

PRESUPERNOVA EVOLUTION IN MASSIVE INTERACTING BINARIES

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ABSTRACT

We have systematically investigated how binary interaction affects the presupernova evolution of massive close binaries and the resulting supernova explosions, using a Henyey-type stellar evolution code that we have modified to allow its application to binary stellar evolution calculations. With our modified code, we are able to follow the effects of mass and angular momentum loss from the binary, as well as mass transfer within the binary system. We find that a large number of binary scenarios can be distinguished, depending on the type of binary interaction and the evolutionary stage of the supernova progenitor at the time of the interaction. In general, the structure of a massive star can be affected in three fundamentally different ways: by mass loss, mass accretion, or common-envelope evolution.

As a result of mass loss by Roche lobe overflow, stars can lose all of their hydrogen-rich envelopes and become helium stars, which are potential candidates for the progenitors of Type Ib supernovae. If the original masses of the binary components are nearly equal, it is possible (for reasonable assumptions about the mass and angular momentum loss rates) that the primary retains part of its hydrogen-rich envelope. In this case, the supernova progenitor would look like a more or less normal red supergiant, even though it may have lost most of its envelope, and the supernova would resemble a classical Type II-L supernova. In most cases, the system remains bound after the explosion, but it may acquire a substantial orbital eccentricity. The system may subsequently become unbound if the original secondary then evolves to become a second supernova.

Mass accretion can also significantly alter the structure of the supernova progenitor, if it takes place after the main-sequence phase of the accreting star. The star may then end its life as a blue supergiant instead of a red supergiant. In this case, the resulting supernova explosion would resemble SN 1987A. At the time of the supernova explosion, the presupernova star still has a stellar or (more likely) a neutron star companion. However, since more than half of the total mass of the system is ejected in the supernova explosion, the system is likely to become unbound after the explosion.

In the most dramatic case of binary interaction, in which a supernova progenitor captures its companion in a common envelope, two different outcomes are possible, depending on whether the envelope is ejected during the spiral-in phase or remains bound. If the envelope is ejected, the progenitor will become a helium star and the subsequent supernova explosion may be of the Type Ib variety. If the binary components merge completely, the final outcome would be a single star with no trace (except for possible chemical anomalies) of the original secondary. If, during the merger, a significant amount of mass is added to the envelope, the final star may again be a blue supergiant (similar to the results of the accretion scenario), and the resulting supernova would belong to the same class as SN 1987A.

In order to assess the importance of the various scenarios, we performed Monte Carlo simulations to estimate the frequencies of occurrence of the individual scenarios. We find that, because of a previous binary interaction, 15%–30% of all massive stars (with initial masses $\geq 8 M_{\odot}$) become helium stars, and another $\sim 5\%$ of all massive stars end their lives as blue supergiants rather than as red supergiants.

These results may be directly applicable to Type Ib supernovae. Our estimate for the frequency of helium stars is comparable to the observed frequency of Type Ib supernovae, and hence we expect that the explosions of helium stars in binaries account for a substantial fraction of all Type Ib events.

Our calculations may also help to answer one of the major puzzles about SN 1987A, namely, the question of why the apparent progenitor (Sk $-69^{\circ}202$) was a blue supergiant rather than a red one, as had been generally expected for the precursors of Type II supernovae. In addition, binary models for SN 1987A may provide plausible explanations for a variety of other anomalies of SN 1987A, ranging from the asymmetric expansion of the ejecta and the variability of the soft X-ray flux to the barium anomaly and the “mystery spot.”

Subject headings: binaries: close — stars: evolution — stars: statistics — supernovae: general — supernovae: individual (SN 1987A)

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1. INTRODUCTION

It is generally believed that the majority of all stars occur in binary systems (see, e.g., Abt & Levy 1976, 1978; Kraicheva et al. 1978, 1979), and the importance of binary evolution has long been recognized in the context of Type I supernovae (Truran & Cameron 1971; Wheeler & Hansen 1971; Whelan & Iben 1973). The presently favored models for the progenitors of Type Ia supernovae—accreting or merging white dwarfs (see, e.g., Iben & Tutukov 1984; Nomoto & Hashimoto 1987)—all involve low- or intermediate-mass binary progenitors. The presupernova evolution of massive binaries has also been studied extensively in order to explain the origin of binaries with neutron-star components (see, e.g., van den Heuvel 1977; Vanbeveren 1991). However, relatively little attention has been paid to the effects of binary interaction on the structure of massive supernova progenitors and the resultant modifications to the subsequent supernova explosions. Chevalier (1976) was the first to suggest that the explosion of helium stars⁶ born in massive close binaries may produce underluminous supernovae. This idea has gained popularity with the recognition that Type I supernovae form three distinct subclasses, now referred to as Types Ia, Ib, and Ic (see, e.g., Panagia 1986; Wheeler & Harkness 1991), and the possible identification of Type Ib/Ic progenitors with the hydrogen-exhausted cores of massive stars (see § 5.1).

In this paper, we investigate systematically how binary evolution can affect supernova progenitors with initial primary masses⁷ in excess of $8 M_{\odot}$. In § 2 we review the relevant aspects of close binary evolution. In § 3 we describe in detail the various possible binary scenarios and discuss the consequences for the resulting supernova explosions. Particular emphasis will be given to models that have not been studied previously. (We note, however, that many of these models were originally proposed as models for the progenitor of SN 1987A; see Joss et al. 1988; Podsiadlowski & Joss 1989; Podsiadlowski, Joss, & Rappaport 1990). In § 4 we attempt to put these models into the general framework of binary stellar evolution theory by estimating the a priori frequencies of the various scenarios. In § 5 we apply our results to observed supernova events, in particular to Type Ib/Ic supernovae and SN 1987A.

2. MASS TRANSFER IN CLOSE BINARY SYSTEMS

The most important form of binary interaction, and the only one we concern ourselves with in this paper, is the direct mass exchange between a Roche lobe filling star and its companion. Following Kippenhahn & Weigert (1967) and Lauterborn (1970), we distinguish among three cases of mass transfer (cases A, B, and C, respectively), which are characterized by the evolutionary phase of the initial primary at the beginning of the mass-transfer phase. Case A mass transfer occurs during the hydrogen core-burning phase of the primary, case B after the hydrogen core-burning phase but before the ignition of central helium, and case C after the helium core-burning phase.

Since the details of the mass-transfer process, as well as the subsequent evolution of the binary, depend sensitively on whether the primary has a radiative or a convective envelope

during mass transfer (Paczynski 1970a), we further distinguish between early and late phases of case B and case C mass transfer, where the primary (the mass donor) has a radiative and a convective envelope, respectively, at the beginning of the mass-transfer phase.

Case A and early case B/case C mass transfer are believed to be generally stable and to occur in a more or less conservative way (i.e., the systemic mass and angular momentum are assumed to be conserved during mass exchange). Late case B/case C mass transfer, on the other hand, may be dynamically unstable, and runaway mass loss may result when the primary has a deep convective envelope and its mass is larger than $\sim 70\%$ of the mass of the secondary (Paczynski & Sienkiewicz 1972). This instability is a consequence of the fact that the radius of a star with a deep convective envelope shrinks more slowly, during adiabatic mass loss, than the radius of the Roche lobe (in fact, the stellar radius may even expand) (Paczynski & Sienkiewicz 1972). The resultant runaway mass loss can only be reversed by the loss of most of the envelope of the primary, or by the reduction of the mass of the original primary to a value appreciably below that of the secondary. The secondary will also start to expand if the mass-transfer time scale is shorter than the thermal time scale of the outer envelope of the secondary (see, e.g., Kippenhahn & Meyer-Hofmeister 1977, but see also the criticism by Shu & Lubow 1981). The secondary then fills its own Roche lobe, and the system enters a common-envelope phase (Paczynski 1976). The common envelope consists mainly of material from the outer hydrogen-rich envelope of the donor, but may also contain matter from the inner helium-rich envelope that is slowly being dredged up. Embedded in this envelope are the dense, small core of the primary and the more or less unaffected companion (if it is still on the main sequence) orbiting about the center of mass of the system. The orbit gradually decays as a result of dynamical friction (Bondi & Hoyle 1944). The details of common-envelope evolution are highly uncertain (see Livio & Soker 1988 for a recent discussion of relevant aspects of common-envelope evolution). The final outcome and the time scale for the spiral-in process depend, among other factors, on the amount of frictional luminosity generated, the efficiency of energy transport in the common envelope, and the angular momentum transfer between the spiraling-in binary and the common envelope. If the common envelope is ejected, the system will become a cataclysmic variable (Paczynski 1976) or, if the original binary was composed of massive stars, a short-period, low-mass Wolf-Rayet binary; if the binary remains bound, the two stellar cores may eventually merge to form a single star (but see also § 3.3).

While this scenario can explain the origin of cataclysmic variables in a straightforward way, it cannot be the generic outcome of late case B/case C mass transfer, since there are a large number of systems (for references see, e.g., Webbink 1986; Eggleton & Tout 1989) that seem to have experienced late case B/case C mass transfer but that have relatively long orbital periods. This indicates that these systems cannot have suffered the dramatic angular momentum losses that are associated with “spiraling-in” during a common-envelope phase. Therefore, these systems must have either avoided a common-envelope phase altogether or survived it nearly unscathed. In addition, there are several massive systems (e.g., VV Cep [Wright 1977], AZ Cas [Cowley, Hutchings, & Popper 1977], and KQ Pup [Cowley 1966]) that appear to be in a late case B/case C mass-transfer phase but that seem not to have encountered the dynamical instability discussed above.

⁶ Throughout this paper we shall refer collectively to stars that have lost all, or almost all, of their hydrogen-rich envelopes as “helium stars.” This definition includes Wolf-Rayet stars.

⁷ Throughout this paper, we shall use the terms “primary” and “secondary” to refer to the originally more massive and less massive components, respectively. Thus, in our nomenclature, the “primary” of a system is always the same star, namely, the star that was initially the more massive.

While the present status of the theory of late case B/case C mass transfer is unsatisfactory, we can think of several mechanisms that may be able to prevent or stabilize dynamical mass transfer. Mass loss by a stellar wind (possibly enhanced owing to the presence of a close binary companion; Tout & Eggleton 1988) may invert the mass ratio, $q \equiv M_2/M_1$ (where M_1 and M_2 are the primary and secondary masses, respectively), before the onset of mass transfer and may thereby lead to stable mass transfer. Even if the mass ratio has not been inverted by the beginning of the mass-transfer phase, wind loss may help to prevent dynamical mass transfer by reducing the mass in the convective envelope relative to that in the core (Paczynski & Sienkiewicz 1972; Hjellming & Webbink 1987). In their study of rapid mass transfer from low-mass giants, Hjellming & Webbink (1987) showed that dynamical mass transfer can be avoided if the fractional core mass of the donor, $\xi_c \equiv M_c/M$ (where M_c is the mass in the compact core and M is the total mass of the star), exceeds a critical value, m_{cr} ($m_{cr} \approx 0.46$ for $q \approx 1$). While their results do not directly apply to massive stars, it is interesting to note that, in models of massive stars which include mass loss by stellar winds (see, e.g., Maeder & Meynet 1987), m_{cr} is larger than ~ 0.46 after helium core burning for all stars more massive than $\sim 15 M_\odot$.

Late case B/case C mass transfer may also be stable if the transfer is pulsed. This may be the result of a pulsational instability in the envelope of the giant donor (Eggleton & Tout 1989) or may be caused by a large orbital eccentricity of the binary. Indeed, the systems VV Cep, AZ Cas, and KQ Pup all have large eccentricities (~ 0.3 – 0.5), and mass transfer seems to occur mainly near periastron.

Whether a common envelope develops also depends on how fast the secondary can accrete matter without filling its own Roche lobe. This depends sensitively on the treatment of the accretion process, which at present is controversial (see the discussion in Shu & Lubow 1981).

It follows from the above discussion that we expect to encounter three qualitatively different types of mass transfer, depending on the initial orbital period, the initial masses of the binary components, and possibly other parameters such as the wind mass-loss rate and the orbital eccentricity. These types are (1) more or less conservative mass transfer, (2) dynamical mass transfer leading to a common envelope and a spiral-in phase, and (3) quasi-dynamical mass transfer. The last type will occur in instances of late case B/case C mass transfer that do not involve a prolonged common-envelope and spiral-in phase; see below for a further discussion (see also Pastetter & Ritter 1989). (We do not exclude the possibility that a substantial amount of mass and angular momentum is lost from the system during quasi-dynamical transfer.)

For definiteness, we shall assume throughout this paper that case A and early case B/case C mass transfer are conservative and that late case B/case C mass transfer is quasi-dynamical for all values of q greater than some critical value q_{cr} ; we rather arbitrarily choose $q_{cr} = 0.9$.

Finally, it is worth noting that it is much more likely for a star to encounter case B or case C mass transfer than case A mass transfer, because of the much larger range of orbital periods for which we expect case B/case C mass transfer (days to decades) relative to that of case A transfer (days). (This is in contrast to the observational situation, where a large majority of interacting binaries are case A or post-case A systems, presumably because of their longer lifetimes.) We therefore expect that case B/case C mass transfer will be particularly important in our study of the effects of binary interaction on supernova

progenitors, and conversely that the study of supernovae and postsupernova systems (i.e., systems with collapsed remnants) may allow us to draw inferences about case B/case C mass transfer.

3. EVOLUTIONARY SCENARIOS

Binary evolution can affect the structure of a supernova progenitor in several fundamentally different ways. Mass transfer can provide the means by which a star either loses part or all of its envelope or adds material (possibly processed by nuclear reactions) to its surface layers. In addition, if mass transfer is dynamically unstable, it may lead to the merger of the two components in a common envelope. The final outcome of such a scenario would look like a *single* star with possibly some rather unusual properties. In the following subsections, we shall systematically explore the evolutionary scenarios in which these possibilities are realized.

3.1. Mass-Loss Models

As we shall show in § 4, at least 20% of all massive stars are expected to experience mass loss via Roche-lobe overflow to close binary companion stars during their lifetimes. As a result, a large fraction of these stars will lose all of their hydrogen-rich envelopes and become helium stars, which are candidates for the progenitors of Type Ib/Ic supernovae (see § 5.1). Here we are mainly interested in cases in which a star loses only part of its envelope. In particular, we wish to (1) investigate the circumstances under which a Roche lobe filling star in a close binary can retain part of its hydrogen-rich envelope and (2) determine the final presupernova appearance of the star.

In this subsection, we assume that the primary fills its Roche lobe after it has finished hydrogen core-burning (i.e., we consider case B or case C transfer; see § 2). We also assume that mass transfer is stable or quasi-dynamical (i.e., does not lead to an extended common-envelope phase). The case of dynamical mass transfer will be treated separately in § 3.3.

3.1.1. Computational Procedure

In order to follow the orbital evolution of systems undergoing stable or quasi-dynamical, nonconservative mass transfer, we employ the method developed by Rappaport, Joss, & Webbink (1982) and Rappaport, Verbunt, & Joss (1983). It is specified by two free parameters, the fraction, β , of the mass lost by star 1 that is accreted by star 2 and the specific angular momentum, α , of any matter lost from the system in units of $2\pi a^2/P$, so that

$$\delta J = \alpha \delta \dot{M}_1 (1 - \beta) \frac{2\pi a^2}{P}, \quad (1)$$

where $\delta \dot{M}_1$ is an incremental mass lost by the initial primary, δJ is the incremental angular momentum of the matter ejected from the system, and a and P are the orbital semimajor axis and period, respectively (this equation is identical to eq. [31] in Rappaport et al. 1982). We assume, in effect, that the orbit is always well approximated by a circle of radius a (where a is a function of time). Since we only consider angular momentum loss resulting from the ejection of matter from the system, equation (1) can be rewritten as the differential equation

$$\frac{dJ}{dM_1} = \alpha(1 - \beta)\sqrt{G(M_1 + M_2)a}, \quad (2)$$

where we have used Kepler's third law in the form

$$\frac{2\pi a^2}{P} = \sqrt{G(M_1 + M_2)a} \quad (3)$$

to eliminate P . Combined with an expression for the total systemic angular momentum,

$$J = \sqrt{\frac{Ga}{M_1 + M_2}} M_1 M_2, \quad (4)$$

equation (2) constitutes a differential equation for J (or a) as a function of M_1 (where we have neglected the rotational angular momentum of the component stars and the angular momentum of the transferring matter). The solution of equation (2) for a (with fixed α and β) can be written as

$$\frac{a}{a^i} = \begin{cases} \frac{M_1 + M_2}{M_1^i + M_2^i} \left(\frac{M_1}{M_1^i}\right)^{2(\alpha-1)} \exp\left[\frac{2\alpha(M_1 - M_1^i)}{M_2^i}\right] & (\beta = 0), \\ \frac{M_1 + M_2}{M_1^i + M_2^i} \left(\frac{M_1}{M_1^i}\right)^{c_1} \left(\frac{M_2}{M_2^i}\right)^{c_2} & (\beta > 0), \end{cases} \quad (5)$$

where

$$C_1 \equiv 2\alpha(1 - \beta) - 2,$$

$$C_2 \equiv -\frac{2\alpha}{\beta}(1 - \beta) - 2,$$

and

$$M_2 = \beta(M_1^i - M_1) + M_2^i,$$

and where variables with superscript i refer to values at the beginning of the mass-transfer phase.

We use a standard Henyey-type stellar evolution code (see Kippenhahn, Weigert, & Hofmeister 1967) to follow the evolution of the initial primary (star 1). We do not calculate the detailed evolution of the initial secondary (star 2), nor do we attempt to determine the amount of mass loss from either component that may have occurred at earlier evolutionary stages, even though mass loss via a stellar wind may be important for avoiding dynamical mass transfer and common-envelope evolution (see the discussion in § 2). We choose an initially circular orbit with a separation, a , such that the system would come into contact during the asymptotic giant branch evolution of the initial primary, resulting in case C mass transfer. We also assume that the orbit remains circular throughout the evolution (see, e.g., Krolik, Meiksin, & Joss 1984; Hut & Paczyński 1984).

Since our code is unable to treat the hydrodynamics of quasi-dynamical mass transfer, we use the following approximate technique to follow the binary evolution during this phase (see also Rappaport et al. 1982; Iben & Tutukov 1987). During each time step of the evolutionary calculation, we checked to determine whether the radius, R_1 , of star 1 exceeded the effective radius, R_L , of its Roche lobe, whose value we determined by application of a formula due to Eggleton (1983):

$$R_L = \frac{0.49q^{-2/3}}{0.6q^{-2/3} + \ln(1 + q^{-1/3})} a. \quad (6)$$

Whenever $R_1 > R_L$, we removed the outermost $\sim 0.2\%$ of the mass of star 1; the appropriate portions of the removed matter were taken to be accreted by star 2 or ejected from the system, as specified by the prescribed value of β . The remainder of star 1 was then allowed to relax to a state of hydrostatic equilibrium on a time scale that was assumed to be short compared with all relevant time scales other than the dynamical

time scale for this star; in particular, we assumed that the distribution of specific entropy, $s(m_r)$, throughout star 1 was fixed, m_r being the mass contained within a spherical shell radius r and centered on the star, which is assumed to be spherical. [In practice this was achieved by replacing the energy transport equation by the equation $s(m_r) = \text{constant}$ (in time).] This procedure neglects the possible hydrodynamic effects of mass motions on the mass-transfer process, but we believe it to be an adequate approximation for our purposes.

We discontinued the unstable mass-transfer process, as estimated by this prescription, when R_1 again became less than R_L (which, of course, is also evolving with time). For a specified initial structure for star 1 and a specified evolutionary epoch at which the system comes into contact, the value of R_1 is uniquely determined by the amount of mass that the star has lost. However, the total amount of mass lost from star 1 is a function of α , β , and the initial values of M_2 and a (see below). Immediately following the unstable mass-transfer stage, star 1 undergoes an epoch of stable Roche-lobe overflow, which proceeds initially on the thermal time scale of the residual stellar core. We are able to follow these evolutionary phases directly using our modified Henyey-type code. We terminate our evolutionary calculations at or shortly before the final nuclear burning stages that immediately precede the supernova event itself.

To test the validity of our numerical procedure, we also carried out several calculations in which mass was taken off on a thermal time scale (instead of a time scale nearly as short as the dynamical time scale) and did not constrain R_1 to be less than R_L . We found that the final presupernova models in these calculations were indistinguishable from the models (with the same envelope masses) obtained with the procedure outlined above. We conclude that *if the envelopes of our presupernova models are in approximate thermal equilibrium, the final properties of our models are independent of the details of the mass-loss episode and are uniquely determined by the final masses of the hydrogen-exhausted core and the hydrogen-rich envelope.*

3.1.2. Numerical Results

To explore the consequences of quasi-dynamical mass transfer, we carried out a number of binary stellar evolution calculations with initial masses for the primary of 10, 12, and 15 M_\odot . (This mass range was chosen because it is appropriate for models of the progenitor of SN 1987A; see Joss et al. 1988.) The results of our calculations are summarized in Figures 1–8. Figure 1 presents the H-R diagram for stars of mass 10, 12, and 15 M_\odot without mass loss. The calculations assume solar abundances ($Z = 0.02$, $Y = 0.28$) and a mixing length equal to 1.5 pressure scale heights, and they include the effects of semi-convection and convective overshooting according to the treatment devised by Iben (1986). The calculations were terminated after carbon burning had been established in the core. Figure 2 shows the locations of the models for the primary in the H-R diagram at the time of the supernova explosion, for a range of residual masses in the hydrogen-rich envelope, m_{env} , of 0.5–5 M_\odot (the rest of the envelope was assumed to be either lost from the system or accreted by the companion, as specified by the value of β). Figure 2 demonstrates that the presupernova luminosities of the models are essentially independent of the mass in the envelope and illustrates the existence of a core mass–luminosity relation even for stars that have nondegenerate or only partially degenerate cores (see, e.g., Refsdal & Weigert 1970; Paczyński 1970b; Iben 1977). More surprisingly, the effective temperatures and, consequently, the radii of the

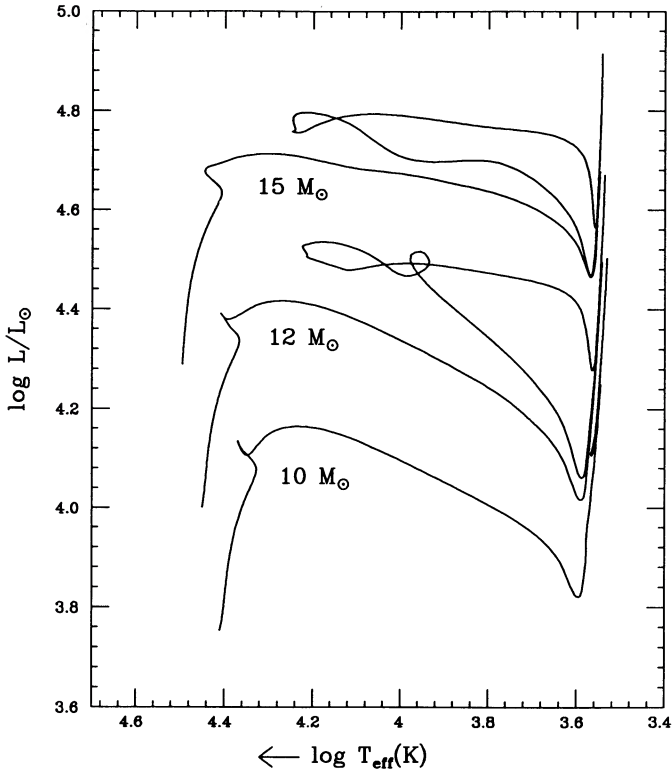


FIG. 1.—H-R diagram (bolometric luminosity L vs. effective temperature T_{eff}) for stars with $M = 10, 12,$ and $15 M_{\odot}$ without mass loss. All calculations assume solar abundances ($Z = 0.02, Y = 0.28$) and a mixing length equal to 1.5 pressure scale heights, and all include the effects of semiconvection and convective overshooting. The calculations are terminated when carbon burning has been established in the core.

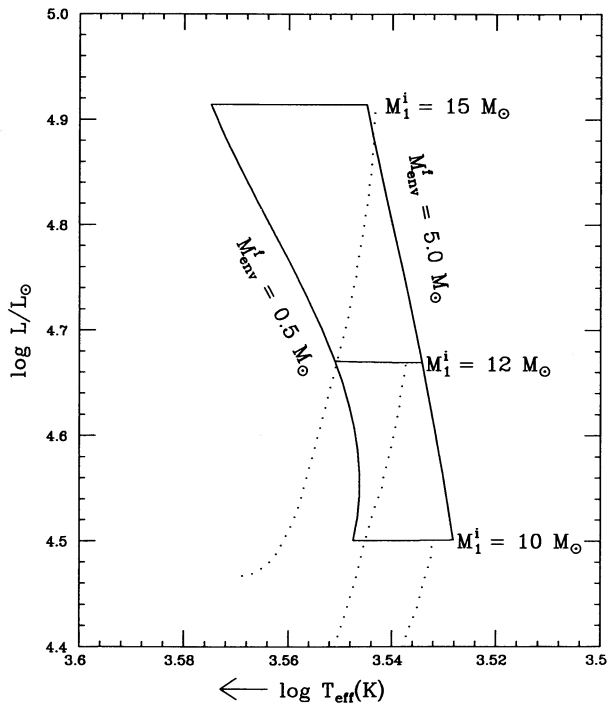


FIG. 2.—Final locations, in the H-R diagram, of presupernova stars that experienced mass loss for initial primary masses, M_1^i , between 10 and 15 M_{\odot} and final envelope masses of the original primary, M_{env}^f , between 0.5 and 5 M_{\odot} . The dotted curves show the asymptotic giant branch tracks of the models presented in Fig. 1 without binary interaction.

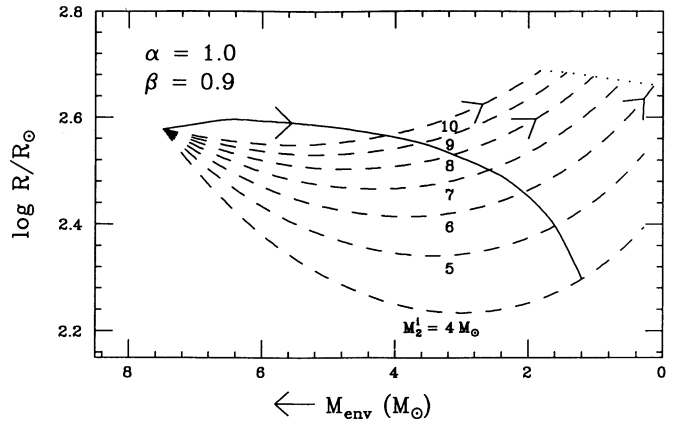


FIG. 3.—Radius R of a massive star as a function of the residual mass, M_{env} , of its hydrogen-rich envelope (increasing toward the left), during a late case C mass-transfer phase, for an initial total mass of $10 M_{\odot}$ and an initial core mass of $2.5 M_{\odot}$. The dashed curves represent the radius of the Roche lobe of the primary as a function of M_{env} , for various values of the initial mass, M_2^i , of the secondary and for illustrative values of $\alpha = 1$ and $\beta = 0.9$. The arrows indicate the direction of evolution. We assume that the evolution of the primary follows the solid curve toward the right during the quasi-dynamical mass-loss phase and then follows the appropriate dashed curve toward the right during the subsequent phases of dynamically stable mass transfer. The dotted curve corresponds to the final presupernova radius of the original primary.

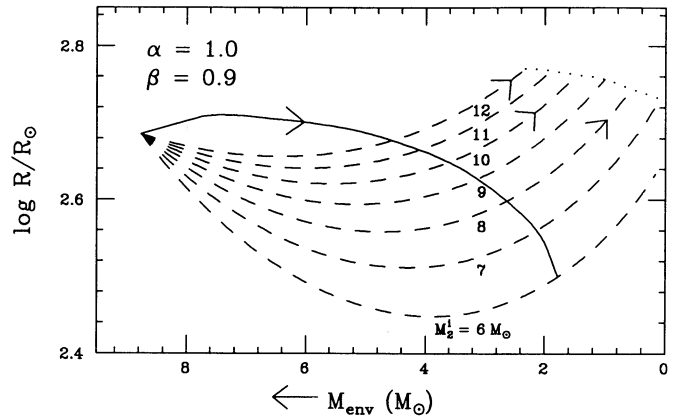


FIG. 4.—Same as Fig. 3, but for $M_1^i = 12 M_{\odot}$

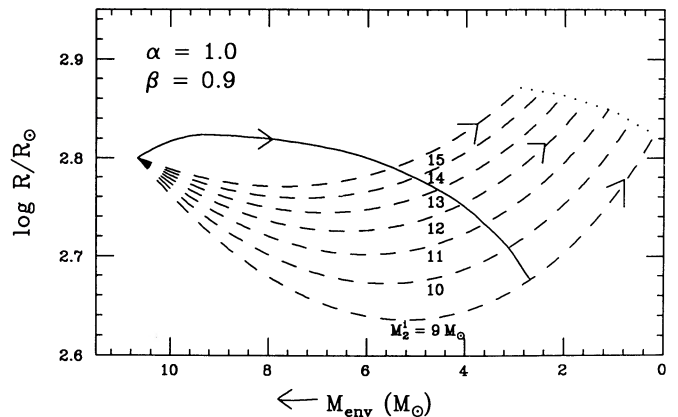


FIG. 5.—Same as Fig. 3, but for $M_1^i = 15 M_{\odot}$

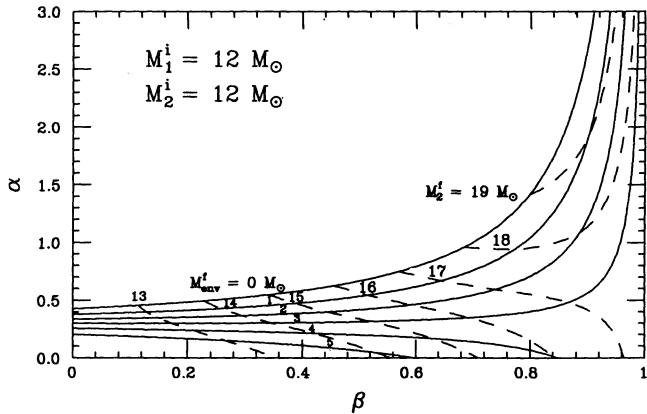


FIG. 6.—Contours of the final envelope mass, M_2^f , of the primary (solid curves) and the final mass, M_1^f , of the secondary (dashed curves), in the α - β parameter plane, at the time of the supernova explosion of the primary after late case C mass transfer, for $M_1^i = 12 M_\odot$ and $M_2^i = 12 M_\odot$.

models are also not very sensitive to m_{env} . This demonstrates that these models also (approximately) follow a core mass-radius relation (see also Joss, Rappaport, & Lewis 1987). This behavior changes abruptly when m_{env} has been reduced to several times $0.1 M_\odot$ (the critical value depends on the core mass and other model parameters, such as metallicity). As soon as m_{env} has decreased below this critical value, the envelope starts to contract on the thermal time scale of the envelope ($\sim 10^3$ yr), and the star moves to the helium main sequence or Wolf-Rayet region in the H-R diagram (see, e.g., Fig. 11 in Abbott & Conti 1987).

Figures 3–5 display the results of three sets of mass-transfer calculations for initial primary masses of 10, 12, and $15 M_\odot$. They show the variation of R_1 with m_{env} , for a range of secondary masses and illustrative values of α and β , namely, $\alpha = 1$ and $\beta = 0.9$. (We expect that α will usually be close to unity for late case B/case C mass transfer, since this situation can be roughly characterized as low-velocity mass loss through the outer Lagrangian point L_2 .) In each case, the initial separation of the binary components was chosen in such a way that the primary would fill its Roche lobe at a predetermined location on the asymptotic giant branch.⁸ The dotted curves in Figures 3–5

⁸ Throughout this paper, we use the term “asymptotic giant” to denote red supergiants that have completed helium core burning. We choose this term (which some other authors use only when referring to stars with degenerate cores) because in all of our calculations the location of these stars on the H-R diagram is “asymptotic” to the first red giant branch (see, e.g., Fig. 1).

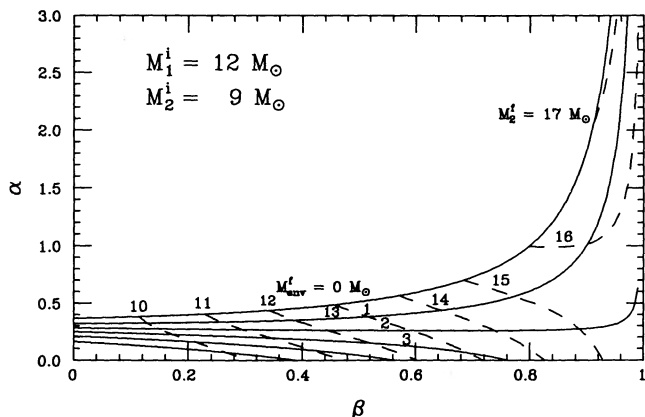


FIG. 7.—Same as Fig. 6, but for $M_1^i = 12 M_\odot$ and $M_2^i = 9 M_\odot$.

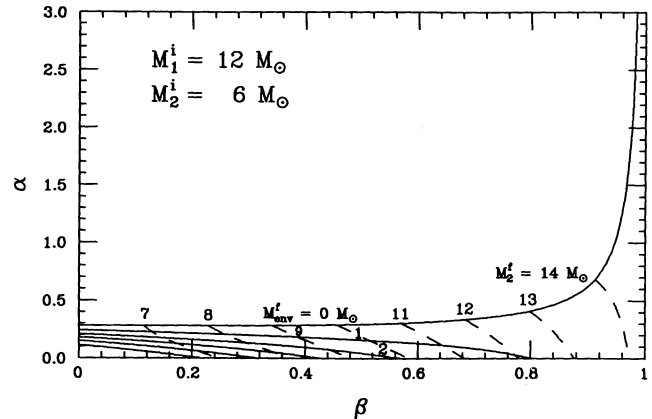


FIG. 8.—Same as Fig. 6, but for $M_1^i = 12 M_\odot$ and $M_2^i = 6 M_\odot$.

correspond to the final presupernova radius of star 1. (Note that the dotted curve cannot be extrapolated to $m_{\text{env}} = 0$, since the final radius decreases drastically when m_{env} has decreased below a certain critical value.) These figures show three main results: First, even if the masses of the binary components are nearly equal, quasi-dynamical mass transfer can only be stabilized (i.e., $R_1 \leq R_L$) after the primary has lost a substantial amount of its hydrogen-rich envelope. Second, if the initial companion mass is less than about one-half of the mass of the initial primary, the primary has to lose all of its hydrogen-rich envelope and become a helium star. Third, even if the masses of the components are very similar, at most a few solar masses can remain in the envelope of the primary at the time of the supernova explosion.

Figures 6–8 illustrate the effects of varying the mass and angular momentum loss parameters, α and β , for the case $M_1^i = 12 M_\odot$. For these calculations it was assumed that the mass transfer took place at the same evolutionary stage as in the corresponding case in Figure 4. We find that the parameter regime for which star 1 can retain a significant amount of matter in its hydrogen-rich envelope decreases drastically with decreasing M_2^i . For $M_2^i = 6 M_\odot$ the original primary is expected to lose most of its envelope before the supernova event (except for a small and anomalous parameter region near $\alpha = \beta = 0$). Even if the initial masses of the binary components are nearly equal (see Fig. 6), star 1 must lose most of its envelope for $\alpha \sim 1$ and $\beta \sim 1$, as we expect for case C mass transfer. On the other hand, Figures 6–8 also show that M_2 may have been significantly increased by the mass-transfer event. As a result, the original secondary may become more luminous than the original primary by the time of the supernova event.

3.1.3. Summary and Discussion

In this subsection we have investigated the consequences of case B or case C mass transfer for the final presupernova appearance of the original primary component in massive binary systems. We have found the following:

1. The primary can retain part of its hydrogen-rich envelope for reasonable assumptions about the mass and angular momentum loss rates, provided that the binary components were originally close in mass.
2. The mass that remains in the hydrogen-rich envelope is at most several solar masses (i.e., the original primary is expected to lose most of its envelope before the supernova event).
3. Even though the original primary in such a system loses a substantial fraction of its total mass, its final presupernova

optical appearance is very similar to what it would have been without mass loss.

4. The original secondary is expected to accrete a substantial amount of the mass lost by the original primary, so that the secondary may become the more massive and luminous star of the system by the time the original primary explodes (the secondary may even explode first) (see also § 3.2).

This last property is particularly important for the identification of supernova progenitors on old photographic plates, since it implies that the most luminous star in the region in which a supernova occurred may be a companion of the progenitor rather than the progenitor itself. In addition, we expect that, after the supernova explosion, such a companion star will be hidden deep within the photosphere of the supernova ejecta and will disappear from our view. We estimate that it will take several years before the companion crosses the photosphere and "reappears" (see also Joss et al. 1988).

Even though the original primary in a stripped-giant model must lose a significant amount of its envelope, its final structure is similar to that of other more typical Type II supernova progenitors, and we surmise that the resulting supernova explosion resembles that of a classical Type II supernova (probably a Type II linear [= Type II-L] supernova; see, e.g., Trimble 1982). Since Type II supernovae form a rather inhomogeneous class (presumably because of a large range of possible core and envelope masses), it may be difficult to identify these systems when they occur in distant galaxies, in which case only very limited information may be available. On the other hand, the feature that all progenitors in the stripped-giant model share, namely, that they have lost a substantial fraction of their envelopes, may have noticeable consequences. In particular, we expect that lower envelope masses increase the initial velocities imparted to the ejecta, and that higher expansion velocities, in turn, produce a more rapid evolution of spectral features and the overall light curve. Lower envelope masses should also reduce the supernova plateau luminosity (see also Joss et al. 1988). We have begun a systematic theoretical investigation of supernovae of this type, which we shall henceforth refer to as Type II (stripped) supernovae. The results of this investigation will be published elsewhere (Hsu et al. 1992).

If the progenitor has lost all of its hydrogen-rich envelope (as we expect in the majority of cases; see § 4), the resulting supernova explosion would be of Type Ib/Ic, and would be characterized by a much faster light-curve evolution and a higher peak luminosity (see also § 5.1).

3.2. Accretion Models

Accretion of material from a companion is the second mechanism that can drastically alter the evolution and the final presupernova appearance of a massive star in a binary system. Mass accretion (generally onto the secondary) is expected to occur in most mass-transfer scenarios, with the probable exceptions of dynamical mass-transfer episodes (since it is the inability to accrete efficiently that leads to the formation of a common envelope; see § 2) and systems in which the secondaries are sufficiently massive that their high luminosities can prevent significant accretion.

The postaccretion evolution of the system depends sensitively on the evolutionary stage of the original secondary at the beginning of the accretion phase. In particular, the evolutionary path depends on whether the secondary (the accreting

component) has already left the main sequence or is still burning hydrogen in its core (i.e., whether the size of the hydrogen-exhausted core, which governs the further evolution of the secondary, has already been established).

3.2.1. Main-Sequence Accretion Scenarios

If the mass-transfer phase occurs before the original secondary has completed core hydrogen burning, the secondary will be rejuvenated as a main-sequence star and will subsequently mimic the standard evolution of a more massive single star (see also Hellings 1983). This is illustrated in Figure 9, which shows the evolution of a star with an initial mass of $15 M_{\odot}$ that accretes $5 M_{\odot}$ before it has finished hydrogen burning in its core (*solid curve*). The evolution after the accretion phase (the dashed portion of the track in Fig. 9) is very similar to the evolution of a single $20 M_{\odot}$ star (see the top panel in Fig. 10).

The further evolution of the original secondary can take several different paths. If the secondary does not fill its Roche lobe during the remainder of its lifetime, its evolution will resemble that of a single star (except that the wind mass-loss rate may be enhanced by the presence of a close binary companion; see Vanbeveren 1987; Tout & Eggleton 1988). The final presupernova appearance of the secondary will be that of a red supergiant, and the resulting supernova explosion will be a typical Type II supernova.

If the original secondary fills its Roche lobe, the system will enter into a second mass-transfer phase (probably after passing through a brief massive X-ray binary phase; see van den Heuvel & Habets 1985). This phase is expected to be dynamically unstable, since, in general, the original primary will already have become a neutron star and since, with extreme mass ratios (typically $\sim 10:1$) between the mass-losing and mass-gaining components, the development of a common-envelope phase seems unavoidable (see also van den Heuvel & Habets 1985). The final outcome of this evolutionary branch depends on whether the envelope of the common-envelope system is ejected or whether the two binary components merge completely. In the first case, the result would be a short-period Wolf-Rayet binary (with an orbital period of the order of days), eventually leading to a Type Ib/Ic supernova (see § 5.1). In the second case, the merged system would be a Thorne-Zytkow

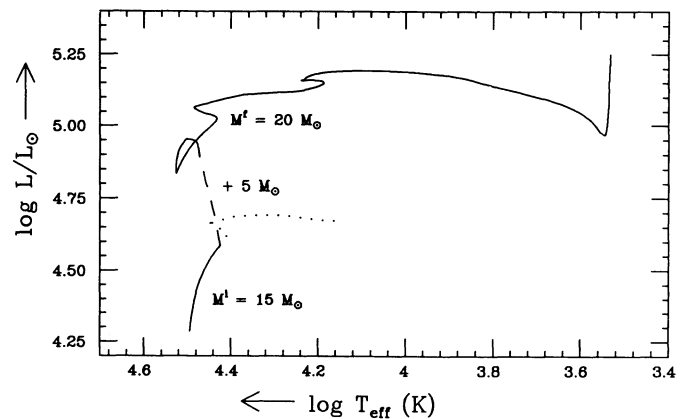


FIG. 9.—Rejuvenation of a main-sequence star of initial mass $15 M_{\odot}$ that accretes $5 M_{\odot}$ near the end of the main-sequence phase. The dashed portion of the track denotes the accretion phase. The evolution after the accretion phase resembles the evolution of a single $20 M_{\odot}$ star (see the top panel in Fig. 10). For comparison, the dotted curve shows the track of a $15 M_{\odot}$ star without accretion until just after the end of the main-sequence phase.

object (i.e., a neutron star embedded in a supergiant; see Gamow & Teller 1938; Thorne & Żytkow 1975, 1977), and the system would avoid a second supernova explosion altogether. We expect that a Thorne-Żytkow object will lose its envelope via a strong stellar wind on a time scale of $\sim 10^7$ yr (for typical red supergiant wind mass-loss rates) and will eventually leave a single neutron star or black hole remnant (perhaps a single millisecond pulsar).

3.2.2. Post-Main-Sequence Accretion

If the accretion phase takes place after the secondary has consumed all the hydrogen in its core (i.e., after it has established the size of its hydrogen-exhausted core), the further evolution of the secondary will differ substantially from the evolution of a single star of the same mass. In particular, it may end its life as a blue supergiant rather than as a red supergiant, which is the generally expected precursor for Type II supernovae (Falk & Arnett 1977; Woosley & Weaver 1985).

Whether the final presupernova star is a red or a blue supergiant depends on some rather subtle aspects of the physics of the stellar envelope and is not entirely amenable to heuristic explanation (see Barkat & Wheeler 1988; Tuchman & Wheeler 1989a, b). The problem is closely related to the question of why isolated stars become red giants, which itself is a controversial subject (see, e.g., Renzini 1984; Weiss 1989).

An important factor in determining the time of transition to the red giant phase is the fractional core mass $\xi_c \equiv m_c/M$, where m_c is the mass of the hydrogen-exhausted core and M is the total mass of the star. It is well known from the theory of the evolution of massive stars that a reduction in envelope mass (for example, by mass loss through a stellar wind) and a consequent increase in ξ_c favors redward motion in the H-R diagram (Maeder 1984). Conversely, a decrease in ξ_c (for example, by accretion of matter from a close binary companion) may prevent the transition to the red supergiant stage (or reverse it if it has already occurred).

In order to determine under what circumstances this mechanism may produce a blue supernova progenitor, we performed a series of stellar evolution calculations wherein such accretion was allowed to occur. In most of our calculations, we assumed an initial composition of $Y = 0.28$, $Z = 0.02$ and utilized the same theoretical assumptions as those given for the calculations presented in § 3.1. We followed the evolution of three stellar models with initial masses of 15, 17, and 20 M_\odot from the zero-age main sequence to the onset of core carbon burning. (This mass range was again chosen because it is representative of models for the progenitor of SN 1987A.) After the termination of the core hydrogen-burning phase, we accreted 5 M_\odot onto the 15 M_\odot model and 3 M_\odot onto the 17 M_\odot model. Thus, all three models had a final mass of 20 M_\odot ; the masses of the hydrogen-exhausted cores were 4.5, 5.3, and 6.4 M_\odot , respectively. We assume that the time that has elapsed since the end of the mass-transfer episode is long compared to the Kelvin time, τ_K , of the progenitor (τ_K is of the order of 10^4 yr). Under these circumstances, the appearance of the progenitor just prior to the supernova event should be essentially independent of the details of the mass-transfer process.

The results of our model calculations are illustrated in Figure 10. We find that models with final values of ξ_c larger than a certain critical value ξ_c^0 are red supergiants (on the Hayashi track in the H-R diagram) just prior to becoming supernovae, while models with $\xi_c < \xi_c^0$ end their lives as blue supergiants.

In order to examine the dependence of the final presuper-

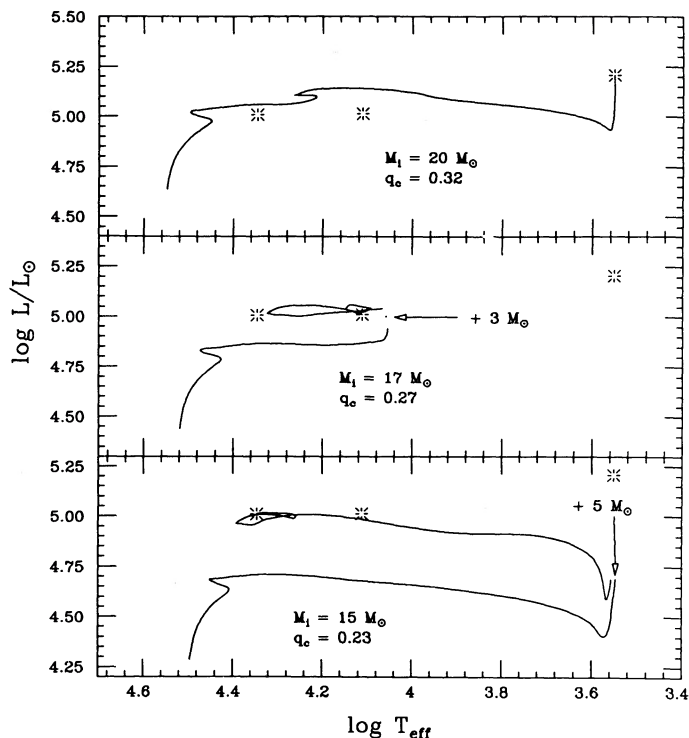


FIG. 10.—Effects of mass accretion on the evolutionary tracks of massive stars in the H-R diagram. *Top panel*: Evolutionary track of a 20 M_\odot star without accretion. *Middle panel*: Evolutionary track of a star with an initial mass of 17 M_\odot that accretes 3 M_\odot after the termination of core hydrogen burning (the dotted portion of the curve denotes the mass-transfer phase; the arrow indicates the onset of mass transfer). *Bottom panel*: Same as above, for a star with an initial mass of 15 M_\odot that accretes 5 M_\odot after the core hydrogen-burning phase; here the small break in the curve denotes the mass-transfer phase. In each case, M_i denotes the initial mass and $\xi_c \equiv M_c/M$ is the final fractional core mass, M_c being the final mass of the hydrogen-exhausted core and $M (= 20 M_\odot)$ the total mass of the star. The asterisks indicate the values of the model parameters just prior to the supernova event. (For comparison, the final parameter values of all three cases are shown in each panel.)

nova properties on the final value of ξ_c , we carried out an additional series of calculations on our model with an initial mass of 15 M_\odot . Keeping the final mass fixed at 20 M_\odot , we artificially varied the value of ξ_c near the end of the helium core-burning phase. We then evolved this series of models to the end of core carbon burning. The results of these calculations are shown in Figures 11 and 12, which show the final presupernova luminosity L and radius R as functions of m_c . For our chosen metallicity ($Z = 0.02$), we find that the critical value of ξ_c that separates blue from red solutions is $\xi_c^0 \approx 0.27$. We carried out additional calculations with $Z = 0.01$ and found that, in this case, the final appearance of the model changes more gradually with ξ_c (these results are shown as the dashed curves in Figs. 11 and 12). Our calculations show that the final radius of the progenitor decreases monotonically with increasing accreted mass (i.e., decreasing ξ_c). We also find that the dependence of the stellar luminosity of a blue supergiant progenitor on the core mass of the progenitor is relatively weak. Hence, the luminosity of a blue progenitor cannot be accurately determined from its core mass if the star has accreted a substantial amount of matter after termination of core hydrogen burning (see, however, Nomoto & Shigeyama 1987; Barkat & Wheeler 1988).

In summary, we find that some of our detailed numerical results are sensitive to the assumed parameters of our models. However, our qualitative conclusions regarding the viability of

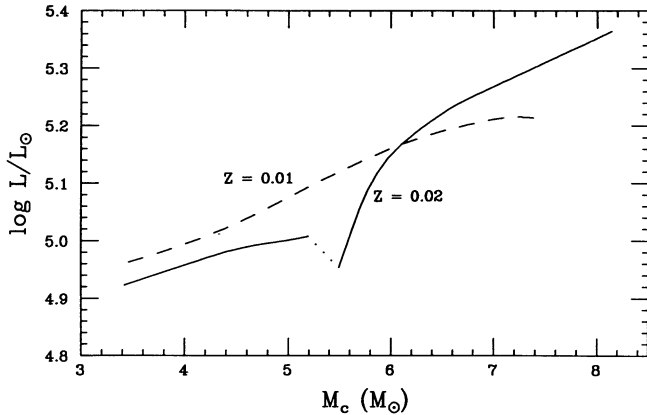


FIG. 11.—Final presupernova luminosity L of a $20 M_{\odot}$ star as a function of the final mass, M_c , of the hydrogen-exhausted core. The solid and dashed curves show our results for metallicities of $Z = 0.02$ and $Z = 0.01$, respectively. (All calculations assume an initial helium abundance of $Y = 0.28$.) The dotted portion of the $Z = 0.02$ curve marks the range in core mass for which the envelope of the immediate supernova progenitor is not in thermal equilibrium.

blue supernova progenitors are insensitive to the assumed metallicity, the treatment of convection, the details of the mass-transfer process, or the amount of mass that may be lost by the supernova progenitor in a stellar wind following the mass-transfer phase. In order that our basic picture be tenable, we require only that at least several solar masses more be accreted by the progenitor than is subsequently lost via a stellar wind, and that the accretion phase take place after the termination of the main-sequence phase of the progenitor.

3.2.3. Post–Main-Sequence Accretion Scenarios

We now consider the binary evolutionary scenarios in which mass transfer as described above can be expected. We require the supernova progenitor to have been a member of a close binary system and to have been originally the less massive star, since the original primary fills its critical lobe first and becomes the mass donor. Since the primary must already have completed core hydrogen burning before the commencement of mass transfer, there are two possible scenarios, involving case B and case C mass transfer, respectively. Since the two sce-

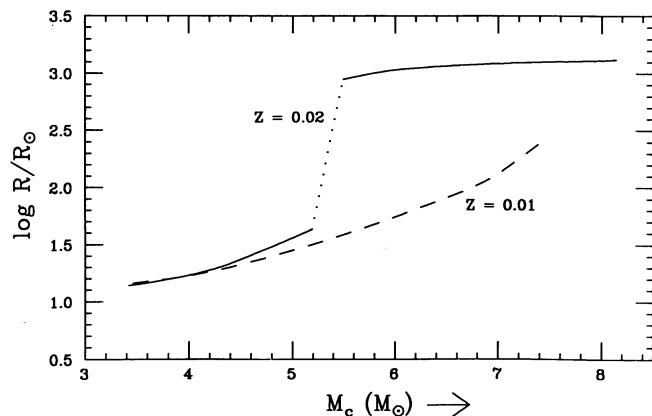


FIG. 12.—Final presupernova radius R of a $20 M_{\odot}$ star as a function of the final mass, M_c , of the hydrogen-exhausted core. The solid curve shows the results for a metallicity of $Z = 0.02$ and the dashed curve for a metallicity of $Z = 0.01$. The dotted portion again marks the transition region between blue and red supernova progenitors.

narios have very different consequences, we shall discuss them separately.

3.2.3.1. The Case B Mass-Transfer Scenario

In the case B mass-transfer scenario, the primary fills its critical lobe when it is on the first red giant branch. Since the secondary must already have left the main sequence prior to the onset of mass accretion, and since the main-sequence lifetime, τ_{MS} , of a massive star is long compared with the time interval Δt from the termination of core hydrogen burning to arrival at the tip of the red giant branch, the mass of the supernova progenitor must be very close to that of the primary. Since the main-sequence lifetime, τ_{MS} , for a star of mass M (in the range of $15\text{--}20 M_{\odot}$) scales approximately as $M^{-1.5}$, it is straightforward to show that the difference ΔM between the mass of the primary star and that of the supernova progenitor is constrained by the inequality $\Delta M/M \lesssim 2\Delta t/3\tau_{\text{MS}}$. Using the results for our $15 M_{\odot}$ model, we find that the initial mass of the secondary must be within $\sim 0.3\%$ of the initial mass of the primary. Binary systems composed of stars with the requisite masses and initial orbital separations (of the order a few AU) should be rather rare. We note, however, that a large fraction of observed close binaries do, in fact, contain two stars of approximately equal mass (Abt & Levy 1978; Tutukov & Yungel'son 1980). (On the other hand, observational selection effects tend to favor the discovery of equal-mass systems.)

Because of the mass increase the post–main-sequence evolution of the secondary may be faster than the corresponding evolution of the original primary. As a result, the secondary may reach the supernova stage earlier than the primary (by as much as $\sim 10^5$ yr for our $15 M_{\odot}$ model). Thus, in this scenario, the secondary may have a stellar companion prior to the supernova event, even though it was originally the less massive star of the system. However, since more than half the total mass of the binary system will be ejected in the supernova explosion, the system will almost certainly not remain bound. (This is strictly true only if the supernova explosion is spherically symmetric. If it is asymmetric, then there is a small but nonnegligible probability that the system remains bound; see, e.g., Bailes 1989.) We estimate that the velocity of the companion relative to the supernova remnant is $\sim 40(M_1/20 M_{\odot})^{1/2}(a/10 \text{ AU})^{-1/2} \text{ km s}^{-1}$, where M_1 is the mass of the progenitor just prior to the supernova event and a is the orbital separation at that time.

3.2.3.2. The Case C Mass-Transfer Scenario

The constraint on the relative masses of the binary components in the case C mass-transfer scenario is much weaker than that encountered in the case B scenario: the secondary must still be originally the less massive of the binary components, but the initial mass of the secondary may differ from that of the original primary by as much as $\sim 10\%$. In this case, mass transfer occurs when the original primary reaches the asymptotic giant branch (i.e., after it has completed helium core burning), whereas the supernova progenitor can be in any preceding post–main-sequence phase. The subsequent evolution is quite different from that of the case B scenario. The original primary undergoes a supernova explosion shortly after the mass-transfer phase and is expected to leave a neutron star or black hole remnant. The binary system remains bound but possibly obtains a substantial eccentricity, $e \simeq 0.1\text{--}0.5$. For an ensuing time of up to $\sim 10^6$ yr, while the progenitor of the second (observed) supernova undergoes advanced evolutionary phases, the neutron star will accrete a portion of any stellar

wind emitted by the progenitor. We can estimate the X-ray luminosity, L_x , resulting from this accretion by use of the Bondi-Hoyle model (Bondi & Hoyle 1944) for wind accretion:

$$L_x \simeq 3 \times 10^{33} \text{ ergs s}^{-1} \left(\frac{\dot{M}}{10^{-6} M_\odot \text{ yr}^{-1}} \right) \left(\frac{v_w}{500 \text{ km s}^{-1}} \right)^{-4} \times \left(\frac{D}{10 \text{ AU}} \right)^{-2} \left(\frac{M_{\text{NS}}}{1.4 M_\odot} \right)^3 \left(\frac{R_{\text{NS}}}{10 \text{ km}} \right)^{-1}, \quad (7)$$

where \dot{M} is the rate of mass loss from the progenitor, v_w is the wind velocity, D is the binary orbital separation ($D = a$ for a circular orbit), and M_{NS} and R_{NS} are the mass and radius of the neutron star, respectively.

More than half the total mass of the binary system will be ejected in the second supernova explosion, and the system will generally become unbound (see, however, the discussion in § 3.2.3.1 above). The older neutron star (i.e., the collapsed remnant of the original primary) should become detectable within a few years after the supernova explosion, either as a radio pulsar or as an X-ray source powered by the accretion of material from the supernova remnant.

3.2.4. Summary and Discussion

We have here shown that mass accretion can drastically alter the further evolution of the secondary component of a close binary and lead to a wide variety of supernova events. If mass accretion takes place before the accreting star has completed its main-sequence phase, it will either end its life in a classical Type II or Type Ib/Ic supernova, or it will become a Thorne-Żytkow object (and eventually an isolated pulsar), thereby avoiding a supernova explosion altogether.

If mass accretion takes place after the secondary has exhausted its core hydrogen supply, and if the star has accreted a sufficient amount of mass, then the final supernova progenitor will be a blue supergiant, and the resulting supernova will then resemble SN 1987A. In this scenario, the final color of the presupernova star depends on the amount of matter that has been added to the progenitor. As studies of SN 1987A have shown (see, e.g., Arnett 1987; Nomoto & Shigeyama 1987; Woosley, Pinto, & Ensmann 1988), smaller presupernova stars produce supernovae that are very different from standard Type II supernovae with red supergiant progenitors (see, e.g., Trimble 1982; Woosley & Weaver 1986). In particular, we expect the velocities imparted to the ejecta to be much higher than in standard Type II supernova, which will lead to rapid evolution of the supernova light curve and color. On the other hand, the plateau luminosity should be significantly lower than in the typical Type II supernova, since a larger fraction of the energy deposited in the ejecta is consumed in the adiabatic expansion of the smaller, more tightly bound progenitor. We conclude that supernovae of this type (which we henceforth shall refer to as Type II [blue] supernovae) form an easily identifiable subclass of Type II supernovae, although they are more difficult to discover because of their lower luminosities.

We note, however, that this subclass itself may not be very homogeneous, since (1) cobalt mixing seems to have been significant in SN 1987A (see, e.g., Shigeyama, Nomoto, & Hashimoto 1988; Woosley 1988) and (2) the final size of the progenitor is a function of the total amount of mass that has been added to the progenitor (see Fig. 12). The added mass, in turn, depends sensitively on the initial parameters of the binary system (see also § 3.1.3).

Finally, we expect that, in most accretion scenarios, the orig-

inal primary of the system has already completed its evolution and left a neutron star or black hole remnant. This may lead to observable interactions between the expanding supernova shell and the collapsed companion and may provide a direct observational test for the existence of a presupernova binary.

3.3. Merger Models

The most dramatic way in which binary interaction can affect the evolution of a star is in the merger of the two components of the system into a common envelope. This is generally expected to occur in late case B/case C mass-transfer scenarios, whenever the mass-losing star is significantly more massive than the mass-gaining star. Even though the precise circumstances and the details of dynamical mass transfer and common-envelope evolution are not well understood (see the discussion in § 2), common-envelope evolution probably occurs quite frequently in nature, since late case B/case C mass transfer is expected to take place for a large range of binary parameters.

The final outcome of common-envelope evolution depends on whether the envelope is ejected or remains bound. If it is ejected, the system will become either a cataclysmic variable (Paczynski 1976) if the mass of the primary's core is $\sim 1.4 M_\odot$ or less, or a low-mass, short-period helium star binary if the primary's core mass is $\sim 1.4 M_\odot$ or greater. In the latter case, the primary may end its evolution in a Type I supernova. We note, however, that if the supernova blast wave strips a significant amount of hydrogen-rich material off the companion, the supernova might be misclassified as a Type II (see Wheeler, Lecar, & McKee 1975; Fabian et al. 1987; also see, however, Livne, Tuchman, & Wheeler 1991).

In this subsection we consider the second possibility, namely, that the envelope remains bound and that the two stellar cores merge to form a single star.

3.3.1. Computational Procedure

To model the merger of two stars in a common-envelope phase, we have further modified our Henyey-type code to take into account the additional gravitational binding of the envelope due to the presence of an immersed companion and the effects of the frictional luminosity generated by the orbital decay of the spiraling-in binary on the structure of the common envelope. In our calculations, we assume an initial helium abundance and metallicity of $Y = 0.25$ and $Z = 0.02$, respectively; we take the mixing length equal to 1.5 pressure scale heights; and we assume the frictional luminosity to be a specified constant throughout the common-envelope phase. Since our calculations are one-dimensional, we must make several additional simplifying assumptions in our modeling of the common-envelope phase. We assume that the common envelope is centered on the core of the supernova progenitor and that the immersed companion (the original main-sequence companion) is a point mass (of mass M_2) at a distance $r(m_p)$ from the center of the progenitor, m_p being the portion of the mass of the progenitor that lies interior to the orbit of the companion. To model the gravitational effect of this point mass, we introduce an effective, nonconstant "gravitational constant," $G'(r)$, by

$$G'(r) = \begin{cases} G & [r < r(m_p)] \\ G[m(r) + M_2]/m(r) & [r > r(m_p)] \end{cases}, \quad (8)$$

where G is the universal gravitational constant and $m(r)$ is the mass of the progenitor enclosed in a sphere of radius r . Using

$G'(r)$ instead of G in the numerical calculations simulates the gravitational potential of an ordinary star that has an additional mass M_2 spread evenly in a spherically symmetric shell (of infinitesimal thickness) at a distance $r(m_p)$ from the center of the star. Although this approach neglects nonspherical effects in the neighborhood of the companion star, it is a good approximation in the outer parts of the common envelope, where the gravitation potential approaches spherical symmetry. Thus, as far as the evolution of the envelope is concerned (which is one of our primary interests, since this evolution determines the appearance of the system), our approximation becomes better as the separation between the two immersed binary components decreases (note that the common-envelope system is expected to spend most of its time at relatively small binary separation; see Meyer & Meyer-Hofmeister 1979). The orbital decay of the two spiraling-in cores is determined in our model by the assumed (constant) frictional luminosity, L_{fric} , and the change in the orbital energy, E_{orb} , of the immersed binary,

$$E_{\text{orb}} = -\frac{Gm_p M_2}{2a}, \quad (9)$$

where $a \equiv r(m_p)$ is the orbital separation of the two cores. The change in separation, $\Delta a = \Delta r(m_p)$, in a time step Δt is obtained from

$$\Delta a = -\frac{2a^2 L_{\text{fric}}}{Gm_p M_2} \Delta t. \quad (10)$$

The frictional luminosity is added as an additional energy source to the mass shell in which the companion resides at any given moment (we neglect the additional energy contribution from accretion of matter onto the main-sequence companion; also see Meyer & Meyer-Hofmeister 1979). Our adopted procedure is similar to the procedure of Meyer & Meyer-Hofmeister (1979). The main difference is our a priori assumption of a constant frictional luminosity. However, this assumption is consistent with the results of the calculations by Meyer & Meyer-Hofmeister, who argue that the orbital decay of the immersed binary is governed by a self-regulating mechanism that keeps the frictional luminosity approximately constant during the spiral-in process.

When the separation between the core and the enveloped main-sequence star has been reduced sufficiently, the Roche lobe of the secondary becomes smaller than the stellar radius, and the subsequent character of the system evolution changes qualitatively. Thereafter, the size of the Roche lobe determines the radius of the secondary. If we assume a fixed main-sequence mass-radius relation for the secondary, the mass of the secondary is also determined. [We use $R = (M/M_\odot)^{0.8}$, but we note that this is only a crude approximation, since the secondary is out of thermal equilibrium.] The secondary then starts to lose mass to the common envelope and is slowly dissipated. We take this process into account by adding the dissipated mass to the mass shell in which the companion is located at any given time. We note that our chosen procedure is not entirely realistic, since we did not model several processes which are likely to be important under some circumstances: (1) We did not include mass loss from the common envelope, which is likely to be substantial and could prevent the merger process from continuing to completion; (2) we did not consider cases in which the secondary is also an evolved star with a compact core (in this case, the two cores would

probably merge, which would lead to a larger mass for the helium core); and (3) we did not include any modifications of the chemical composition profile near the primary's core. Such changes could be caused by either the dissolution of a slightly evolved secondary or the centrifugally driven dredge-up of processed material from the primary's core (Meyer & Meyer-Hofmeister 1979).

3.3.2. Numerical Results

Figures 13–15 display the results of two representative merger calculations involving case B and case C mass transfer.

For the case B scenario, we modeled the merger of a $3 M_\odot$ main-sequence star with a $16 M_\odot$ red supergiant (with a hydrogen-exhausted core of $4.5 M_\odot$) on the first red giant branch. For illustrative purposes, we held the frictional luminosity constant in this calculation at $L_{\text{fric}} = 4 \times 10^4 L_\odot$. The solid curve in Figure 13 represents the evolutionary track of a $16 M_\odot$ star without binary interaction, and the dot-dash curve shows the evolutionary track of the $16 M_\odot$ star after it has merged with the $3 M_\odot$ main-sequence star. (For clarity, the common-envelope phase itself is not shown in Fig. 13.) Figure 14 displays the radius of the common envelope and the orbital separation of the spiraling-in binary as functions of time since the beginning of the common-envelope phase.

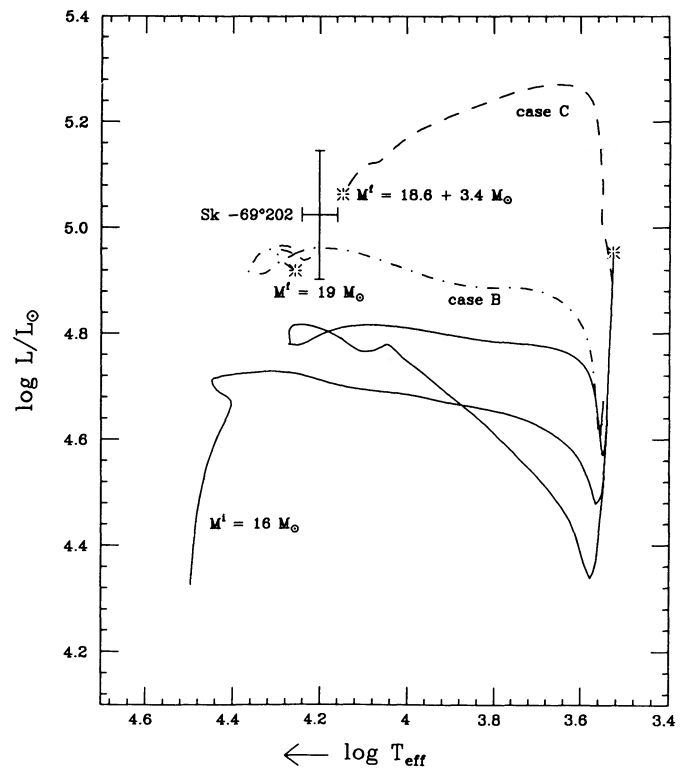


FIG. 13.—Evolutionary tracks in the H-R diagram of a $16 M_\odot$ single-star model (solid curve) and two illustrative merger calculations (dashed and dot-dash curves). The dot-dash curve shows the evolutionary track of a $16 M_\odot$ star after it has completely merged with a $3 M_\odot$ main-sequence star in a case B common-envelope phase (the common-envelope phase itself is not shown), and the dashed curve shows the evolution of a $16 M_\odot$ star which is still in the process of merging with a $6 M_\odot$ main-sequence star (case C scenario). In the latter case, the merger has not been completed by the time of the supernova explosion. The asterisks mark the locations of the models at the time of the respective supernova explosions, and the error bars indicate the location of Sk $-69^\circ 202$ for comparison.

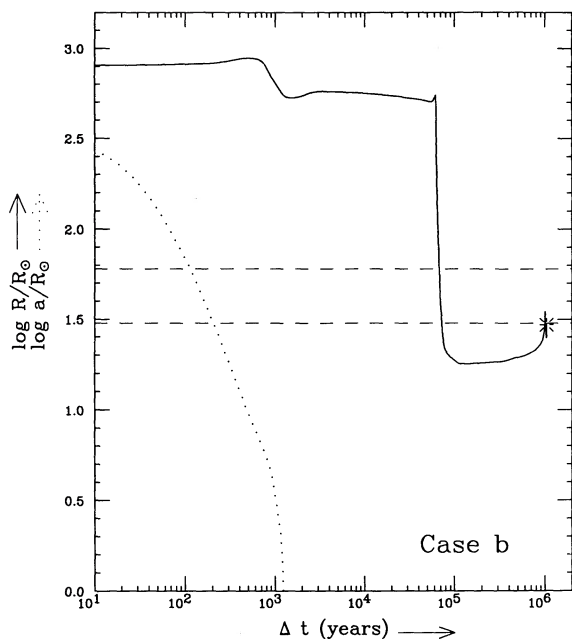


FIG. 14.—Radius R of the common envelope (solid curve) and separation a of the immersed binary (dotted curve) as a function of time, Δt , since the beginning of the common-envelope phase, for a $3 M_{\odot}$ main-sequence star merging with a $16 M_{\odot}$ red supergiant on the first red giant branch (case B scenario). The frictional luminosity was kept constant at $4 \times 10^4 L_{\odot}$ during the common-envelope phase (which lasts ~ 1300 yr). The dashed lines indicate the range of acceptable values for the radius of the progenitor of SN 1987A. The asterisk marks the radius of the model just before the supernova explosion.

For our chosen value of L_{fric} , the secondary has completely dissolved after only ~ 1300 yr. Thus, the final outcome of the common-envelope phase is a single star of mass $19 M_{\odot}$ with a $4.5 M_{\odot}$ core. Such a star is very similar to the models we presented in § 3.2, wherein the mass in the hydrogen-rich envelope had been increased relative to the mass in the hydrogen-exhausted core by the accretion of matter from a binary companion. As in our earlier calculations, the star spends most of its helium core-burning phase and the final stages of its evolution as a blue supergiant (see Figs. 13 and 14). Our calculations were terminated at the end of the carbon core-burning phase.

Since the typical spiral-in time in the merger model is of the order of 10^3 – 10^4 yr (see also Taam, Bodenheimer, & Ostriker 1978; Meyer & Meyer-Hofmeister 1979), which is much shorter than the remaining evolutionary time in any case B scenario, we expect that, in this case, the merger will always have been completed by the time of the supernova explosion. However, this may not be true if the common-envelope phase is the result of a case C mass-transfer event. The remaining lifetime for a massive star ($M \gtrsim 14 M_{\odot}$) on the asymptotic giant branch is only $\sim 10^4$ yr; for a star of mass $20 M_{\odot}$ it is ~ 4000 yr. Since this time scale is of the same order as the spiral-in time, it seems likely that, in this case, the merger of the two stars would not have been completed by the time of core collapse.

To illustrate this case, we modeled the merger of a $6 M_{\odot}$ main-sequence star with a $16 M_{\odot}$ star on the asymptotic giant branch. We here took L_{fric} to be constant at a value of $1 \times 10^4 L_{\odot}$. The dashed curve in Figure 13 displays the evolutionary track of the resulting composite system in the H-R diagram,

and Figure 15 shows the radius of the common envelope and the orbital separation of the spiraling-in binary as functions of time since the beginning of the common-envelope phase. We find that the added mass of the secondary increases the gravitational binding of the envelope and triggers a runaway contraction of the envelope (this contraction is just the reverse of the process that drives post-main-sequence stars to the red giant branch; see § 3.2). At the time of the supernova explosion, the common-envelope system resembles a blue supergiant, but the envelope still contains the orbiting cores of the two merged stars. (In our example, the final mass of the secondary is $\sim 3.4 M_{\odot}$ and the separation is $\sim 9 R_{\odot}$.) We note that, for significantly larger values of the frictional luminosity, the common envelope would remain extended throughout the common-envelope phase (a large frictional luminosity counterbalances the gravitational effect of the added mass and can prevent contraction of the envelope), and the merger of the two stars would have been completed before the supernova event. The final system would again be an isolated star with an increased envelope mass (similar to the case B scenario described above).

3.3.3. Discussion

We have here investigated the consequences of the merger of the two components of a binary system and found that, in most cases, the final system will have the appearance of a more or less ordinary isolated star. However, we expect that in many cases the mass in the envelope of this “new” star will be significantly increased (provided that the mass of the secondary is not too low and that the mass-loss rate during the common-envelope phase is not too drastically enhanced). The presupernova star may then resemble a blue supergiant rather than a

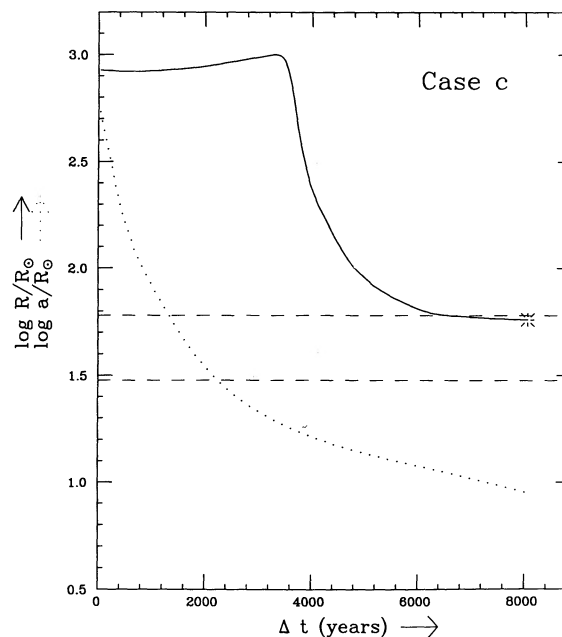


FIG. 15.—Radius of the common envelope (R ; solid curve) and separation of the immersed binary (a ; dotted curve) as functions of time, Δt , since the beginning of the common-envelope phase, for a $6 M_{\odot}$ main-sequence star merging with a $16 M_{\odot}$ red supergiant on the asymptotic giant branch (case C scenario). The frictional luminosity was kept constant at $10^4 L_{\odot}$. The asterisk marks the radius of the model just before the supernova explosion; at this point, the mass of the companion was $3.4 M_{\odot}$.

red one. Indeed, the final structure of the star should be very similar to the structure of the stars in the accretion scenarios discussed in § 3.2, and we conclude that the resulting supernova explosion should be of the same type as in the previous model (i.e., Type II [blue]). The main difference between these two models is that the progenitor in the merger model is an isolated blue supergiant without a surviving companion to provide a test of the model. A possible imprint of the progenitor's binary history may come in the form of chemical anomalies in the envelope, since the frictional luminosity during the spiral-in phase should induce convective currents that may dredge up nuclear-processed material (e.g., nitrogen- and helium-rich material, and possibly s-processed material; see also Taam et al. 1978; Meyer & Meyer-Hofmeister 1979; Iben & Tutukov 1985). Such abundance anomalies may be detectable in spectra of the progenitor, in circumstellar material, or in the outer layers of the supernova ejecta. In addition, we expect that the progenitor in a merger scenario will be rapidly rotating; such rotation may lead to an asymmetric supernova explosion and may provide another signature of a merged system (see also Chevalier & Soker 1989).

We also found that, in a case C scenario, the remaining evolutionary time for very massive stars may be of the same order as the spiral-in time. It is then possible that the merger would not be completed by the time of the supernova explosion, so that the progenitor would still have an immersed companion at the time of the explosion. In this case, the presupernova common-envelope system may appear either as a blue or a red supergiant (depending on the values of the frictional luminosity and other parameters). An immersed companion at the time of the supernova explosion may also affect the supernova itself. For example, the presence of the companion may provide a trigger for hydrodynamical instabilities that drive the mixing of core material into the outer layers of the ejecta.

4. MONTE-CARLO SIMULATION OF BINARY SCENARIOS

In § 3 we systematically explored the consequences of interaction in binary systems for the evolution of massive supernova progenitors and found that binary interaction can lead to a variety of different supernova types. In order to put the various scenarios into the general context of supernova theory, we attempt in this section to estimate their a priori probabilities.

Figure 16 provides an overview of evolutionary scenarios for massive stars with initial masses between $8 M_{\odot}$ and $20 M_{\odot}$. The diagram is considerably simplified, but should contain the most important channels. Several other cases can be imagined, particularly if multiple mass-transfer scenarios are considered more systematically (as was done for low- and intermediate-mass binaries in the series of papers by Iben and Tutukov; see Iben & Tutukov 1987 and references therein). We have also made a number of simplifying assumptions in the diagram; for example, we assume that case A mass transfer (where mass transfer commences while the primary is still on the main sequence; Kippenhahn & Weigert 1967) always leads to a merger of the two components, whereas it is conceivable that the primary is gradually transformed into a helium star without ever passing through a common-envelope phase.

The percentages given in Figure 16 are estimates for the probability that a stellar system containing an initial primary with an initial mass in the chosen mass range passes through a particular evolutionary channel. (Note that our definition of "initial primary"—the initially more massive star of a stellar system—also includes isolated stars.) These estimates are weighted averages of the results of the Monte Carlo simulations described below and should be considered to be only very rough approximations.

Estimating the a priori probabilities for the different evolutionary channels in Figure 16 is difficult, since the statistical

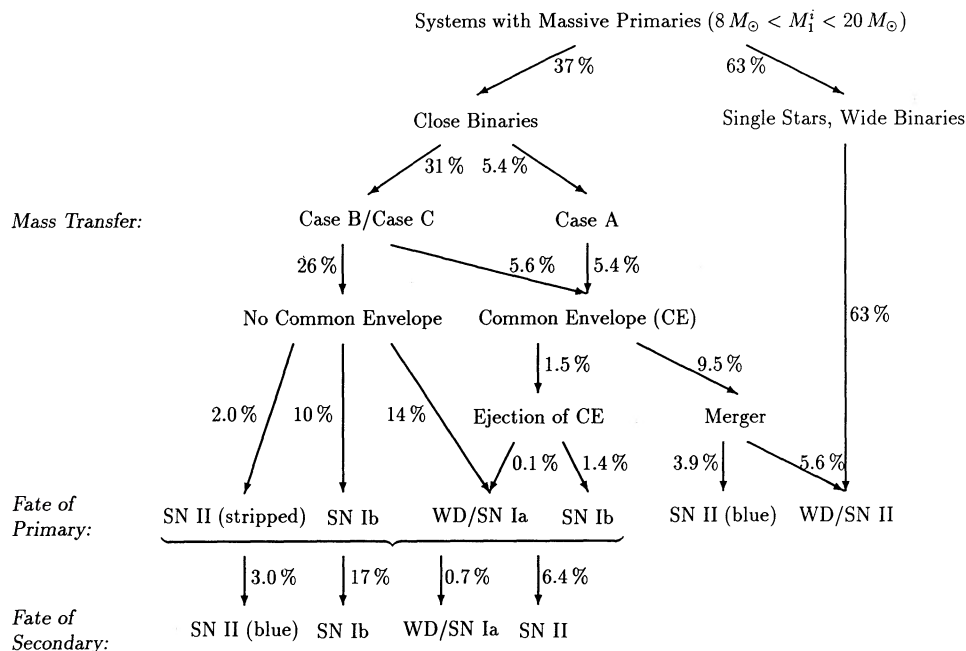


FIG. 16.—Summary of evolutionary scenarios for systems containing massive primaries with masses between $8 M_{\odot}$ and $20 M_{\odot}$ (simplified; see text). The percentages give the (theoretical) probabilities that a system with an initial primary in the chosen mass range passes through the particular evolutionary channel. The calculations assumed that 50% of all massive stellar systems are binaries with periods of less than 100 yr. The probabilities are based on Monte Carlo simulations and are very approximate (see text).

data on multiple systems are very incomplete, and some of the major phases in the evolution of binary systems are poorly understood theoretically. Uncertainties in the stellar evolution calculations also affect our estimates. For example, the ratio of the number of case B to case C mass-transfer events and the ratio of the number of accretion events to that of merger events depend sensitively on whether a star of a given mass undergoes a first red giant phase before the onset of core helium burning (which, in turn, depends sensitively on the assumed opacities, mass-loss rates, and so forth; for a recent discussion see Fitzpatrick & Garmany 1990). Hence, in order to carry out the Monte Carlo simulations, we found it necessary to make a number of assumptions; although we were guided by several observational and theoretical studies, some of our assumptions are rather arbitrary, and all of our Monte Carlo results should consequently be considered tentative. Nevertheless, we believe that the results illustrate the importance of binary evolution in the study of core-collapse supernovae, since, as we shall see, they indicate that a significant fraction of all massive stars are likely to be affected by interaction with a binary companion. Our discussion of the individual assumptions will also illustrate the gaps in our understanding of binary evolution and highlight the areas that need improvement.

4.1. Binary Statistics

Our estimates of the distributions of initial binary properties are based on the extensive studies of multiple systems by Abt & Levy (1976, 1978) and Kraicheva et al. (1978, 1979). (For simplicity, we assume that the current observed primary was the original primary of the system, and we take the observed distributions to be best estimates of the initial distributions.) Although the two studies differ in their samples of systems and methods of analysis, many of their conclusions are similar. In particular, both studies conclude that duplicity in stellar systems is probably the rule rather than the exception. Both studies even suggest that the statistics (when properly extrapolated and corrected for selection effects) are consistent with all stars having at least one companion.

Here we are only interested in systems with massive primaries which are close enough so that mass transfer takes place during the course of their evolution. In their study of binaries with B IV and B V primaries, Abt & Levy (1978) found that 38% of all primaries in their sample of 39 systems have companions with masses greater than $0.66 M_{\odot}$ and periods shorter than 10 yr; when they correct their results for incompleteness, this percentage increases to 47%. This high frequency of close binaries has been challenged by Morbey & Griffin (1987; but see also Abt 1987), who were not able to confirm the orbital periods, and in several cases not even the binary nature, of a large number of the systems in the sample of Abt & Levy. Since the binary frequency is the single most important input parameter in our simulations, we use a range of values for the binary frequency; specifically, we assume that between one-third and two-thirds of all massive systems have companions with orbital periods shorter than 100 yr.

Kraicheva et al. (1978) have shown that the primary masses in close binaries are consistent with a Salpeter (1955) initial mass function. We therefore adopt this distribution for the primary masses, i.e., we assume that

$$\psi(M_1^i) dM_1^i \propto (M_1^i)^{-2.35} dM_1^i. \quad (11)$$

It is generally believed that the masses of the two components in a binary system with an orbital period less than

$\sim 10\text{--}100$ yr are strongly correlated (see, however, Duquennoy & Mayor 1990; Abt, Gomez, & Levy 1990), and that the distribution function $\Phi(q_i)$ for the initial mass ratio $q_i \equiv M_2^i/M_1^i$ (where M_1^i and M_2^i are again the initial masses of the initial primary and secondary, respectively) is peaked at $q_i = 1$ (presumably because of the formation mechanism). (To within a normalization constant, $\Phi(q) dq$ is the space density of binary systems with mass ratios between q and $q + dq$.) In our simulations, we use two different distribution functions for the initial mass ratio: an analytic fit to a Popov distribution (Popov 1970),

$$\Phi_P(q_i) = 0.034e^{5q_i}, \quad (12)$$

and the distribution adopted by Abt & Levy (1978),

$$\Phi_{AL}(q_i) = \frac{5}{4}q_i^{1/4}. \quad (13)$$

These two distributions are plotted in Figure 17.

Finally, to completely specify the distribution of initial properties of binary systems, we assume that the distribution function, $\Psi(P_i)$, for the initial orbital periods, P_i , is constant in $\log P_i$ for $P_i < 100$ yr (Abt & Levy 1978 find only a mild peak around 14 yr) and has a short-period cutoff determined by the condition that the primary fills its Roche lobe immediately after it has settled on the zero-age main sequence. (Note that this last assumption may lead to an overestimate of case A mass-transfer events; see also Kraicheva et al. 1978.)

4.2. Theoretical Assumptions

In all of our Monte Carlo simulations, we assume that the first mass-transfer phase takes place when the radius, R_1 , of the primary exceeds the radius of its Roche lobe (see eq. [6]). The evolutionary stage of the original primary at the beginning of the mass-transfer phase unambiguously determines the type of mass transfer (see § 2).

4.2.1. Common-Envelope Evolution

As we discussed in § 2, the circumstances under which a system enters into a common-envelope phase are not well understood. For definiteness we assume that a common envelope forms when the Roche lobe-filling component is significantly more massive than its companion ($q_i < 0.9$) and possesses a deep convective envelope.

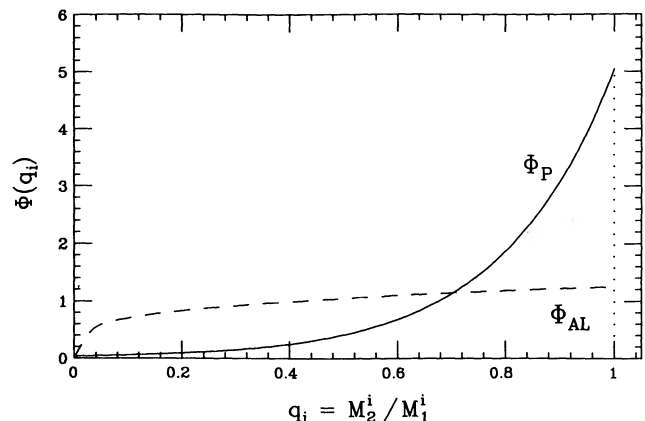


FIG. 17.—Distribution functions for the initial mass ratio, $q_i \equiv M_2^i/M_1^i$, in close binary systems. The solid curve represents an analytical fit to a Popov distribution (eq. [12]), and the dashed curve the distribution obtained by Abt & Levy (eq. [13]).

Whenever a common envelope forms, we must decide whether this leads to the merger of the two binary components or whether the envelope is ejected. Following Livio & Soker (1988), we define an efficiency parameter, α_{CE} , by

$$\alpha_{\text{CE}} = \frac{\Delta E_{\text{bind}}}{\Delta E_{\text{orb}}} \simeq \frac{2a_f(M_1 - M_1^c)(M_1 + M_2)}{M_1^c M_2 R_1^0}, \quad (14)$$

where M_1^c is the mass of the hydrogen-exhausted core of the primary, R_1^0 is the radius of the primary at the beginning of the common-envelope phase, and a_f is the orbital separation of the binary components when the radius of the secondary first exceeds its Roche lobe radius. (Afterward, the secondary is slowly dissipated and the orbital energy of the immersed binary starts to decrease in magnitude; see also § 3.3.) It is often assumed (see, e.g., Iben & Tutukov 1985) that the common envelope is ejected when α_{CE} (or a similarly defined parameter) decreases below unity. Physically, this implies that the envelope is ejected when the energy released by the orbital decay of the immersed binary exceeds the binding energy of the envelope. However, this criterion implicitly assumes that all of the energy generated by the orbital decay is deposited in the envelope rather than being radiated away (i.e., it is assumed that energy transport in the common envelope is very inefficient). This is probably not very realistic when the envelope is convective, Livio & Soker (1988) propose that the critical value of α_{CE} is near 0.3 on the basis of their hydrodynamical calculations of the ejection process. We here adopt this value and thus assume that the common envelope is ejected when α_{CE} is less than 0.3.

4.2.2. Evolution without a Common-Envelope Phase

If no common envelope forms, we follow the subsequent evolution using the method developed in § 3.1.1, which is characterized by the free parameters α and β . For specificity, we restrict the allowed parameter regime by assuming that β lies between 0.8 and 1.0 (i.e., mass transfer is nearly conservative) and α lies between 0.7 and 1.3 (which is the expected range if mass loss from the system occurs through or near L_2).

In several cases, the final presupernova appearance of the secondary (and consequently the supernova type) depends on whether the secondary has already left the main sequence at the beginning of the mass-transfer phase (see § 3.2). We take this into account by assuming that the secondary has already left the main sequence when q_i exceeds a critical value, which lies between 0.992 and 0.996 (depending on the primary mass) for a case B mass-transfer event, or between 0.90 and 0.92 for a case C event.

4.2.3. Fate of the Binary Components

The final fate of a star depends primarily on the mass of the hydrogen-exhausted core that the star develops during its evolution. In particular, we assumed that stars with final hydrogen-exhausted core masses above $2 M_{\odot}$ (corresponding to a main-sequence mass of $8 M_{\odot}$ in isolated stars; Nomoto 1984) experience core collapse and form neutron star (or black hole) remnants, while stars with lower core masses either become degenerate dwarfs (WD in Fig. 16) or undergo a disruptive thermonuclear explosion. If, in this last case, the star has lost all of its hydrogen-rich envelope by the time of the supernova explosion, we call the resulting supernova a Type Ia. We use this classification because this supernova type is

probably related to the observational class of Type Ia supernovae. We note, however, that the thermonuclear explosion of a helium star will be different in detail from the explosion of a degenerate dwarf (see also Nomoto 1982). In our simulations, we cannot always distinguish whether a particular evolutionary channel leads to the formation of a stable degenerate dwarf or to a thermonuclear explosion. This is because helium stars with masses below $2 M_{\odot}$ become helium giants before they ignite carbon and may lose all of their helium-rich envelopes in a second mass-transfer phase (which we have not modeled). In this case, they may end their evolution as degenerate carbon-oxygen dwarfs (see also the discussion in § 5.1). We therefore included degenerate dwarfs and Type Ia supernova in a single category (WD/SN Ia in Fig. 16).

The optical appearance of a core-collapse supernova explosion, on the other hand, depends sensitively on the mass in the hydrogen-rich envelope and the radius of the progenitor. All together, we consider four types of core-collapse supernovae: SN II, SN II (blue), SN II (stripped), and SN Ib. The progenitors of the first two types both have large, hydrogen-rich envelopes ($M_{\text{env}} \gtrsim 3 M_{\odot}$), but the progenitor is a red supergiant in the first case and a blue supergiant in the second (see the models in §§ 3.2 and 3.3). In our simulations, we assume that binary evolution leads to a blue supernova progenitor if the mass in its hydrogen-rich envelope has been increased (after the termination of the main-sequence phase) by 30% over its initial mass (this applies both to merger and to accretion scenarios and is probably a conservative assumption). Supernovae of Type II (stripped) are assumed to have red supergiant progenitors with depleted hydrogen-rich envelopes ($M_{\text{env}} \lesssim 3 M_{\odot}$; see § 3.1), while the progenitors of Type Ib/Ic supernovae have no hydrogen in the envelope and are very compact.

4.3. Results and Discussion

Table 1 summarizes the results of our Monte Carlo simulations. It presents the estimated frequencies of the various supernova types in Figure 16 for two binary frequencies (one binary for every three stellar systems in Table 1A and two binaries for every three stellar systems in Table 1B) and three selected mass ranges. The first figure in each column is based on the Popov distribution (eq. [12]) for the initial mass ratio, q_i , while the figures in parentheses are based on the Abt-Levy distribution (eq. [13]). The range of values in the two cases is a measure of the uncertainties in these estimates, although some of the estimates are probably even more uncertain than this comparison would suggest. The last column contains the averages for the whole mass range of primary masses under consideration weighted by the Salpeter (1955) initial mass function (eq. [11]). The resultant weighted averages of the individual evolutionary channels are shown in Figure 16 (for a Popov distribution and a binary frequency of 50%).

While all the results presented in this section should be considered tentative, they distinctly illustrate the importance of binary evolution for our understanding of supernova explosions in massive systems. The main conclusions of our Monte Carlo study are as follows:

1. The evolution of a large fraction ($\sim 20\% - 35\%$) of all massive stars is substantially affected by interactions with close binary companions. In most cases, the resulting supernova explosions differ substantially from ordinary Type II supernovae. We emphasize that this basic conclusion is essentially

TABLE 1
RELATIVE FREQUENCIES OF SOME SUPERNOVA TYPES

Supernova Type	8–11 M_{\odot}	11–15 M_{\odot}	15–20 M_{\odot}	Weighted Average
A. Assuming One Binary for Every Three Systems				
SN II	88% (87%)	81% (80%)	76% (76%)	83% (83%)
SN II (stripped)	0.5% (0.2%)	1.5% (0.5%)	0.9% (0.3%)	0.9% (0.3%)
SN II (blue)	3.7% (3.4%)	2.0% (1.8%)	3.6% (1.6%)	3.2% (2.4%)
Accretion	1.1% (0.4%)	0.7% (0.2%)	3.2% (1.0%)	1.4% (0.4%)
Merger	2.6% (3.0%)	1.3% (1.6%)	0.4% (0.6%)	1.8% (2.0%)
SN Ib	8.1% (9.4%)	16% (18%)	20% (22%)	13% (15%)
B. Assuming Two Binaries for Every Three Systems				
SN II	73% (71%)	63% (60%)	55% (55%)	66% (64%)
SN II (stripped)	1.2% (0.4%)	3.0% (1.1%)	1.7% (0.6%)	1.9% (0.6%)
SN II (blue)	8.0% (7.6%)	3.9% (3.7%)	6.7% (3.0%)	6.4% (5.1%)
Accretion	2.3% (0.8%)	1.3% (0.4%)	6.0% (2.0%)	2.8% (0.9%)
Merger	5.7% (6.8%)	2.6% (3.3%)	0.7% (1.0%)	3.6% (4.2%)
SN Ib	18% (21%)	31% (35%)	36% (42%)	26% (31%)

NOTE.—Shown are the relative frequencies of various core-collapse supernova types in systems with massive primaries ($8 M_{\odot} < M_1 < 20 M_{\odot}$), based on Monte Carlo simulations of the evolutionary scenarios in Fig. 16. The calculations assume that one-third (in Table 1A) and two-thirds (in Table 1B), respectively, of all systems are binaries with periods less than 100 yr. The frequencies refer to the percentages of all stars (not systems, as in Fig. 16) that experience a particular supernova explosion. The first figure in each item assumes a Popov distribution (eq. [12]) for the initial mass ratio, while the figure in parentheses assumes the distribution by Abt & Levy (eq. [13]). The last column contains the weighted averages of the individual cases, where the weights are determined from the Salpeter 1955 initial mass function for the mass of the primary (eq. [11]).

independent of the theoretical and observational assumptions that go into the simulations, since these assumptions mainly determine the different branching ratios for the various evolutionary channels and not the total number of affected supernova progenitors; it depends only on the well-established high frequency of close binary systems.

2. Some 15–30% of all massive stars are expected to lose all of their hydrogen-rich envelopes as a direct consequence of binary interaction. These stars are good candidates for Type Ib/Ic supernovae (see § 5.1).

3. In a significant fraction of cases ($\sim 5\%$), binary evolution will lead to a compact, blue progenitor with a substantial hydrogen-rich envelope. The resulting supernova explosion will resemble SN 1987A (see § 5.2).

4. Only in a limited parameter regime (in 1%–2% of the cases considered) is it possible for a massive primary to retain part of its hydrogen-rich envelope after a mass-loss event. If this is the case, the resulting presupernova star will be a red supergiant with a small hydrogen-rich envelope.

Unfortunately, a detailed comparison between the various scenarios and observed supernovae is not yet possible, since the properties of the supernova explosions in many of the scenarios discussed in this paper have not been fully explored theoretically, and since supernova statistics are too incomplete at the present time. Progress on both fronts is expected in the near future. Hsu (1991) has begun a systematic investigation of supernova explosions in massive binaries, and many of the results of the modeling of SN 1987A can easily be generalized to apply to our Type II (blue) supernovae. On the observational side, the advent of automated supernova searches (see, e.g., Kare et al. 1982), with the promise of detecting a large number of supernovae per year, may soon be able to provide the needed statistics.

5. APPLICATIONS

5.1. Type Ib/Ic Supernova

In §§ 3 and 4 we found that a large fraction of stars in massive close binaries lose all of their hydrogen-rich envelopes and thereby become helium stars. These stars are good candidates for the progenitors of Type Ib supernovae (for reviews of their observational properties see Panagia 1986; Porter & Filippenko 1987). Models for the progenitors of Type Ib/Ic supernovae include isolated Wolf-Rayet stars (Begelman & Sarazin 1986; Cahen, Schaeffer, & Cassé 1986; Chevalier 1986; Harkness et al. 1987), accreting degenerate dwarfs (Branch & Nomoto 1986; Panagia 1986), and helium stars in close binaries (Wheeler & Levreault 1985; Uomoto 1986). While theoretical atmosphere models suggest that the mass in the ejecta of these supernovae is large and hence points toward massive Wolf-Rayet stars as the progenitors of such supernovae (Harkness & Wheeler 1991), recent hydrodynamical models of the supernova explosion (Ensmann & Woosley 1988; Shigeyama et al. 1990) seem to favor lower mass helium stars formed in a binary environment. Both progenitor types could in principle contribute to this supernova class. On the other hand, we find in our simulations that $\sim 15\%$ – 30% of all massive stars (with initial masses between 8 and $20 M_{\odot}$) end their lives as helium stars with masses between 2 and $6 M_{\odot}$. This frequency is consistent with estimates for the frequency of Type Ib/Ic supernovae (Panagia 1986; van den Bergh, McClure, & Evans 1987) without requiring isolated Wolf-Rayet stars as additional contributors. If this is the case, the explosions of massive, isolated Wolf-Rayet stars might form a separate supernova class. Supernovae of this class should be less frequent than Type Ib/Ic supernovae (since their massive progenitors are relatively rare), and may be even less luminous than

Type Ib/Ic supernovae. Some evidence for this possibility may come from Cas A. The fact that there is no historical record of Cas A, even though it exploded around A.D. 1700 at a distance of only ~ 3 kpc (van den Bergh 1971), suggests that it was less luminous than a typical Type Ib/Ic supernova (see also Chevalier 1976).

In addition to helium stars with masses above $2 M_{\odot}$, our simulations also produced a comparable number of helium stars with masses larger than the Chandrasekhar limit of $\sim 1.4 M_{\odot}$ but less than $\sim 2 M_{\odot}$. These stars are not expected to experience core collapse or to leave neutron star remnants. Since they probably are completely disrupted in the thermonuclear explosion, they have, on occasion, been previously considered as candidates for the progenitors of classical Type Ia supernova (see, e.g., Nomoto 1982); in § 4 we tentatively called these stars Type Ia progenitors. Indeed, our frequency estimates are consistent with this possibility. However, since helium stars in this mass range become helium giants before they ignite carbon (Paczynski 1971; Nomoto 1982), most of these helium stars will experience a second mass-loss phase and be transformed into degenerate CO dwarfs (see, e.g., Iben & Tutukov 1985). Nevertheless, we expect that a fraction of these helium stars (mainly those that remain in relatively wide orbits after the first mass-transfer phase) can either avoid a second mass-transfer phase altogether or lose only part of their helium envelopes during this phase and end their evolution in a thermonuclear explosion. Since their presupernova structure is very different from that of a degenerate dwarf (Nomoto 1982), the resulting supernova explosions should, in principle, be distinguishable from classical Type Ia supernovae (i.e., the explosions of accreting/merging degenerate dwarfs).

5.2. SN 1987A

SN 1987A was the first close, naked-eye supernova since Kepler's supernova in 1604 and has presented us with many puzzles and mysteries. One of the major surprises and remaining mysteries of this event is the question of why the apparent progenitor was a blue supergiant, Sk $-69^{\circ}202$ (Kirshner et al. 1987; Walborn et al. 1987), rather than a red one, the generally expected precursor for Type II supernovae (Falk & Arnett 1977; Woosley & Weaver 1985).

The problem is not a lack of theoretical models to explain a blue progenitor—there are numerous ones—but the fact that most such models face rather serious objections. These models invoke ad hoc modifications to the theory of stellar evolution, a rather low metallicity for the progenitor, and/or a certain amount of fine tuning. Furthermore, many of the models seem to be inconsistent with independent observational constraints on the theory of massive stars.⁹ Models that rely on low metallicity alone (Arnett 1987; Hillebrandt et al. 1987; Truran & Weiss 1987) seem to be ruled out because they are unable to account for the observed number of red giants in the Large Magellanic Cloud (LMC; Humphreys 1984). Models invoking in addition a low helium abundance, a nonstandard treatment of turbulent convection, and an absence of significant mass loss from the progenitor star (Woosley et al. 1988) cannot explain

the distribution of stars in the H-R diagram for massive stars (Maeder & Meynet 1987; Tuchman & Wheeler 1989a, b). Models that invoke mass loss (Maeder 1987) require not only mass-loss rates that are much higher than those found in previous observational and theoretical investigations (Chiosi & Maeder 1986; Dupree 1986) but also extreme fine tuning of those rates. Similarly, models in which the progenitor was on a late Cepheid loop and did not have time to return to the red (Saio, Kato, & Nomoto 1988) need a considerable amount of fine tuning of both the mass-loss rate and the assumed helium enhancement within the progenitor, as well as a low metallicity. In fact, most of the models cited above require a metallicity ($Z \simeq \frac{1}{4} Z_{\odot}$) that is substantially lower than the metallicity inferred from a large number of metallicity indicators (Smith 1980; Harris 1983; Becker, Mathews, & Brunish 1984) for young stars in the LMC.

Binary evolution can solve the puzzle of the progenitor in two fundamentally different ways. First, it may hide the true progenitor; second, it may produce a blue progenitor as a direct consequence of a previous interaction with its companion. In models of the first type (Fabian et al. 1987; Joss et al. 1988), the progenitor would not have been the blue supergiant Sk $-69^{\circ}202$ but a previously undetected, relatively faint companion star. However, models of this type have difficulties in explaining the supernova light curve and other observed features of the SN 1987A explosion (see Hsu et al. 1991). Furthermore, by the end of 1990, the central prediction of such models, namely, the reappearance of Sk $-69^{\circ}202$, seemed to be ruled out by the bolometric light curve of the supernova (Suntzeff et al. 1991).

The accretion and merger models discussed in §§ 3.2 and 3.3 belong to the second class of models. The major advantage of either model over single-star models for SN 1987A is that a blue progenitor can be understood very naturally within the framework of *conventional* binary stellar evolution theory, without resort to ad hoc assumptions or modifications of the input physics (although our merger scenarios somewhat depend on some aspects of common-envelope evolution that are not well understood).

In addition, these binary models may account for many of the other anomalous features of SN 1987A. In particular, the natural structure of our presupernova models (in both the accretion and merger models) is sufficiently similar to those of single star models (Arnett 1987; Nomoto & Shigeyama 1987; Woosley et al. 1988) that one can expect these models to produce fits to the supernova light curve which are entirely as good as those achieved in the single-star models.

The asymmetric expansion of the ejecta, as inferred from polarization measurements and speckle interferometry (Cropper et al. 1988; Papaliolios et al. 1989), also has a natural explanation in a binary model, since one expects the progenitor to be rotationally flattened as a result of the spin-up it experienced either during the mass-accretion phase (in the accretion model) or during the spiral-in phase (in the merger model; see also Livio & Soker 1988; Chevalier & Soker 1989; Hillebrandt & Meyer 1989). Further evidence in favor of a flattened envelope structure comes from the ring of ejected material, discovered by Wampler et al. (1990) and confirmed by the *Hubble Space Telescope* (Jacobsen et al. 1990). The rotation axis of this ring approximately coincides with one of the symmetry axes of the ejecta (as inferred from the polarization and speckle observations). Plausible origins for the ejection of this material are a Be star phase of the progenitor in an accretion model or the common-envelope phase in a merger

⁹ At least one earlier model calculation (Lamb, Iben & Howard 1976) assumed only standard input physics but nevertheless produced blue supergiant supernova progenitors. However, these calculations cannot account for the observed red supergiant population in the H-R diagram of massive stars in the Galaxy or the Large Magellanic Cloud (Humphreys 1984; see Podsiadlowski 1991 for a more detailed discussion).

model. In both cases, the mass outflow will take place preferentially in the equatorial plane and lead to ringlike structures around the presupernova star. We also note that this ring is likely to become a stumbling block for many single-star models (see Chevalier & Soker 1989; Podsiadlowski 1991).

Moreover, the core mass of the supernova progenitor may be considerably lower (as low as $\sim 4 M_{\odot}$) in our scenarios than in most single-star scenarios; this may reduce the requisite optical depth of the ejecta and thereby decrease the amount of mixing between the interior and outer layers of the ejecta required to explain the early appearance of X- and γ -radiation (Dotani et al. 1987; Matz et al. 1988; see also Nomoto & Shigeyama 1987; Pinto & Woosley 1988; Bussard, Burrows, & The 1989).

Binary models may also provide plausible mechanisms for the various chemical peculiarities that have been reported for the progenitor of SN 1987A (particularly the high nitrogen abundance in the circumstellar material [Fransson et al. 1989], which may suggest a high nitrogen abundance in the envelope of the progenitor, and the barium anomaly in the supernova ejecta [Williams 1987]. These anomalies may result from the dredge-up of nuclear-processed material during the spiral-in phase in the merger model (see § 3.3 and Hillebrandt & Meyer 1989) or may be the consequence of rotational mixing in the accretion model (see also Podsiadlowski & Joss 1989).

Finally, if, at the time of the supernova explosion, the progenitor still had a binary companion (possibly immersed in a common envelope), this companion may have naturally introduced a low-density funnel in the supernova shell through which plasma might have escaped from the system soon after the explosion to produce the "mystery spot" (Nisenson et al. 1987; Rees 1987). A companion may also supply material for sporadic accretion onto the young pulsar, which may explain the variability of the soft X-ray flux (Bandiera, Pacini, & Salvati 1988; Fabian & Rees 1988).

5.3. *Puppis A*

Winkler et al. (1989) recently made the interesting suggestion that the supernova which produced the *Puppis A* remnant may have occurred in a binary system in which the secondary exploded only ~ 3000 yr after the primary. This hypothesis is based on their detection of a swirl of material near the center of the *Puppis A* supernova remnant that has the appearance of a

supernova remnant itself. Since the kinematic age of this second remnant is ~ 3000 yr younger than the age of the larger remnant, they speculate that this may have been a system where the initial masses of the two components were nearly equal and that mass accretion onto the secondary sped up its evolution so that the secondary exploded shortly after the primary. Their suggestion is remarkably similar to the case B accretion model discussed in § 3.2 (see also Podsiadlowski & Joss 1989). However, we found that, as a result of the added mass, the original secondary should evolve faster than the primary and may even explode first. Since, in this case, the original primary would most likely have been a compact helium star, this could also explain why the second supernova remnant in *Puppis A* is so inconspicuous. However, as we discussed in § 3.2, systems of this type should be extremely rare, since mass transfer must commence after the original secondary has finished its main sequence phase but before the primary has reached the tip of the first red giant branch.

6. CONCLUSIONS

We have systematically analyzed how binary evolution can affect the presupernova structure of massive stars and the subsequent supernova explosions. In the course of this investigation, we discovered several new evolutionary scenarios that may lead to rather distinct core-collapse supernovae. We estimated that roughly 20%–35% of all core-collapse supernovae may fall in one of these classes (where we also included Type Ib/Ic supernovae), and we concluded that a complete theory of core-collapse supernovae cannot be attained without fully considering the intricacies and complications of binary stellar evolution. One of the main goals of binary stellar evolution theory, even though not within reach at the present time, should be to understand the various evolutionary channels binary evolution allows (see Fig. 16) and to be able, in conjunction with improved observational statistics and/or a better understanding of the star formation process, to derive the a priori probabilities of the various scenarios. Only when this has been achieved can we hope to understand the evolution of massive close binary systems and the nature of the supernova explosions that such systems produce.

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