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WHY DID THE PROGENITOR OF SN 1987A UNDERGO THE BLUE-RED-BLUE EVOLUTION?

HIDEYUKI SAIO
Department of Astronomy, University of Tokyo

MARIKO KATO
Department of Astronomy, Keio University

AND

KEN'ICHI NOMOTO
Department of Earth Science and Astronomy, University of Tokyo
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ABSTRACT

Why was the progenitor of SN 1987A blue and how much hydrogen-rich envelope was retained in the progenitor have been major issues in the theoretical modeling of SN 1987A. As inferred from the observations, the progenitor of SN 1987A very likely evolved first to become a red supergiant and then returned to the blue. We have performed systematic evolutionary calculations for a star of initial mass 20 $M_\odot$ to clarify how the evolutionary path depends on mass loss, metallicity, and helium abundances and under what conditions the star evolves like the progenitor of SN 1987A. We have found that the star evolves from the blue to the red when the mass of the hydrogen-rich envelope significantly decreases and comes back from the red to the blue before carbon ignition if the helium abundance is sufficiently enhanced by mass loss and mixing. For lower metallicity, such an evolution occurs for a wider range of parameter space. Although the mass loss is important, the progenitor can retain a 5–10 $M_\odot$ hydrogen-rich envelope.

Subject headings: stars: evolution — stars: individual (SN 1987A) — stars: interiors — stars: mass loss — stars: supernovae — stars: supergiants

I. INTRODUCTION

Observations of SN 1987A in the Large Magellanic Cloud are providing us with important materials to test the theory of massive star evolution and supernova explosion. Among the new findings from SN 1987A, including the first detection of neutrinos, X-rays, and gamma rays, is the identification of Sk −69°202 as the most likely progenitor of SN 1987A (West *et al.* 1987; Kirshner *et al.* 1987; Gilmozzi *et al.* 1987). Surprisingly it was a B3 blue supergiant. Massive stars have been thought to end their lives as red supergiants or Wolf-Rayet stars. In fact, typical Type II-P supernovae are well modeled by the explosions of red supergiants (e.g., Chevalier 1981). The occurrence of a Type II supernova from such a blue supergiant progenitor has not been known before. Therefore, the evolutionary origin of the blue supergiant progenitor has been one of the major yet unresolved issues of SN 1987A (e.g., Nomoto 1988).

Let us summarize the properties of Sk −69°202. Its luminosity is $\sim 1 \times 10^5\ L_\odot$, which corresponds to the presupernova luminosity of a helium core of $M_{\rm core} \sim 6\ M_\odot$ (Woosley *et al.* 1987; Nomoto, Shigeyama, and Hashimoto 1987; Nomoto and Hashimoto 1988). Its main-sequence mass must be $M_{\rm ms} =$ 17–20 $M_\odot$ which depends on the $M_{\rm core}$–$M_{\rm ms}$ relation and thus on the convective overshooting during hydrogen burning (Hillebrandt *et al.* 1987; Maeder 1987*a*). From the luminosity and the spectral type, the radius of Sk −69°202 is estimated to be $\sim 3 \times 10^{12}$ cm.

Even if Sk −69°202 were not the progenitor, the following observations and modelings strongly indicate that the progenitor was a blue supergiant similar to Sk −69°202.

1. The early light curve of SN 1987A reached a plateau, but its luminosity is ~20 times lower than the typical plateau luminosity of Type II-P supernovae. Such a less luminous plateau is well modeled with a progenitor whose radius is much smaller than that of red supergiants (Arnett 1987*a*; Shigeyama *et al.* 1987; Shigeyama, Nomoto, and Hashimoto 1988; Woosley, Pinto, and Ensman 1988).

2. It took only 3 hr from the neutrino burst (Hirata *et al.* 1987; Bionta *et al.* 1987) to the optical brightening at 6.4 mag (McNaught 1987). This requires the progenitor's radius to be of the order of 10^{12} cm in order for the shock wave to propagate through the envelope in sufficiently short time (Shigeyama *et al.* 1987; Shigeyama, Nomoto, and Hashimoto 1988; Arnett 1987*b*; Woosley 1988).

The question then is why the progenitor of SN 1987A evolved to become a blue supergiant at the explosion. Basically two reasons have been advanced: (1) One reason is the low metallicity of the LMC, which is one-third to one-fourth of our Galaxy. With such low metallicity and without mass loss, Hillebrandt *et al.* (1987) and Arnett (1987*a*) found that their 15–25 $M_\odot$ stars remain blue throughout the evolution without becoming red. Woosley, Pinto, and Ensman (1988) found that 15–25 $M_\odot$ stars without mass loss evolve to the red supergiant and return to the blue if the metallicity is low and the Ledoux criterion is applied to convective stability. (2) The other reason is mass loss during the evolution. Maeder (1987*a*) and Wood and Faulkner (1988) have taken into account mass loss and shown that the 17–20 $M_\odot$ stars evolve to a red supergiant, undergo extensive mass loss, and return to the blue when the mass of the hydrogen-rich envelope, $M_{\rm env}$, is reduced below 1 $M_\odot$.

From the observational side, the following facts are important: (1) the existence of bright red supergiants in the LMC corresponding to stars of main-sequence mass up to $\sim 50\ M_\odot$

(Humphreys and Davidson 1978); (2) UV observations of SN 1987A that show the existence of a circumstellar shell with an expansion velocity less than 30 km s^{-1} (Panagia *et al.* 1987), where nitrogen is overabundant relative to carbon and oxygen (Kirshner 1988). The existence of a dust shell is also inferred from IR observations (Chalabaev, Perrier, and Mariotti 1987), which may indicate that the star spent some time in the red supergiant phase before becoming a blue supergiant. To expose the nitrogen-rich layer, the progenitor should have undergone significant mass loss (Maeder 1987*b*).

The mass of the hydrogen-rich envelope, M_{env}, at the explosion has been constrained by the light curve model (Woosley, Pinto, and Ensman 1988; Nomoto, Shigeyama, and Hashimoto 1987; Woosley 1988; Nomoto and Shigeyama 1987). The slow increase of the light curve up to the peak requires a relatively slow expansion of the core; this requires the existence of an envelope of at least 3 $M_{\odot}$, more likely 6–10 $M_{\odot}$. Using different approaches, Kirshner (1988) and Dopita (1988) also obtained relatively large envelope masses.

To summarize, observations of SN 1987A suggest the blue-red-blue evolution and a significant mass loss during evolution, yet the existence of a moderately massive hydrogen-rich envelope at the explosion. On the other hand, no evolutionary calculations, to the authors' knowledge, have been performed with mass loss to demonstrate the blue-red-blue evolution retaining a moderate mass envelope. To do so, we have made systematic calculations. In this paper we report our new findings concerning under what conditions a massive star undergoes a blue-red-blue evolution while retaining a moderate mass envelope before a supernova explosion. The dependence of the evolutionary path on mass loss, metallicity, and change in the helium abundance in the envelope associated with mass loss is discussed.

II. MODELS AND INPUT PHYSICS

The initial mass of the star adopted is 20 $M_{\odot}$. The star was evolved with a stellar evolution code which is a modified version of that used by Nakamura, Saio, and Sugimoto (1978). We used the opacity approximation formulae of Stellingwerf (1975) in the region of $T < 10^7$ K and of Iben (1975) in the region of $T > 10^7$ K. Metallicity, Z (mass fraction of the heavy elements), and the mass-loss rate, $\dot{M}$, are the parameters in our models as summarized in Table 1. Z_0, Z_1, and Z_2 denote $Z = 0.005$, 0.02, and 0.044, respectively. The mass fraction of helium is $Y = 0.25$ for Z_0 and Z_1 and $Y = 0.35$ for Z_2. The mass-loss rate is adopted from the empirical formula as a function of L and T_{eff} by de Jager, Nieuwenhuijzen, and van der Hucht (1988). We multiplied by a factor of f, and M_0, M_1, and M_2 stand for $f = 0$, 3, and 5, respectively. Applying such factors to the empirical relation of mass-loss rate is probably not unreasonable considering the large uncertainties in an empirical relation. Furthermore, we note here that the amount of lost mass is much smaller in our calculations than that of Maeder's (1987*b*) evolutionary model with $f = 0.4$ being used. This difference arises from the fact that his model stays in the red supergiant region with a large mass-loss rate during the core helium burning phase, while our models stay in the blue supergiant region in most of the helium burning phase.

TABLE 1

MODELS FROM THE BLUE TO THE RED

Model	dM/dt	Z	Color	$\log T_{eff,1}$ (K)	$M_{env}/M_{\odot}$
Z_0M_0	0	0.005	Blue	4.13	14.4[a]
Z_0M_1	3	0.005	Yellow	3.79	11.1
$Z_0M_2Y_0$	5	0.005	Red	3.61	9.2[b]
Z_1M_0	0	0.02	Blue	4.04	14.4
$Z_1M_2Y_0$	5	0.02	Red	3.57	9.2
Z_2M_0	0	0.044	Red	3.56	13.3

[a] Case A.
[b] Cases B and C.

In treating convective and semiconvective mixing we have to choose one of the two criteria for the occurrence of convective instability, i.e., the Schwarzschild or the Ledoux criterion. It has been known for some time that the evolutionary tracks of massive stars in the H-R diagram depend sensitively on which criterion is adopted (see, e.g., Chiosi and Summa 1970) because the Ledoux criterion tends to suppress the occurrence of shell convection above the hydrogen burning shell. The existence of a composition gradient can stabilize the normal convection according to the Ledoux criterion. However, in such cases the overstable convection grows in the thermal time scale of the region (see e.g., Shibahashi and Osaki 1976). This indicates that the Schwarzschild criterion should be adopted rather than the Ledoux criterion for the stellar evolution which proceeds in a nondynamical time scale. Therefore, we adopt the Schwarzschild condition in our evolutionary calculations, i.e., in the semiconvective layer the hydrogen abundance is determined to satisfy the convective neutrality condition in a way similar to that described by, e.g., Chiosi and Summa (1970). The overshooting is assumed to be negligible (Langer 1985). The standard mixing length theory is employed for the convective layer in the outer envelope, in which the ratio of the mixing length to the pressure scale height is set to be 1.5.

To analyze the evolutionary calculation, the hydrostatic and thermal equilibrium envelope is calculated using a code developed by Kato (1985). Important input physics is the same as used in the evolutionary calculation.

III. EVOLUTION IN THE H-R DIAGRAM

Evolution in the H-R diagram from the zero-age main-sequence through carbon ignition at the center is shown in Figure 1 for some models with metallicity Z_0. The stars show three patterns of the evolutionary path depending on the parameters.

Case A.—The star never becomes a red supergiant. It will become a supernova as a blue supergiant. In Figure 1, the evolutionary track of the model Z_0M_0 ($Z = 0.005$ and no mass loss) is shown as an example for this case.

Case B.—The star evolves to become a red supergiant and remains red until the supernova explosion. The evolutionary track shown in Figure 1 is for the model of $Z_0M_2Y_0$ ($Z = 0.005$, extensive mass loss, and no artificial enhancement of helium in the envelope).

Case C.—The star evolves to become a red supergiant and returns to the blue at carbon ignition. It will explode as a blue supergiant. The dashed line in Figure 1 is for the model $Z_0M_2Y_2$ (the same as $Z_0M_2Y_0$ but with artificially enhanced helium abundance in the envelope; see below).

Such an evolutionary path depends on (1) the mass-loss rate, $\dot{M}$ (or more appropriately, the mass of the hydrogen-rich envelope, M_{env}); (2) the metallicity of the envelope, Z; (3) the enhancement of the helium abundance, Y, in the hydrogen-rich envelope as summarized in Tables 1 and 2. The choice of convective stability criterion is also important (e.g., El Eid, Baraffe,

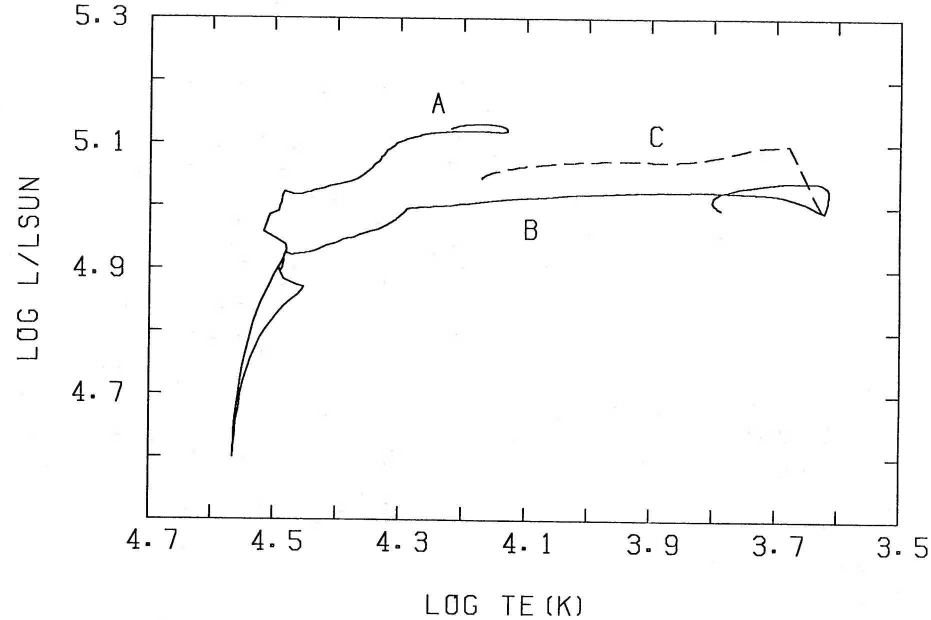

FIG. 1.—Evolutionary tracks in the H-R diagram of the initially 20 $M_\odot$ star. Cases A, B, and C correspond to models Z_0M_0, $Z_0M_2Y_0$, $Z_0M_2Y_2$, respectively. Here Z_0 stands for $Z = 0.005$, Y_0 and Y_2 for $Y_m = 0.25$ and 0.4, respectively, and M_2 for $f = 5$ times as large as de Jager, Nieuwenhuijzen, and van der Hucht's (1987) formula.

and Weiss 1987; Truran and Weiss 1987; Woosley, Pinto and Ensman 1988) as will be mentioned in § V*a*. In the following subsections, which are based on our calculation employing the Schwarzschild criterion, we focus on the dependence on other parameters and discuss:

i) Under what condition the star becomes red or remains blue;

ii) Under what condition the star which once became red comes back to the blue.

a) *Evolution from Blue to Red*

All models ignite helium in the blue supergiant stage where $\log T_{\rm eff} \sim 4.3$. During helium burning, the effective temperature $T_{\rm eff}$ gradually decreases and attains its lowest value $T_{\rm eff,\,1}$ after helium is exhausted at the center. Table 1 summarizes the dependence of $T_{\rm eff,\,1}$ on the various parameters. Two parameters are crucial for this stage of evolution: mass loss (or $M_{\rm env}$) and metallicity, Z.

i) *Metallicity*

We confirmed the basic features of the previous studies without mass loss (Brunish and Truran 1982; Hillebrandt *et al.* 1987; Arnett 1987*a*), i.e., for lower Z, $\log T_{\rm eff,\,1}$ is higher. Our models tend to be bluer compared to the models of the previous studies. This difference may be ascribed to the difference in opacity. However, we note that the location in the H-R diagram is sensitive to the detailed treatment of the convective and semiconvective region (Truran and Weiss 1987).

TABLE 2

MODELS FROM THE RED TO THE BLUE FOR MODEL M_2 ($M_{\rm env} \sim 9.2\ M_\odot$)

Model	Z	Y_m	Color	$\log T_{\rm eff,\,h}$ (K)
$Z_0M_2Y_0$	0.005	0.25	Red	3.80[a]
$Z_0M_2Y_1$	0.005	0.35	Blue	4.05
$Z_0M_2Y_2$	0.005	0.4	Blue	4.17[b]
$Z_1M_2Y_2$	0.02	0.4	Red	3.58
$Z_1M_2Y_3$	0.02	0.53	Blue	>4.35

[a] Case B.
[b] Case C.

ii) *Mass Loss*

Mass loss has an effect in making the evolutionary tracks redder. For Z_0M_0 the mass of the hydrogen-rich envelope, $M_{\rm env}$, at the carbon ignition is as large as 15 $M_\odot$, and it ignites carbon in the blue supergiant region (track A in Fig. 1). For the model $Z_0M_2Y_0$ with a large mass-loss rate, carbon ignition occurs when $\log T_{\rm eff} = 3.79$ (track B in Fig. 1), and $M_{\rm env}$ has decreased to $\sim 9\ M_\odot$. As discussed in § IV, this behavior is closely related to the fact that there is no blue supergiant envelope solution for the corresponding luminosity if $M_{\rm env}$ is too small.

b) *Evolution from Red to Blue*

After helium exhaustion at the center, the star evolves blueward. However, the blueward excursion is not extensive for the model $Z_0M_2Y_0$ (track B in Fig. 1). The envelope solutions as will be described in § IV (also in Barkat and Wheeler 1988) suggest that the most important parameter to affect the blueward evolution is helium abundance in the envelope. During core hydrogen and helium burning, mixing due to semiconvection and shell convection enhances the helium abundance in the inner part of the envelope. The effects of mass loss and the surface convection on the Hayashi line bring the enhanced helium abundance to the surface. We expect that the helium abundance and its distribution in the envelope depends on the amount of mass loss and the depth of the surface convection, both of which have large uncertainties according to our present knowledge.

To demonstrate the effect of helium abundance, Y, in the envelope, we artificially increased Y in the hydrogen-rich envelope up to Y_m at the central helium exhaustion phase. Before the enhancement, the helium abundance generally decreases outward in the envelope. The helium abundance, Y, is set to be Y_m in the region where $Y < Y_m$ originally. For larger Y_m the blueward excursion is more extensive as seen from the highest $T_{\rm eff}$ attained ($T_{{\rm eff},\,h}$ in Table 2). For $Y_m = 0.4$ ($Z_0 M_2 Y_2$, track C in Fig. 1), $T_{{\rm eff},\,h} = 1.5 \times 10^4$ K, which is consistent with Sk $-69°202$. We would like to emphasize here that this model has an intermediate-mass envelope, $M_{\rm env} = 9.2\ M_\odot$, which is required to explain the light curve of SN 1987A.

The necessary Y to bring the star to the blue is larger for larger Z. In other words, the star with smaller Z tends to move blueward with slight increase in Y, while the star with larger Z tends to remain red unless Y is increased substantially. The necessary Y would be larger for smaller $M_{\rm env}$ as anticipated from the envelope solution (§ IV).

IV. ENVELOPE SOLUTION

The evolutionary behavior in the H-R diagram can be understood in terms of the existence or nonexistence of an equilibrium stellar model in a certain limited region of the H-R diagram. The location in the H-R diagram of the equilibrium models for the advanced stages of evolution may be estimated by obtaining the structure of the hydrogen-rich envelope, because a large density difference between the core and envelope makes the structure and evolution of the core almost independent of the hydrogen-rich envelope (Hayashi, Hoshi, and Sugimoto 1962). For given boundary conditions, i.e., the inner boundary at the core edge and the outer boundary at the photosphere, the envelope solution is obtained with $M_{\rm env}$ as an eigenvalue.

We adopted the mass and the radius of the helium core (at the carbon ignition) as the inner boundary conditions, i.e., $M_{\rm core} = 5.45\ M_\odot$ and $r = 0.6\ R_\odot$, and the temperature at the photosphere, $T_{\rm eff}$, as an outer boundary condition. Assuming L = constant and uniform composition ($Z = 0.005$ and Y parameter), the envelope solution is obtained with $M_{\rm env}$ being an eigenvalue as a function of L and Y. The result is shown in Figure 2 for log $T_{\rm eff}$ (K) = 4.2. (This relation depends only slightly on $T_{\rm eff}$.) For a given Y (or L), the envelope solution exists only for a limited range of L (or Y) for $10^{-2}\ M_\odot < M_{\rm env} < 14.55\ M_\odot$; here the upper limit of $M_{\rm env}$ comes from our assumption that the initial mass of the star is 20 $M_\odot$. For given Y and L in the above range, there exist two envelope solutions, one with $M_{\rm env} > \sim 1\ M_\odot$ and the other with $M_{\rm env} < \sim 1\ M_\odot$. For a given $M_{\rm env}$, L is higher for larger Y because of smaller electron scattering opacity and larger mean molecular weight.

The relation in Figure 2 is transformed into the H-R diagram in Figure 3 for $Y = 0.395$. The solid and the dashed lines show the solution for $M_{\rm env}$ = constant with $M_{\rm env} > 1\ M_\odot$ and $M_{\rm env} < 1\ M_\odot$, respectively. Since the relation in Figure 2 depends only slightly on $T_{\rm eff}$ for log $T_{\rm eff} > 4$, these lines are almost flat in the H-R diagram. The envelope solution approximately corresponds to the evolutionary path of the contracting envelope from the red to the blue. The solution with small $M_{\rm env}$ (Fig. 3, *dashed lines*) may be close to the path obtained by Maeder (1987*a*) and Wood and Faulkner (1988), while the large $M_{\rm env}$ solution corresponds (*solid lines*) to the path of case C in Figure 1 and to the path obtained by Woosley, Pinto, and Ensman (1988).

Our envelope solutions are consistent with the allowed region in the ($M_{\rm env}$, Y)-space obtained by Barkat and Wheeler (1988; see also Wheeler, Harkness, and Barkat 1988). The filled circles in Figure 3 indicate the models in which all luminosity comes from the hydrogen-burning shell at the bottom of the hydrogen-rich envelope; these models approximately lie on the border line between the allowed and excluded region in the Barkat and Wheeler's $M_{\rm env}$-Y diagram.

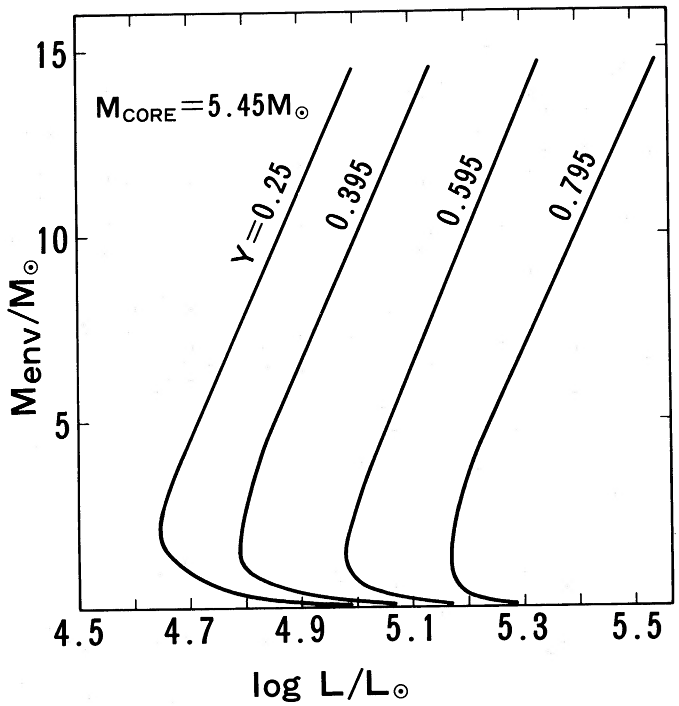

FIG. 2.—Envelope solutions with outer boundary of log $T_{\rm eff} = 4.2$ and inner boundary conditions that fit to the core at $M_r = 5.45\ M_\odot$ and $r = 0.6\ R_\odot$. Ordinate is the mass of the hydrogen-rich envelope ($M_{\rm env}$ = total mass $M - 5.45\ M_\odot$) given as a function of luminosity L and the mass fraction of helium Y.

The $M_{\rm env}$-L relation depends also on the metallicity, Z. Figure 4 shows the loci of solutions for log $T_{\rm eff} = 4.2$ in the log L-Z plane. For smaller Z, L is higher for the same Y and $M_{\rm env}$ because of smaller opacity. In other words, larger $M_{\rm env}$ is required in order that higher Z models are blue supergiants.

V. WHY THE BLUE-RED-BLUE EVOLUTION?

With the aid of the envelope solutions, the evolutionary behavior shown in Figure 1 and its parameter dependence is understood as follows.

a) *Evolution from the Blue to the Red*

If $M_{\rm env}$ and Y of the envelope after helium core burning are close to the blue supergiant envelope solution given in Figure 2, the star remains blue without undergoing extensive redward evolution. This is the case for the relatively large $M_{\rm env}$ and small Y, i.e., for the star that retains most of its original hydrogen-rich envelope.

On the contrary, if the star loses a significant fraction of its envelope, the blue supergiant envelope solution disappears for the given L, as seen in Figure 3. Since another envelope solution with the same L exists on the Hayashi line (Fig. 3), the star moves redward to become a red supergiant (see also Lauterborn and Siquig 1974; Barkat and Wheeler 1988). This is the main reason why the mass-losing star does not stay in the blue as far as the Schwarzschild criterion is adopted.

If the Ledoux criterion for the convective instability were used, mixing due to the shell convection would be suppressed,

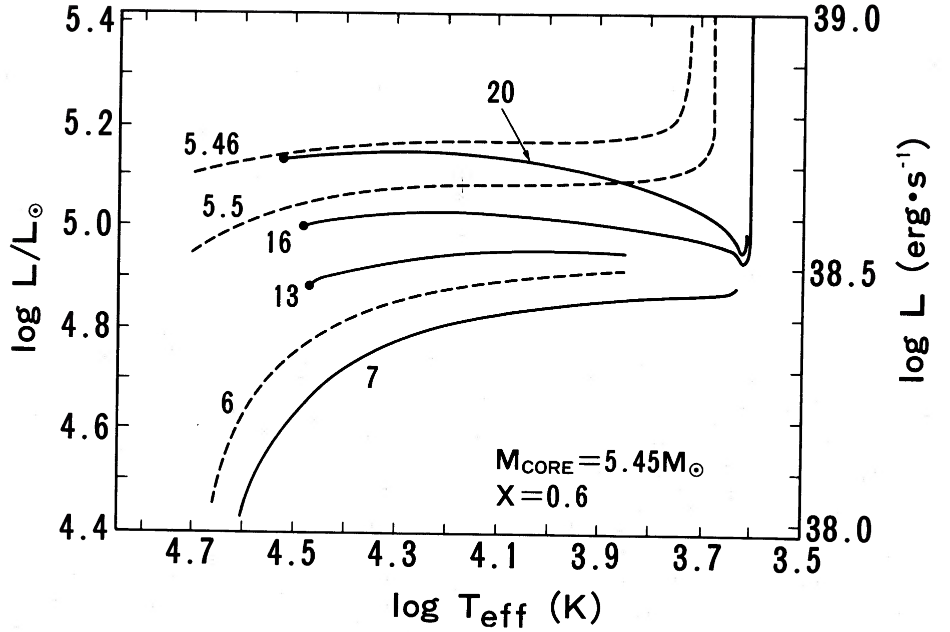

FIG. 3.—Envelope solutions for the same inner boundary condition as in Fig. 2 and for $Y = 0.395$. Lines for the constant total mass (M = envelope mass $M_{env} + 5.45\ M_\odot$) are shown in the H-R diagram. There exist double solutions with $M_{env} > 1\ M_\odot$ (*solid line*) and $M_{env} < 1\ M_\odot$ (*dashed line*). Filled circles indicate the models where the nuclear energy generation rate due to hydrogen shell burning is equal to the luminosity. Models with higher T_{eff} than the filled circles are excluded because the temperature at the bottom of the envelope exceeds that of hydrogen burning shell.

and the resulting composition profile would be similar to that for an intermediate-mass ($M < 10\ M_\odot$) star. It is known that the existence of a gradient in hydrogen abundance just above the hydrogen-burning shell make a central helium burning star red (e.g., Lauterborn and Siquig 1974). This explains why in a massive star model with Ledoux criterion helium ignition occurs in the red supergiant phase (e.g., Chiosi and Summa 1970; Woosley, Pinto, and Ensman 1988; El Eid, Baraffe, and Weiss 1987).

As seen in Figure 4, in order for a star to be a blue supergiant

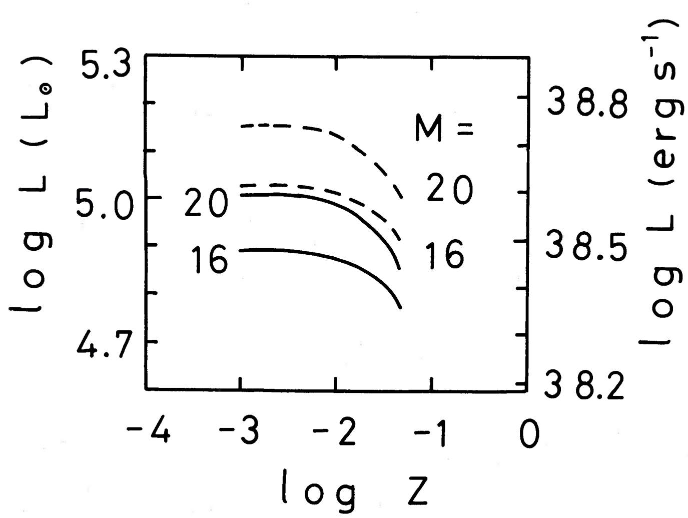

FIG. 4.—Envelope solutions for different metallicity. For log $T_{eff} = 4.2$, the lines for the constant total mass ($M = M_{env} + 5.45\ M_\odot = 20$ and $16\ M_\odot$) are given as a function of the luminosity L and the mass fraction of heavy elements Z. Solid and dashed lines are for helium abundance $Y = 0.255 - Z$ and $0.4 - Z$, respectively.

a total mass larger than $20\ M_\odot$ is required for log $L/L_\odot = 5.0$ for $Z > 0.02$. Accordingly, as the core evolves and the luminosity L is determined by its core mass almost independently of the metallicity in the envelope, a $20\ M_\odot$ star with a large Z evolves redward. On the contrary, the star with smaller Z has envelope solutions for possible M_{env} in the blue supergiant region and thus can remain blue as the core evolves.

b) *Evolution from the Red to the Blue*

A blueward evolution begins after the central helium exhaustion. As the C–O core contracts, helium shell burning becomes active. The resulting expansion of the helium layer triggers the blueward evolution (Lauterborn 1973). Whether the blueward evolution is extensive enough to enter into the blue supergiant region depends mainly on the envelope mass M_{env} and the helium abundance. Models Z_0Y_1, Z_0Y_2, and Z_1Y_3 return from the Hayashi line to the blue at the carbon ignition (see Table 2). This is consistent with the existence of static blue supergiant models with $M_{env} \sim 10\ M_\odot$ and enhanced helium abundance. (Woosley *et al.*'s 1988 models with Ledoux criterion return to the blue without enhanced helium abundance because they have a large M_{env} and the hydrogen shell burning changed the hydrogen distribution to a more or less discontinuous profile.)

As discussed in § V*a*, the star that evolved to the red may have too small M_{env} or too small Y to be consistent with a blue supergiant envelope solution. However, the red supergiant star undergoes mass loss and mixing and changes its M_{env} and Y. If M_{env} and Y match the blue supergiant envelope solution, the star moves blueward in the H-R diagram before carbon ignition (or during core carbon burning phase). That is probably the reason why the progenitor of SN 1987A was blue just before the explosion.

If this interpretation is correct, only stars in a narrow range of (M_{env}, Y) can become blue and end up their life as a blue supergiant. Such a match of (M_{env}, Y) is more likely to occur for smaller Z because M_{env} of a blue supergiant should be rather large for $Z > 0.02$, as seen in Figure 4.

In our models, it takes $\sim(1\text{–}2) \times 10^4$ yr for the star to move from the red to the blue. However, this time scale depends on when the helium enhancement takes place and this could be shorter.

VI. CONCLUDING REMARKS

Based on our evolutionary calculation and analysis, the evolution of the progenitor of SN 1987A is understood as follows: The star had $\sim 20\ M_\odot$ at its birth and evolved with mass loss from its hydrogen-rich envelope. During helium burning, the star was initially a blue supergiant, but its envelope mass became too small to remain blue. Thus the mass loss drove the star to move gradually redward. Before reaching the Hayashi line, the star lost more than 5 $M_\odot$. During the red supergiant phase, the envelope mass was still decreasing and the mean helium abundance increased. The envelope became sufficiently helium-rich due to mass loss or internal mixing before the blueward excursion began. The blueward excursion was extensive enough to result in a blue supergiant at carbon ignition. This extensive blueward excursion is explained by the existence of a blue supergiant static solution with an envelope as massive as $\sim 10\ M_\odot$. At the supernova explosion, the progenitor had a moderately massive envelope and, hence, appeared as a Type II supernova.

This scenario is quite consistent with many of the observed features of SN 1987A as summarized in § I and the theoretical light curve that requires the existence of a 5–10 $M_\odot$ envelope. Especially, the helium enhancement in the envelope must be closely related to the observed nitrogen overabundance in the circumstellar shell. The uniqueness of SN 1987A is almost entirely due to its blue supergiant origin. Although the blue-red-blue evolution of massive stars more frequently occurs in low-metallicity galaxies, it could also occur in more metal-rich galaxies if the envelope mass and helium abundance would match. Therefore, it would be interesting to search for SN 1987A–like Type II supernovae in other galaxies, including our Galaxy.

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MARIKO KATO: Department of Astronomy, Keio University, Hiyoshi, Kohoku-ku, Yokohama 223, Japan

KEN'ICH NOMOTO: Department of Earth Science and Astronomy, College of Arts and Sciences, University of Tokyo, Komaba, Meguro-ku, Tokyo 153, Japan

HIDEYUKI SAIO: Department of Astronomy, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan