that merging of two stars in a close binary is responsible for the formation of a thin H-rich envelope. As a progenitor of type Ic supernova 1994I, we propose a bare C+O star that has lost both its H and He envelope after a common-envelope phase. By generalizing these scenarios, we show that common-envelope evolution in massive close binary stars leads to various degrees of stripping off of the envelope of a massive star. This naturally leads to an explanation of the origin of type II-L, IIn, IIb, Ib, and Ic in a unified manner. The binary hypothesis to explain the diversity of supernovae can be substantiated with new information on SN IIb 1993J and SN Ic 1994I. Model light curves are compared with observations. Since extensive mass loss is essential for the binary scenario, circumstellar interactions are examined for comparison with X-ray observations.

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1. Introduction

Supernovae are classified as type I and type II according to the absence or presence of hydrogen lines in their spectra, and further subdivided into Ia, Ib, Ic, II-P, II-L, IIb, and IIn (e.g., Branch *et al.* 1991; Filippenko 1991). The presence of strong Si lines and He lines defines type Ia and type Ib, respectively, while type Ic is characterized by the lack or weakness of these lines. The light curves of type II-P supernovae (SNe II-P) have a plateau, while those of type II-L (SNe II-L) show a linear decline.

It has been suggested that the diversity of SNe II originates from the progenitor's different main-sequence mass ranges, i.e., SNe II-L from 7–10 $M_\odot$ (Swartz *et al.* 1991) and above 10 $M_\odot$ SNe II-P, and that type Ib/Ic supernovae (SNe Ib/Ic) originate from He stars of different mass range in binary systems (Nomoto *et al.* 1990). However, the exact supernova - progenitor connection for these types has been a controversial issue.

The recent nearby supernovae, SN 1993J in M81 and SN 1994I in M51, have been identified as type IIb (SN IIb) (e.g., Schmidt *et al.* 1993) and type Ic (e.g., Wheeler *et al.* 1994), respectively, adding more diversity of supernovae (i.e., IIb) but shedding new light on the classification and their evolutionary origins. Here we show that common-envelope evolution in massive close binary stars can provide a plausible explanation of the observational diversity.

For SN Ic 1994I, we will discuss a C+O star progenitor model, with three possible evolutionary paths to form it (Section 2). Light curves are particularly useful probes to discriminate the progenitor's mass (Section 3). For SN IIb 1993J, we propose that merging of two stars in a close binary is responsible for the formation of a thin H-rich envelope of the progenitor, as opposed to the conservative mass transfer scenario (Section 4). We then generalize the binary scenario to show that common-envelope evolution in massive close binary stars leads to various degree of stripping off of the envelope mass of massive star. This naturally explains the origin of supernova types, namely, II-L, IIb, Ib, and Ic, in a unified manner, depending on the mass ratio q of component stars and the initial separation R_0 (Section 4).

Another clue to the understanding of the nature of these nearby supernovae in relation to the binary hypothesis is the extensive mass loss from progenitors to form dense circumstellar matter. Circumstellar interactions are studied using a realistic ejecta model of SN 1993J to compare with X-ray observations (Section 5).

2. Progenitors of type Ic Supernovae

At the time of explosion, progenitors of SNe Ib/Ic have lost their hydrogen-rich envelope, and most of the helium envelope as well for SNe Ic. Two cases are possible (Wheeler & Harkness 1990): (1) stellar wind in Wolf-Rayet stars and (2) Roche lobe overflow in binary stars. Both these cases may actually occur as SNe Ib since SNe Ib light curves show a significant diversity from slow to fast decline.

For SNe Ic, however, earlier models have some difficulties to account for the observations. (1) WC/WO Wolf-Rayet stars are so massive that the light curve declines too slowly (Woosley *et al.* 1993). (2) Low-mass helium star models in binaries (Shigeyama *et al.* 1990; Nomoto *et al.* 1990; Woosley *et al.* 1995) have too much helium to be consistent with the lack of He features in the spectra of type Ic SN 1987M (Filippenko *et al.* 1990; Lucy 1991; Swartz *et al.* 1993).

These difficulties have led to the suggestion that C+O stars which have lost even their He envelope are the progenitors of SNe Ic (Yamaoka *et al.* 1993; Swartz *et al.* 1993). In a massive binary, a bare C+O star can form after two stages of mass transfer (Bhattacharya & Van den Heuvel 1991). The first mass transfer occurs when the more massive star has formed a helium core, and its envelope expands to fill the Roche lobe. The H-rich envelope is lost and a helium star is produced. After core He burning, the helium star expands and may again fill its Roche lobe, depending on its mass M_α. This second mass transfer is more likely to occur for lower mass helium stars because they attain larger radii (Habets 1986); for example, the maximum radii of helium stars with $M_\alpha = 3.3$, 4.0, 6.0, and 8.0 $\mathrm{M}_\odot$ are 3.7, 3.0, 1.9, and 1.3 $\mathrm{R}_\odot$, respectively (Nomoto & Hashimoto 1988), while helium stars less massive than 2.7 $\mathrm{M}_\odot$ even expand to red giant dimensions (Habets 1986).

In case the second mass transfer occurs to a more massive companion, mass transfer will be conservative (i.e., most of the transferred mass is accreted by the companion), and the He star probably retains part of its envelope. On the other hand, if the companion is less massive, the helium star may lose its entire envelope and produce a bare C+O star. The following three different evolutionary paths (A, B, C) are possible for the formation of C+O stars as illustrated in Fig. 1.

Path A: Initially, the binary system consists of star 1 and star 2 whose main-sequence masses are $M_1 \approx 11$–$16\,\mathrm{M}_\odot$ and $M_2 \approx 1$–$4\,\mathrm{M}_\odot$, respectively, i.e., their mass ratio q is between ~0.1 and ~0.25. Because of the extreme mass ratio, the first mass transfer is highly non-conservative. This almost inevitably leads to the formation of a common envelope (Van den Heuvel 1994) and the subsequent spiral-in (Pols *et al.* 1991) of star 2 and the core of star 1. In many cases, the spiral-in causes the stars to merge into a single star, but if the initial orbital separation is large enough, the binary system probably survives the spiral-in. It then consists of helium star 1 of 2.2–4 $\mathrm{M}_\odot$ and main-sequence star 2

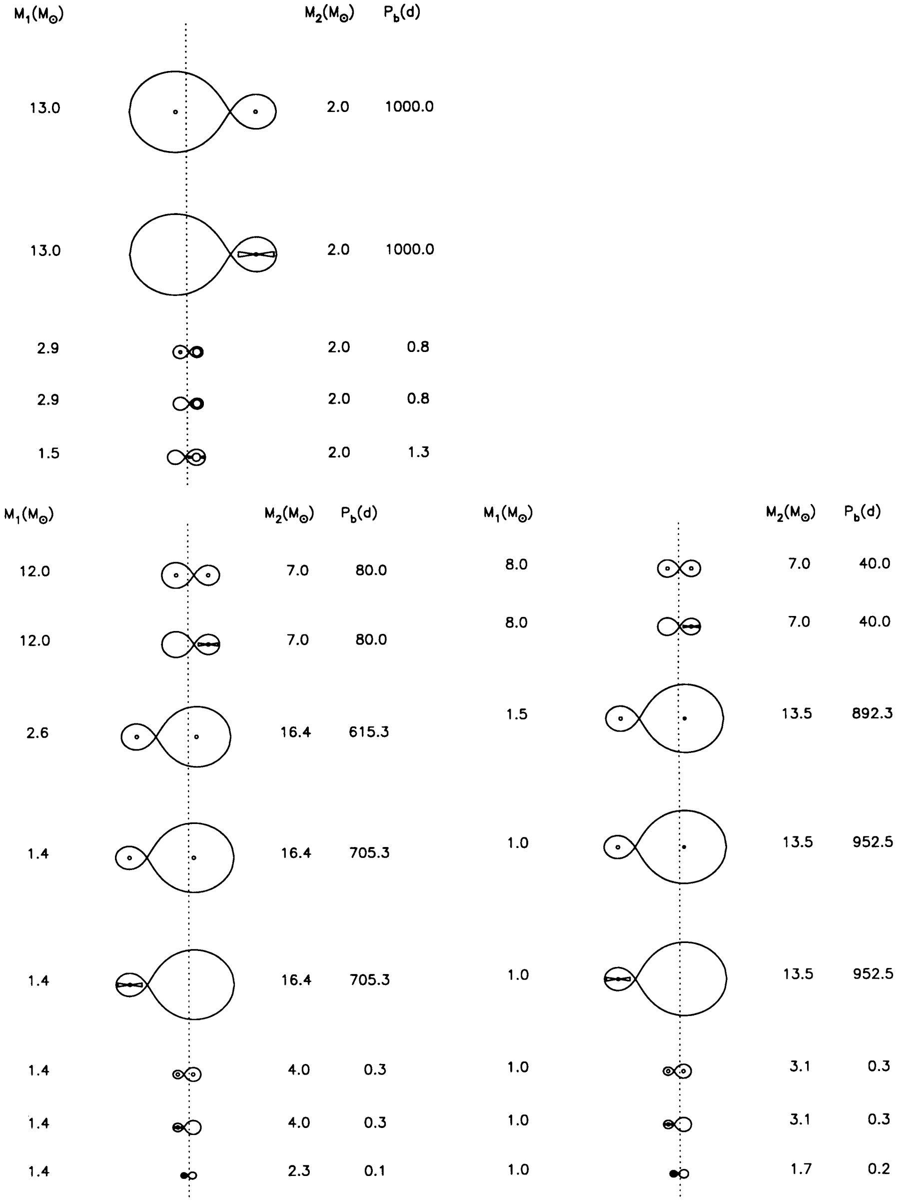

Figure 1. Schematic overview of evolutionary paths leading to the formation of bare C+O stars (see text): Path A with a 2.0 $M_\odot$ main-sequence companion (upper), Path B with a 1.4 $M_\odot$ neutron star comparnion (lower left), and Path C with a 1.0 $M_\odot$ white dwarf companion (lower right). Evolutionary changes in the masses and orbital period are shown.

of 1–4 $M_\odot$, in a much closer orbit. Helium star 1 subsequently expands and undergoes a second, non-conservative mass transfer onto star 2, losing its He envelope. Star 1 then becomes an almost bare C+O star with a low-mass main-sequence companion.

Path B: Initially star 1 is massive enough to evolve through core collapse ($M_1 \gtrsim 11\,M_\odot$), leaving a neutron star. The initial mass ratio is not too small, $q \gtrsim 0.4$, so that mass transfer from star 1 to star 2 is quasi-conservative and star 2 becomes more massive than 11 $M_\odot$. Star 2 subsequently evolves to fill its Roche lobe. Since star 1 is a compact star and is much less massive than star 2, it will inevitably spiral into the envelope of star 2. Like in Path A, the binary may either merge, or it may survive the spiral-in. The resulting binary system then consists of helium star 2 of 2.2–4 $M_\odot$ and compact star 1 of 1.4 $M_\odot$ in a close orbit. Helium star 2 expands to fill its Roche lobe and undergoes another non-conservative mass transfer to star 1. This leads to the formation of C+O star 2 and a neutron star companion.

Path C: Initially star 1 has a mass in the range ~6–11 $M_\odot$ and becomes a C+O or ONeMg white dwarf. The initial mass ratio is close to unity, so that the mass transfer from star 1 to star 2 is almost conservative, and star 2 becomes more massive than 11 $M_\odot$. Further evolution is similar to Path B since star 1 is a compact white dwarf. Star 2 inevitably undergoes non-conservative mass transfer to star 1 twice and becomes a bare C+O star with a white-dwarf companion.

Fig. 2 shows the second mass transfer in Path B, i.e., evolutionary tracks in the H-R diagram of 4 $M_\odot$ helium star binaries with a 1.4 $M_\odot$ neutron star companion (Pols *et al.* 1994). Here the solid, dashed, and dotted lines show the cases for a single He star, $P_{\rm orb} = 0.3$ d, and $P_{\rm orb} = 0.1$ d, respectively. The tracks have been computed with non-conservative mass transfer; the ejected mass is assumed to leave the system via a jet or symmetric wind from the neutron star. The calculations terminate at central carbon ignition. Mass transfer in the $P_{\rm orb} = 0.3$ d system is stable (on a thermal time scale), but becomes unstable in the 0.1 day system after transfer of a few tenths of a solar mass. The mass transfer rate in the 0.3 day system is $\sim 10^{-5}\,M_\odot\,{\rm yr}^{-1}$. The final mass of the He star in the 0.3 day system is 2.7 $M_\odot$ with the CO core mass being 2.24 $M_\odot$. It seems likely that part or all of the remaining 0.46 $M_\odot$ of He envelope can be transferred during carbon burning, leaving an almost bare C+O star remnant.

The C+O star thus formed through these paths explodes as a SN Ic. If a substantial He envelope is retained in the second mass transfer, the explosion would be a SN Ib. For the latter case of SNe Ib, the ejected mass is significantly smaller than that for the >5 $M_\odot$ He star model, thereby forming a light curve with steeper decline. In this scenario, the spectroscopic

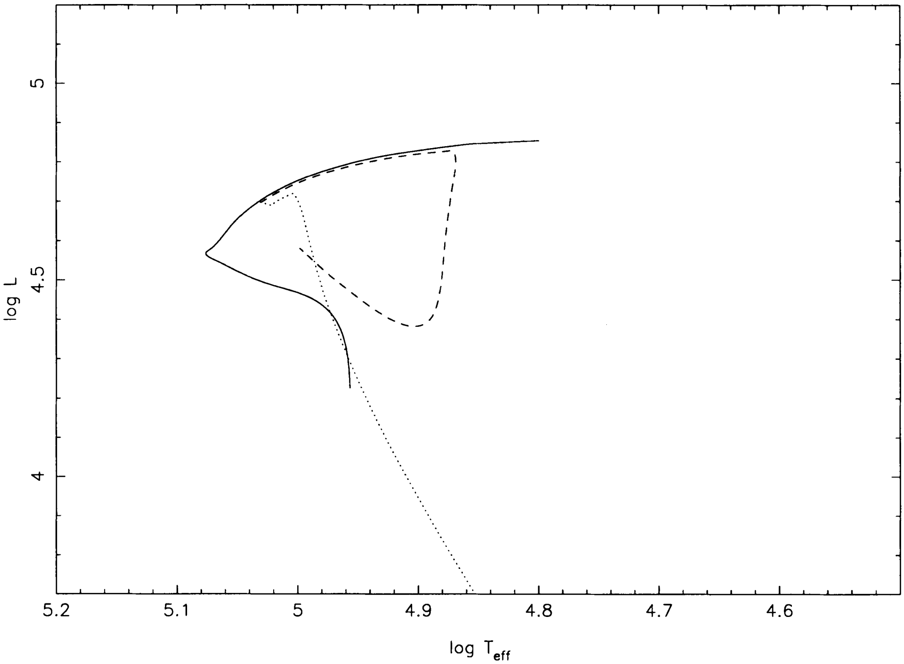

Figure 2. The second mass transfer in Path B, i.e., evolutionary tracks in the H-R diagram of 4 $M_\odot$ helium star binaries with a 1.4 $M_\odot$ neutron star companion (Pols *et al.* 1994). Shown are the cases for a single He star (solid line), $P_{\rm orb} = 0.3$ d (dashed line), and $P_{\rm orb} = 0.1$ d (dotted).

and photometric features of SNe Ib and SNe Ic are predicted to form a continuous sequence rather than distinct phenomena.

The explosion of a C+O star is likely to leave a neutron star behind. Unless a kick velocity is too high, the binary system would survive because of the small ejecta mass. A companion of the neutron star would be a low mass main-sequence star, a C+O white dwarf, or a neutron star in a short and eccentric orbit.

The formation rate of C+O stars and the resultant SN Ic rate from the above paths may be estimated as follows. We use an initial mass function $\Psi(m) \propto m^{-2.7}$ and a q-distribution $\Phi(q) = 2\ (1+q)^{-2}$. We estimate the probability S that the binary survives after the spiral-in without merging to be $S \sim 0.25$ (path A) and 0.5 (paths B and C) from the relative range of initial separations. The fraction of binaries that evolve conservatively as a function of primary mass is taken from Pols *et al.* (1991). We then obtain the relative rates of type Ic with respect to type II supernovae as ~0.015 (path A), 0.025 (B), and 0.065 (C) for a close binary fraction of 0.5. Note that Path C is the most important channel, mainly due to the shape of the initial mass function. In total, the expected type Ic frequency is ~0.1 times that of SNe II. This is probably consistent with the observed relative ratio between SNe Ic and SNe II, if SN Ib and SN Ic rates are comparable (van den Bergh 1991; see, however, Muller *et al.* 1992).

3. Light Curve Models for SN Ic 1994I

We apply the above scenario to SN Ic 1994I. The simplest evolutionary path is as follows. The progenitor was a 13–18 $M_\odot$ star on the main sequence. Through Roche lobe overflow the 13, 15, and 18 $M_\odot$ stars became He stars with $M_\alpha = 3.3$, 4.0, and 5.0 $M_\odot$ and then lost their helium envelopes to become C+O stars with $M_{C+O} = 1.8$, 2.1, and 2.9 $M_\odot$. Hereafter these models are called CO18, CO21, and CO29, respectively (Nomoto *et al.* 1994).

The mass cut is chosen to produce 0.07 $M_\odot$ of ^{56}Ni. The deposited energy is set to produce the kinetic energy of explosion $E = 10^{51}\,\mathrm{erg\,s^{-1}}$ for CO18, CO21, and CO29, and $E = 6\ 10^{51}\,\mathrm{erg\,s^{-1}}$ for the lower explosion energy model CO21L. It is noticeable that the ejecta masses of $M_{\rm ej} = 0.5$ and 0.9 $M_\odot$ for CO18 and CO21 are significantly smaller than the Chandrasekhar mass. Even for CO29, $M_{\rm ej}$ is still as small as 1.5 $M_\odot$ (Hashimoto *et al.* 1993).

Since the C+O star is compact with a radius of ~0.2 $R_\odot$, the light curve is not due to shock heating but is powered by the radioactive decay chain $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$. For a detailed comparison with observations, monochromatic light curves for the C+O star models have been calculated and are compared with observations (Schmidt & Kirshner 1994) in Fig. 3. The slopes of the calculated light curves are found to be sensitive to the models as follows:

CO18: Both the rise time and the decline are far too short compared with the observations. The main cause is that the diffusion time scales in the envelope are too short, suggesting the need for a more massive model to increase the diffusion time scale and, consequently, to produce a broader and flatter maximum.

CO21 : This model gives almost perfect agreement between the slopes of the theoretical and observed shapes of the light curves for the monochromatic B, V, R and I band and the bolometric light curve as well (Iwamoto *et al.* 1994). This means that the diffusion time scales, the energy input and the temperature structure are about correct. From the light curve fits, a distance modulus of 29.2 ± 0.3 mag is derived for M51. Also a high interstellar reddening, $E(B-V) = 0.45$

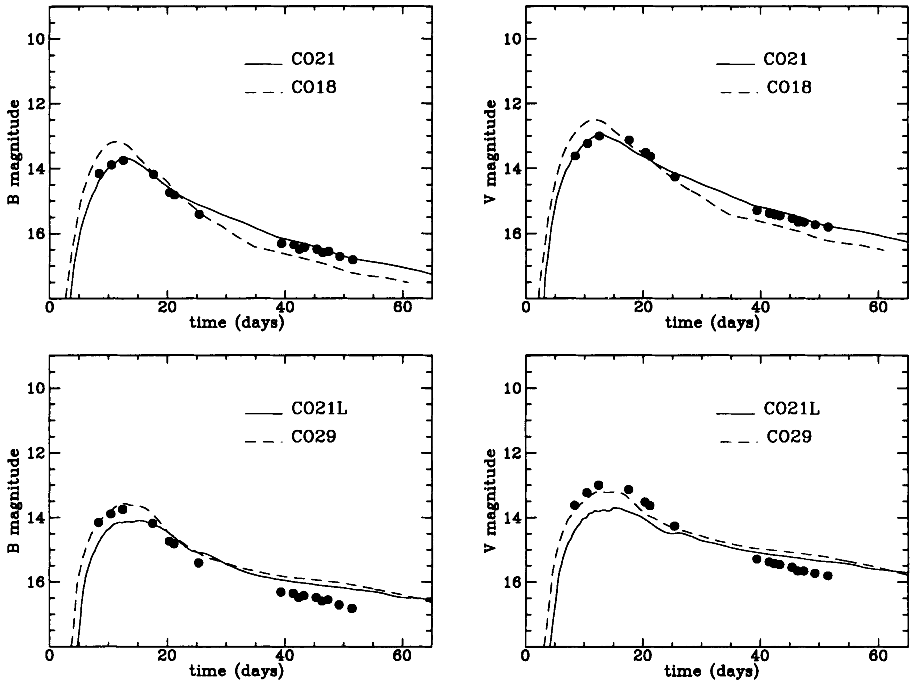

Figure 3. Theoretical monochromatic light curves for models CO18, CO21, CO29, and CO21L (Iwamoto *et al.* 1994), in comparison with observations of SN 1994I (Schmidt & Kirshner 1994).

$(A_V \sim 1.4\,\mathrm{mag})$ is required. The ejected ^{56}Ni mass is found to be $0.07^{+0.035}_{-0.025}\,M_\odot$.

CO29 : The photosphere recedes nicely at maximum light. At later times, however, the light curve declines too slowly because the escape probability changes only little with time due to the lower expansion velocities compared with CO21.

CO21L : Due to the small expansion rate, the escape probability for γ rays is significantly higher than for CO21. This keeps the photosphere hot, i.e., the opacity hardly drops at maximum light and, consequently, the maximum is not well pronounced compared to CO21. At later times, the decline of the light curve is too slow for the same reasons as for CO29.

Wolf-Rayet star models are clearly too massive to be consistent with the light curves of SN 1994I, because even the smallest WC star model has $2.7\,M_\odot$ of ejecta (Woosley *et al.* 1993), which is significantly more massive than the $1.5\,M_\odot$ for CO29.

However, the late time oxygen line emissions of SN1994I suggest that models with somewhat lower expansion rates than CO21 are favored (Fransson 1994). Such slower models CO29 and CO21L are not consistent with the light curve, however. Mixing of ^{56}Ni would lead to a faster decline of the light curves for these models. Large scale mixing due to Rayleigh-Taylor instabilities may not be expected for these C+O star models because of the lack of both H and He layers and the associated density jumps (Hachisu *et al.* 1991). If the expansion should certainly be slower than for CO21, a new mechanism of mixing is required unless the star has a rather massive He envelope.

4. Progenitor of SN 1993J

SN 1993J has revealed important new features of supernovae [see Wheeler & Filippenko (1994) for a review and references]. It has been identified as a type II supernova (SN II) from hydrogen features. The light curve of SN 1993J is distinctly different from those of previously known SNe II. It was obvious that this peculiar light curve of SN 1993J cannot be accounted for by an explosion of an ordinary red supergiant (RSG) with a massive hydrogen-rich envelope, which produces a light curve of a SN II-P (Nomoto *et al.* 1993).

As will be described in Section 3, the light curve of SN 1993J can be understood as the explosion of an RSG whose hydrogen-rich envelope is as small as $\lesssim 1\,M_\odot$ (Nomoto *et al.* 1993; Podsiadlowski *et al.* 1993). The thin-envelope model has been confirmed by the spectral changes which shows growing features of helium and oxygen, so that SN 1993J can be classified as a SN IIb (Woosley *et al.* 1988; Filippenko *et al.* 1988).

The progenitor of SN 1993J is likely to have lost most of its H-rich envelope due to the interaction with its companion star in a binary system. The binary scenario raised the following questions: (1) what controls the mass of the remaining H-rich envelope of the progenitor, and (2) what is the relation of SN 1993J with other types of supernovae, such as SNe IIn, II-L and Ib/Ic.

4.1. CONSERVATIVE MASS TRANSFER SCENARIO

As a possible evolutionary scenario leading to the progenitor of SN 1993J, a *Case C* binary evolution has been proposed (Podsiadlowski *et al.* 1993; Woosley *et al.* 1994; Ray *et al.* 1993). This scenario postulates that (1) the initial separation between the two component stars is so large that the mass transfer from the progenitor started only after helium was exhausted in the core, and (2) mass ratio $q = M_1/M_2$ between the progenitor 1 and the companion star 2 is close to unity, so that the mass transfer from the progenitor is more or less conservative.

In Case C mass transfer, however, the primary star has a convective envelope, thereby transferring mass to the companion star on a dynamical time scale, at least in its early phase. Such an evolution is described by assuming the non-dimensional specific angular-momentum loss from the system α and the ratio β between the mass accreted by star 2 and the mass lost by star 1 as arbitrary parameters (Podsiadlowski *et al.* 1992; Rathnasree & Ray 1992). It is seen that, even for $q < 1$ and $\beta \sim 1$, the radius of the mass donor exceeds the Roche lobe. Nevertheless the response of the companion star or the formation of the common envelope was not calculated, i.e., there has been no consistent set of calculations of both the dynamical mass loss from the progenitor and the response of mass receiving companion. Thus it is possible that even if q is initially smaller than 1 due to earlier wind mass loss from star 1, Case C mass transfer leads quickly to the formation of a common envelope. Thus, although the Case C scenario may be possible for a narrow parameter space, an alternative scenario is worth exploring.

4.2. NON-CONSERVATIVE MASS TRANSFER SCENARIO

Evolutionary paths of close binaries depend significantly on the mass ratio q of component stars and the initial separation R_0. Here we consider binary systems consisting of star 1 and star 2 whose main-sequence mass ratio q is significantly smaller than unity. Star 1 evolves to form a He core and its H-rich envelope expands to fill its Roche lobe. Because of the extreme mass ratio, the mass transfer is highly non-conservative. This almost inevitably leads to the formation of a common envelope and the subsequent spiral-in of star 2 and the core of star 1.

The spiral-in deposits the orbital energy in the envelope due to viscous evolution. Subsequent-common envelope evolution is so complicated that we take a simplified approach. From energy considerations, we assume that spiral-in yields the following outcome.

1. If the deposited orbital energy, E_g, is larger than the binding energy of the common envelope, E_b, almost all envelope material is ejected before star 2 is dissolved. In other words, the binary system survives the spiral-in and then consists of helium star 1 and main-sequence star 2 in a much closer orbit. Since E_g is larger for larger R_0, this case occurs when R_0 is larger than a certain limit. (Here the time scale is so short that radiation loss is negligible.)
2. If $E_g < E_b$, on the contrary, the two stars merge into a single star, i.e., star 2 is completely dissolved in the common envelope before all

the envelope mass is ejected. The resulting single star 1 retains some envelope material. The envelope mass $M_{\rm env}$ after merging depends on the deposited energy $E_{\rm g}$ relative to $E_{\rm b}$. Larger $E_{\rm g}/E_{\rm b}$ induces larger amount of mass loss and forms a lower-mass envelope when the merging is completed. In terms of R_0, such a merging occurs when R_0 is smaller than a certain limit. The remaining envelope mass is smaller for larger R_0. Afterwards star 1 would expand to become an RSG but its $M_{\rm env}$ could be significantly smaller than, say, $5\,{\rm M}_\odot$.

The non-conservative scenario predicts the formation of a single neutron star, in contrast to the binary neutron star (in an eccentric orbit) predicted by the conservative mass transfer scenario.

5. Supernova Types and Merging

Based on the above spiral-in scenarios 1 and 2, we can present a new interpretation of the origin of various types of supernovae, in particular IIb, II-L, and IIn.

1. **SN Ib:** In this case, the spiral-in forms a pair of helium star 1 and main-sequence star 2. If the helium star mass exceeds $\sim 2.5\,{\rm M}_\odot$, it evolves through Fe core collapse and explodes as a SN Ib because of the presence of helium (e.g., Ensman & Woosley 1988; Shigeyama *et al.* 1990).
   SN Ic: If the mass of helium star 1 is smaller than $\sim 5\,{\rm M}_\odot$, its helium envelope expands possibly to exceed the Roche lobe (Habets 1986; Nomoto & Hashimoto 1988). After the loss of the helium envelope, star 1 becomes a C+O star. The explosion of the C+O star is triggered by Fe core collapse and must be observed as a SN Ic.
2. In this case, the two stars merge to form a single core and lose a significant fraction of their common envelope due to frictional heating. Unless the envelope mass becomes as small as $10^{-2}\,{\rm M}_\odot$, the envelope of the merged star should expand to an RSG size. If the helium core mass exceeds $\sim 2.5\,{\rm M}_\odot$, a supernova explosion is triggered by Fe core collapse and observed as a type II. We propose that the progenitors of IIb, II-L, and possibly IIn are these merged stars and the difference in the types originates from the difference in the mass of the H-rich envelope $M_{\rm env}$ as follows.
   SN IIb: If $M_{\rm env} \lesssim 1\,{\rm M}_\odot$, the pre-supernova configuration would be similar to that of SN 1993J. Their light curves around the second peak and tails must be similar to SNe Ib (Section 5). SN 1993J continues to exhibit strong Hα emissions, while SN 1987K (also IIb, see Filippenko 1988) did not show H-emission lines at late phase. Late time Hα emission in SN 1993J is powered by X-rays from circumstellar interaction

(Section 6, Clocchiatti & Wheeler 1994). Further study is needed to understand whether such a difference stems from the difference in $M_{\rm env}$ (and thus density structure) or in the circumstellar matter density (or some other parameters).

SN II-L: If $M_{\rm env} \sim 2$–$3\,{\rm M}_\odot$, the radius of the RSG is as large as that of an ordinary RSG. However, because $M_{\rm env}$ is small, the expansion velocity at the bottom of the H-rich envelope is higher. This leads to a shorter duration of the plateau, i.e., SN II-L (e.g., Shigeyama & Nomoto 1990; Swartz *et al.* 1991; Blinnikov & Bartunov 1993).

SN IIn: If the envelope mass remains as large as $M_{\rm env} \gtrsim 5\,{\rm M}_\odot$ possibly due to the large initial mass of star 1, the star becomes an ordinary RSG after merging. It eventually explodes as a SN II-P. However, its CSM would consist of the material ejected during spiral-in and the RSG wind material. The structure of CSM originating from spiral-in is likely to be asymmetric; the mass ejection may form a bipolar jet or disk like material. The mass loss rate during the RSG phase could be larger than for an ordinary RSG because of the larger mass and extra heating due to merging. This case might correspond to SN IIn, like SN 1988Z (e.g., Filippenko 1991).

6. Circumstellar Interaction in SN 1993J

The merging model for the progenitor of SN 1993J predicts the presence of (probably) asymmetric outer circumstellar matter (CSM) formed through a merging process and more symmetric inner CSM formed by the wind from the red supergiant.

Suzuki *et al.* (1995) have constructed a hydrodynamical model of interaction between the ejecta of SN 1993J and CSM to account for the basic features of X-ray emissions from SN 1993J as observed with OSSE, ASCA, and ROSAT for the first 570 days (also Fransson *et al.* 1994). This model consists of a realistic ejecta model and clumpy CSM.

The collision between the ejecta and CSM creates a reverse shock which is radiative, to form a cooling dense shell in the ejecta. X rays emitted from the reverse shock are mostly absorbed by this shell. Early hard X rays are well modeled as thermal emissions from shocked CSM. The CSM density inferred from X-ray observations is as high as $\dot{M}/v_w = (3$–$4)\ 10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}/(10\,{\rm km\,s}^{-1})$ which is rather high compared with the mass loss rate estimated for the 13–15 ${\rm M}_\odot$ model. In the merging progenitor model, this problem could be resolved because mass loss rate can be enhanced due to extra heating in the envelope produced by merging.

The above model indicates that CSM has a spatially variable density gradient. In the inner layer, the gradient has to be shallower than that of

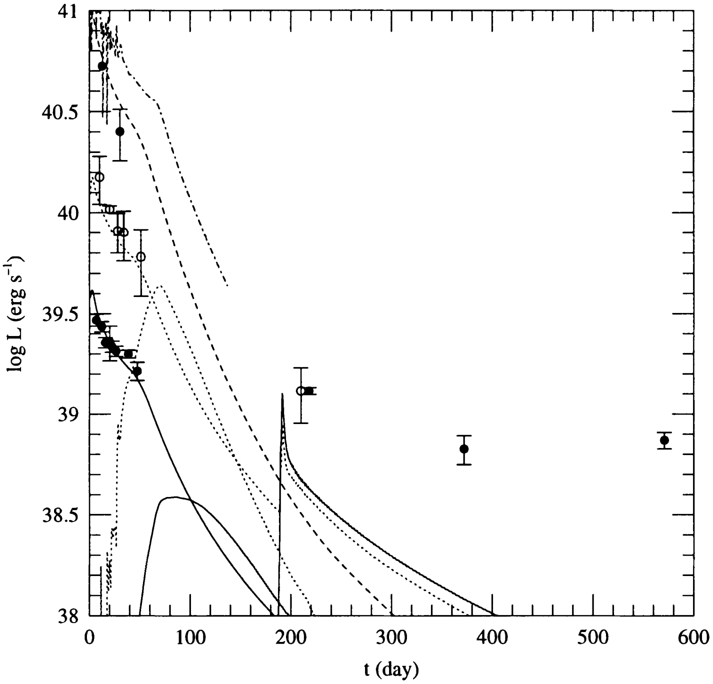

Figure 4. Calculated X-ray light curves in the 0.1–2.4 keV (solid), 1–10 keV (dotted), and 50–150 keV (dashed) bands, which are compared with observations with ROSAT, ASCA (open circles), and OSSE, respectively. The upper three lines which decline monotonically after day 6 show the homogeneous CSM components, while the lower two lines (solid and dotted) show the ejecta components that escape from being absorbed by the dense shell. The total luminosity of X-rays emitted from the ejecta is shown by the dash-dotted curve through day 140. Faster decline from day 50 is due to the steeper density gradient of homogeneous CSM. The sudden increase around day 190 is due to the collision with a spherical thin shell clump.

a steady wind to be consistent with the slow decline of the 0.1–2.4keV light curve. In the outer layers, CSM is highly clumpy so that the density gradient of inter-clump matter is steeper. Soft X-rays at late times are mostly emitted from the shocked high density clumps as seen in Fig. 4 (see legend).

The clumpy circumstellar structure can account for other important features of SN 1993J as well (Van Dyk *et al.* 1994). In particular, the steep density gradient of inter-clump matter leads to weak deceleration of the ejecta and shocked CSM, i.e., the expansion velocities of the shocked ejecta and CSM decrease only slowly. This is consistent with (i) a roughly constant maximum velocity of hydrogen ($\sim$10 000 km s^{-1}) as observed in Hα features (Patat *et al.* 1995; Fransson 1994), and (ii) the average expansion velocity of the radio shell over 240 days, which is as high as 15 000±2 000 km s^{-1} for a distance of 3.63±0.34 Mpc (Marcaide *et al.* 1995).

In the non-conservative binary evolution scenario for the progenitor of SN 1993J (Nomoto *et al.* 1994, 1995) clumpy CSM could form as follows. Firstly the spiral-in of a companion star into the progenitor leads to the ejection of a common envelope. Later stellar-wind material from the red supergiant progenitor would collide with previously ejected common-envelope matter. As a result of the deceleration of wind matter, the wind velocity would be lower at a larger distance, i.e., the density gradient would be shallower than for a steady wind, and CSM would be more clumpy as it is closer to the common-envelope matter. This model predicts the collision of the blast shock wave with former common-envelope matter, which would lead to some enhancement of soft X-ray fluxes and relatively low-velocity Hα emissions; this might correspond to the latest ROSAT observations showing recent leveling off of the X-ray flux (Zimmermann *et al.* 1994) and the HST observations of Hα features suggesting a collision with ring-like matter (Kirshner 1994).

Another future event would be an enhancement of X-ray fluxes when the reverse shock reaches the H/He interface where the density sharply increases (Shigeyama *et al.* 1994; Woosley *et al.* 1994). If the enhancement is observed, its date will provide information on the thickness of the H-rich envelope and propagation speed of the reverse shock.

In this way, X-ray emissions from circumstellar interactions provide important information on the internal structure of the supernova ejecta (such as the density gradient), as well as mass loss from the progenitor. Detailed study of circumstellar interaction would thus provide an important clue to the progenitor's evolution, especially its binary nature, for SNe IIb, II-L, and IIn.

7. Concluding Remarks

We have proposed that except for *classical* SNe I and SNe II (SNe Ia and II-P), all other supernova subtypes (SNe Ib, Ic, IIb, II-L and IIn) can be explained as Fe core collapse of massive ($\gtrsim$10 M$_\odot$) stars in close binary systems. In other words, the main-sequence mass range of the progenitor of SNe Ib, Ic, IIb, and II-L and thus their nucleosynthesis may be similar to those of SNe II-P, except for the SNe II-P from the 8–10 M$_\odot$ AGB stars (Hashimoto *et al.* 1993).

If the above proposal is correct, light curves and spectra of SNe Ib, Ic, IIb, II-L, especially those of recent nearby events, are particularly useful to obtain the ^{56}Ni and O masses as a function of the main-sequence mass. The ^{56}Ni mass estimates are closely related with the neutron star mass estimate (Thielemann *et al.* 1995). From the light curve shape, we may infer the ejecta mass (i.e., the progenitor's mass) and the ^{56}Ni mass for the calculated extent of mixing. The produced ^{56}Ni mass (and the progenitor's main-sequence mass) is estimated as $0.09 \pm 0.02\,M_\odot$ (13–$14\,M_\odot$) for SN 1993J ($A_V = 0.4$mag) and $0.07^{+0.035}_{-0.025}\,M_\odot$ (14–$15\,M_\odot$) for SN 1994I. Combining with $0.075 \pm 0.01\,M_\odot$ ^{56}Ni for SN 1987A ($\sim 20\,M_\odot$, Arnett *et al.* 1989; Nomoto *et al.* 1994), the ejected ^{56}Ni mass seems to be not too sensitive to the progenitor's mass. [Earlier estimates of the $\sim 0.15\,M_\odot$ ^{56}Ni for SNe Ib/Ic being $\sim$1/4 of those for SNe Ia (Panagia 1987) are higher than the above values, which probably suggests the necessity of reexamination of the distances and/or extinction for SNe Ib/Ic.]

The light curve tails of SNe II-L would provide a useful information on whether SNe II-L have massive progenitors. Recent observations of SN II-L 1990K (Cappellaro *et al.* 1994) have shown that its late light curve is similar to that of SN 1987A, suggesting the progenitors of *bright* II-L may be similarly massive. This is consistent with the binary merger model but not with the AGB model (Swartz *et al.* 1991). For normal II-L, more observations are needed.

To conclude, our hypothesis implies that the observational diversity of supernovae can be the result of a single mechanism of explosion, i.e., a gravitational collapse of an Fe core, combined with merging of stars in close binary systems.

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