Progenitors and Hydrodynamics of Type II and Ib Supernovae

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We review critical physics affecting the observational characteristics of those supernovae that occur in massive stars. Particular emphasis is given to 1) how mass loss, either to a binary companion or by a radiatively driven wind, affects the type and light curve of the supernova, and 2) the interaction of the outgoing supernova shock with regions of increasing ρr^3 in the stellar mantle. One conclusion is that Type II-L supernovae may occur in mass exchanging binaries very similar to the one that produced SN 1993J, but with slightly larger initial separations and residual hydrogen envelopes ($\sim$1 $M_\odot$ and radius $\sim$ several AU). The shock interaction, on the other hand, has important implications for the formation of black holes in explosions that are, near peak light, observationally indistinguishable from ordinary Type II-p and Ib supernovae.

1. Some Generalities

There is broad agreement regarding the qualitative evolution of single stars sufficiently massive to ignite carbon burning non-degenerately (e.g., Woosley & Weaver 1986; Weaver & Woosley 1993; Nomoto & Hashimoto 1986, 1988). Given the usual, relevant caveats about the treatment of convective mixing, convective overshoot, and semiconvection, it is agreed that stars of approximately 8 to 12 $M_\odot$($\pm$1 $M_\odot$ depending upon initial helium abundance and convective parameters) will *not* proceed to silicon burning in hydrostatic equilibrium, but will stop prior to central neon ignition and experience a complicated subsequent evolution in which degenerate flashes play an important role. Stars of larger mass, up to perhaps 100 $M_\odot$ on the main sequence, will ignite carbon, neon, oxygen, and silicon burning non-degenerately and develop an iron core of from $\sim$1.25 to 2 $M_\odot$. The collapse of this iron core owing to electron capture and photodisintegration instabilities, will produce either a neutron star or a black hole and, at least frequently, give rise to an outgoing shock which explodes the star (see articles elsewhere in this volume by Janka and by Burrows).

Though of limited mass range, stars of 8 - 12 $M_\odot$ are of considerable interest and uncertain evolution. Stars of 8 to 10 $M_\odot$ (all mass ranges here uncertain to $\pm$1 $M_\odot$) burn carbon to produce degenerate ONeMg cores of about 1.1 $M_\odot$ (Nomoto 1984, 1987; Hashimoto, Iwamoto, & Nomoto 1993). The core grows by accretion through thin hydrogen and helium shells until either a) thin shell flashes lead to the loss of the hydrogen envelope leaving an ONeMg white dwarf (Nomoto 1984; Weaver & Woosley, unpublished), or b) the core grows to 1.38 $M_\odot$ and a central density of $\sim 9.5 \times 10^9$ g cm^{-3} at which point electron capture ignites degenerate oxygen burning. What follows is controversial (Canal, Isern, & Labay 1992; Nomoto & Kondo 1991; Timmes & Woosley 1992) and depends on a careful physical depiction of the propagating burning front. Our own recent calculations (Timmes & Woosley, 1994b) show that central ignition at this density should lead to core collapse. One thus expects a subsequent evolution qualitatively sim-

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ilar to that accompanying iron core collapse in larger stars, but with some observational distinctions. First, the density gradient at the edge of the ONeMg core is very steep. Little ^{56}Ni will be produced. Mayle & Wilson (1988) calculate ~0.002 $M_\odot$ of ^{56}Ni for a model of this sort. Also the envelope mass might be smaller than for the higher mass stars (e.g., 15 $M_\odot$) responsible for Type II-p supernovae. Swartz, Wheeler, & Harkness (1991) have suggested that such stars might be the progenitors of Type II-L supernovae, though the ^{56}Ni mass they assume (0.03 $M_\odot$) may be too large for this class of model. More work is needed both on the explosion model and the pre-explosive mass loss to clarify the observational properties of these supernovae.

The range 10 to 12 $M_\odot$ also gives rise to interesting and uncertain evolution. Woosley, Weaver, & Taam (1980) first modelled the evolution of these stars which burn neon and oxygen in a series of degenerate shell flashes while still in stable equilibrium. Similar results have been found by Nomoto & Hashimoto (1988), but much uncertainty remains. Does the series of flashes progress smoothly to the center or are some flashes so violent as to lead to envelope ejection several years before the supernova explodes (as Woosley & Weaver found)? Is an iron core ever produced? A proper study again requires the careful treatment of the burning. This time the burning front propagates *inwards* and is bounded by a convective region. Timmes & Woosley (1994a) have recently determined the physical properties of such flames in the steady state - their temperatures and velocities as a function of composition, radius, and density. It remains to incorporate these analytic results into a stellar evolution code and properly model stars in this mass range. Preliminary indications from this study are, though, that the neon burning flame will propagate smoothly to the center without violent flashes. The flashes observed in earlier studies may have been due to finite zoning. Still the full evolution of these stars, especially beyond neon burning remains very uncertain. Above 11 (or 12) $M_\odot$, the presupernova evolution becomes simpler, less influenced by the effects of degeneracy, and the final configurations better determined. Weaver & Woosley (1993) have calculated a variety of presupernova models for variable masses and rates for $^{12}C(\alpha,\gamma)^{16}O$. A new grid of models which includes more masses and a range of metallicities is in preparation (Weaver & Woosley 1994) and essentially complete. Sample models are available upon request by e-mail. The iron masses for this second set of models, as defined by various criteria, are given in Fig. 1. These models all employed a total rate (E1 + E2) for the $^{12}C(\alpha,\gamma)^{16}O$ rate corresponding to an S-factor at 300 keV of 170 keV barns. This is consistent with recent analyses by Buchmann et al. (1993), who found 57± 13 keV barns for the E1 part, Zhao et al. (1993), who found 95± 44 keV barns for the E1 part, and Barker & Kajino (1992) who estimate that the E2 part is approximately one half of the E1 part. A smaller value, such as the 100 keV barns used by Caughlan & Fowler (1988) and in many stellar evolution studies since, is also consistent with the data.

For the stars considered, the iron core boundary is very nearly the same, whether defined by an abrupt increase in the electron mole number, Y_e, or the inner edge of the silicon shell. For stars in the 11 to 18 $M_\odot$ range this core has a mass near 1.4 $M_\odot$ (because of neutrino losses, the neutron star would be smaller should a mass cut develop here). For stars of 18 $M_\odot$ and above, the star has a substantial silicon shell, the base of the oxygen shell providing an entropy jump that sometimes is relevant in setting the remnant mass in "delayed" explosions. We shall see later that the explosion may have difficulty ejecting all the mass outside of the iron core for stars heavier than 25 $M_\odot$ leading to the possibility of black hole formation. Thus it may be that neutron stars originate from just those stars in the 11 to 25 $M_\odot$ range. Determination of the actual mass cut requires a difficult calculation, but the iron core (baryonic) masses here range from about 1.35 to 1.8 $M_\odot$, a reasonable range for neutron star masses that are observed.

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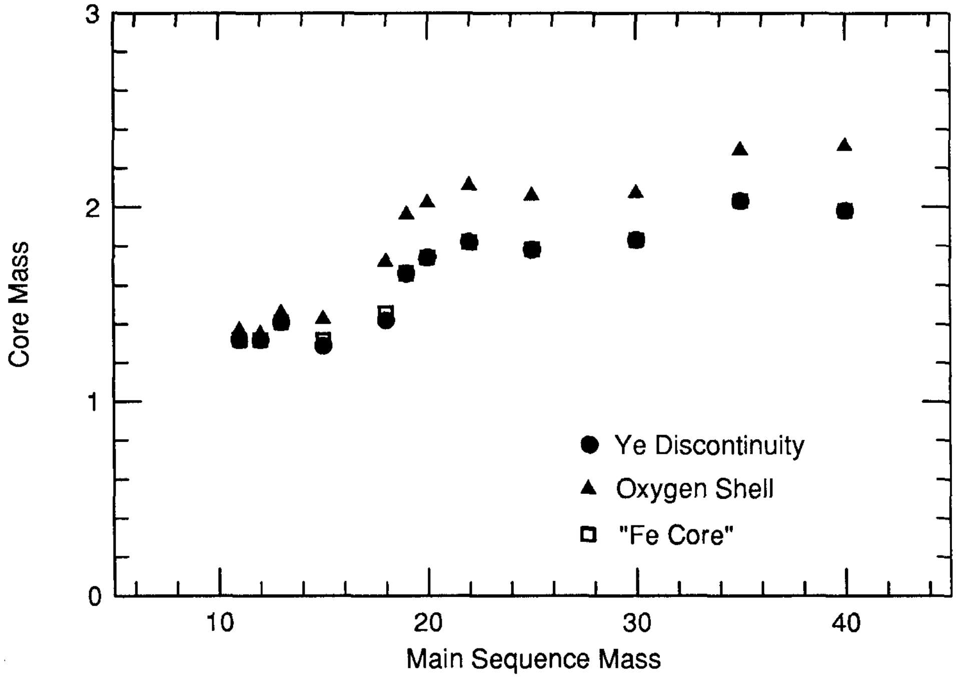

FIGURE 1. Iron core masses as defined by that location where Y_e increases discontinuously to near 0.50 moving outwards in the star and by the condition that the mass fraction of all iron group elements exceed 0.5. Also given is the location of the oxygen burning shell.

Explosion of any of these stars should produce a Type II-p supernova with properties mainly dependent upon how much envelope has been lost (probably a small amount for M less than about 25 $M_\odot$) and the mass of ^{56}Ni produced in the explosion. Eastman et al. (1994) have recently computed the light curve for a typical 15 $M_\odot$ model. The absolute magnitudes are given in Fig. 2.

2. The Effects of Mass Loss

For stars that do not lose their entire envelope, the principal effect of mass loss is to shorten and otherwise alter that stage in the supernova's life when luminosity comes from shock deposited energy released by recombination. For stars that have experienced little mass loss, the envelope has a mass of 10 - 15 $M_\odot$. For stars above 30 $M_\odot$, this mass declines precipitously even for single stars. In a binary, of course, depending upon the initial separation and companion mass, any star may lose all or a portion of its envelope when it becomes a red giant. Consider first those stars that are in binaries. Podsiadlowski, Joss, & Hsu (1992) have surveyed the hydrogen and helium burning evolution of a large number of massive stars and derived statistics for supernova progenitors of Type II-p, Ib (assumed to occur if the star loses its entire envelope), and Type II "stripped" (low mass residual envelope). See their Table 1. Recently, in our attempts to model SN 1993J, we have carried out similar studies but have assumed conservative mass transfer and followed the evolution of the primary to iron core collapse. Some representative models are given in Table 1.

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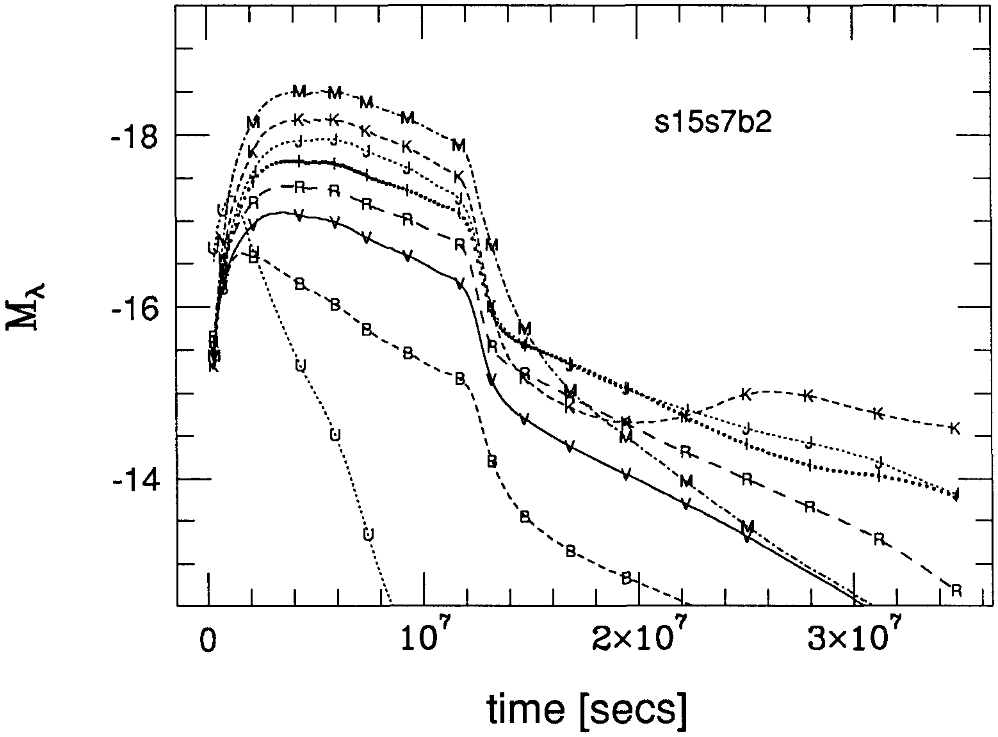

FIGURE 2. Multiband photometry of a 15 $M_\odot$ model supernova (Model s15s7b2 of Weaver & Woosley 1994) which had a final kinetic energy at infinity of 1.23 $\times 10^{51}$ erg and produced and ejected a mass of ^{56}Ni equal to 0.058 $M_\odot$ (Eastman et al. 1994).

TABLE 1. Binary Evolution

Model	Initial a (AU)	Final a (AU)	Companion ($M_\odot$)	Final R_R (AU)	Mass ($M_\odot$)	M_{env} ($M_\odot$)	R_{preSN} (10^{13} cm)	L_{preSN} (10^{38})
11A	2	6.4	8	1.60	3.09	0.20	2.15	1.66
11B	3	8.2	8	2.11	3.43	0.54	2.57	1.67
13A	3	9.1	9	2.29	3.67	0.15	2.86	2.32
13B	4	12.0	9	3.03	3.69	0.18	3.86	2.33
13C	5	14.3	9	3.65	3.80	0.28	4.89	2.32
15A	3	7.8	10	2.03	4.54	0.19	2.80	3.32
15B	4	10.5	10	2.71	4.55	0.19	3.56	3.39
15C	4.5	11.6	10	3.02	4.57	0.21	4.03	3.38
15D	5	9.8	10	2.70	5.51	1.16	3.48	3.31
15E	3	8.1	10	2.08	4.45	0.37	2.76	2.12

Models from Woosley, Eastman, and Weaver (1993); Model name gives mass the star originally had on the main sequence.

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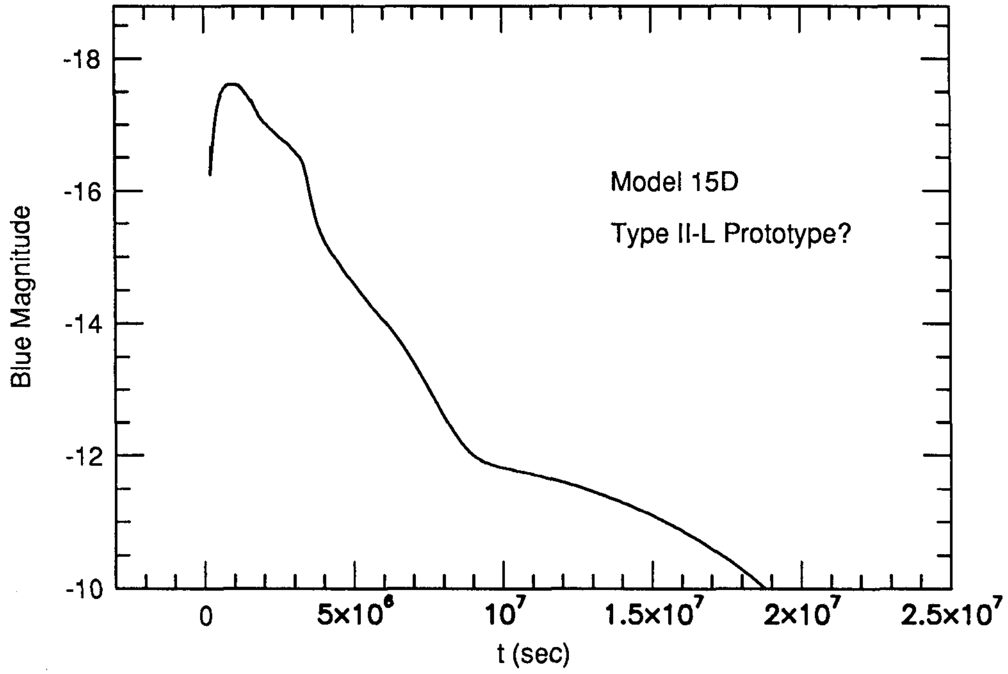

FIGURE 3. The explosion of Model 15D (M_{env} = 1.16 $M_\odot$; ^{56}Ni mass = 0.073 $M_\odot$) produces a blue band light curve very similar to what is seen in Type II-L supernovae (Woosley, Eastman, & Weaver 1994).

The stars in Table 1 all share a quasidynamic phase of mass loss that occurs on approximately a Kelvin-Helmholtz time scale (for the envelope) as the primary first becomes a red supergiant. For stars that employ moderate semiconvective mixing this episode occurs late during helium core burning ($Y_c \sim 0.05$ to 0.15) and removes all but ~ 1 $M_\odot$ of the envelope. A second phase of rapid mass transfer often ensues when the star makes the transition from helium core burning to carbon ignition. During this period, which now occurs on a Kelvin-Helmholtz period for the *core* (as modified by neutrino losses), the star shifts from a helium core plus hydrogen shell power source to a thick helium shell source. The surface luminosity increases, the radius attempts to increase, and mass loss ensues. We find that all the models in Table 1 are nearly filling their Roche lobes at the time of explosion. The slight difference between the Roche radius (R_R) and the presupernova radius is a consequence of the way we implement the mass loss numerically, $\dot{M} \propto (R/R_R)^n$ with n a large number, here arbitrarily taken to be 50.

Many of these models converge on a final envelope mass less than 0.30 $M_\odot$. Roughly 0.2 $M_\odot$ of (helium-rich) envelope is necessary to sustain a red supergiant photosphere of several AU. Were the mass to drop below this value, owing say to continuing radiative or pulsationally driven mass loss, the radius would shrink rapidly and the explosion would resemble Type Ib. For some choices of orbital separation, however, e.g., Model 15D, the Roche radius of the presupernova star is sufficiently large that the envelope stays at ~ 1 $M_\odot$ at the time of explosion.

As Fig. 3 shows, stars like Model 15D may be promising candidates for producing Type II-L supernovae. There is considerable observational variation in observations of Type II-L, but the blue magnitude of this model is in good qualitative agreement with

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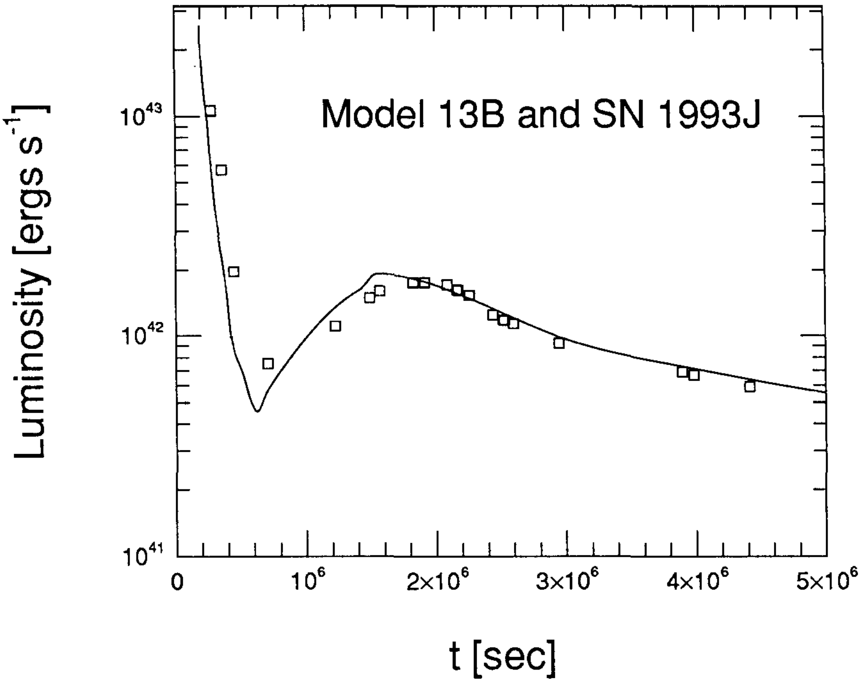

FIGURE 4. The explosion of Model 13B gives a bolometric light curve in good agreement with what was observed in SN 1993J (Woosley, Eastman, & Weaver 1994).

the template defined by Doggett & Branch (1985). Fig. 4 shows the *bolometric* light curve of a model that lost more of its envelope (Model 13B) and now presents a display very similar to what was observed in SN 1993J (Wheeler & Filippenko, this volume; Schmidt et al. 1993). This is typical of many of the models in Table 1.

Should the star lose all, or nearly all, of its remaining envelope, the supernova will be Type Ib. If the mass transfer is in a binary, it is important whether the envelope is removed early in helium burning or late. For the models in Table 1 closer separations or (much) larger mass loss rates while inside the Roche radius would have led to the loss of the entire envelope but little else. In that case the presupernova star would closely resemble a helium core equal to the presupernova mass evolved without mass loss. Such models have been extensively studied in the literature and can give good agreement with observations for helium core masses around 3 or 4 $M_\odot$ (e.g., Ensman & Woosley 1988; Shigeyama et al. 1990). However, there is another way to make Type Ib from a more massive star. Single stars more massive than about 35 $M_\odot$ may lose their envelopes and a substantial part of the helium core mass as well (Woosley, Langer, & Weaver 1993). The same final state may also be characteristic of stars that lose their envelopes to a close binary companion early in their evolution and then have accelerated mass loss as a Wolf-Rayet star (Woosley, Langer, & Weaver 1994). For reasonable assumptions regarding the mass loss rate of Wolf-Rayet stars, there may be a pile up of final masses around 3 to 4 $M_\odot$. Figure 5 shows the composition of a star, initially composed of 10 $M_\odot$ of helium, and evolved assuming a mass dependent mass loss rate. This star is distinguishable from helium cores evolved without mass by the large surface abundances of carbon and oxygen (and correspondingly low abundance of helium). Still more massive progenitors would have similar final masses but less helium at the surface. Perhaps this helium deficiency

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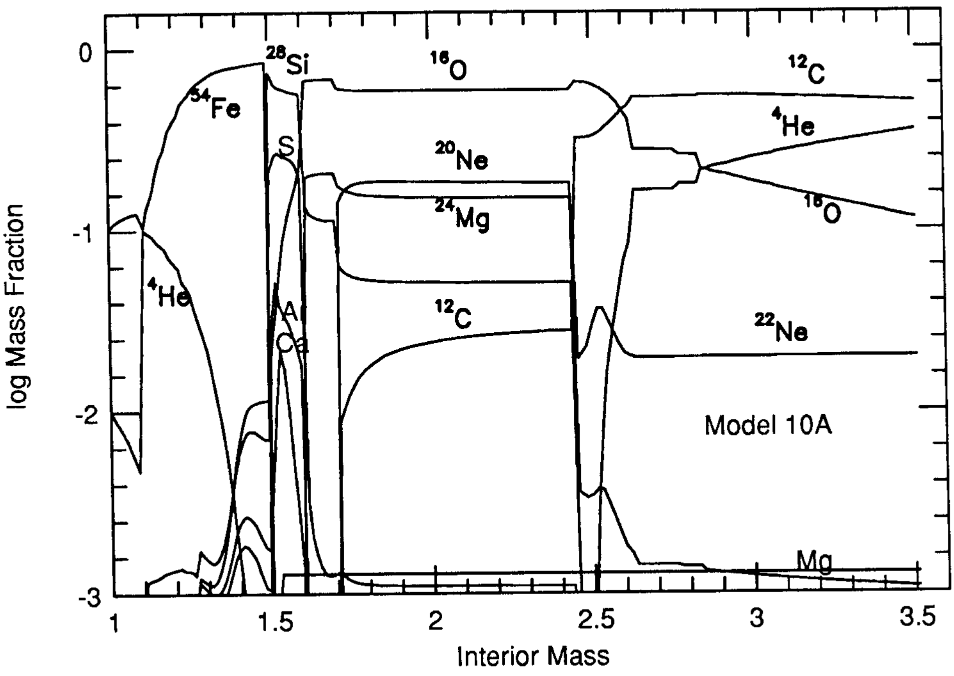

FIGURE 5. Composition of a 10 $M_\odot$ helium core evolved with mass dependent mass loss as a Wolf-Rayet star. The composition is sampled at the time of core collapse (Woosley, Langer, & Weaver 1994).

corresponds to that reported for supernovae of Type "Ic" (Harkness & Wheeler 1990). Chosing a mass cut at the base of the oxygen shell (1.60 $M_\odot$) in this model and simulating an explosion which gives 1.0 $\times 10^{51}$ erg of kinetic energy at infinity produces 0.08 $M_\odot$ of ^{56}Ni and a light curve given in Fig. 6. Unlike the light curves in Figs. 2,3, and 4, this one was calculated using the stellar hydrodynamics code, KEPLER, and is only approximate. Still it is not a bad fit to Type Ib supernovae.

3. Shock Propagation, Mixing, and Fall Back

One of the enduring lessons of SN 1987A has been a better understanding of the Rayleigh-Taylor (RT) instability responsible for mixing in the explosion (Chevalier & Klein 1978; Hachisu et al. 1990; and Fryxell, Müller & Arnett 1991; Herant & Benz 1992). Recently this same sort of mixing has been studied in the explosion of ordinary red supergiants (Herant & Woosley 1994). That paper also discusses the Sedov solution for shock waves propagating in a density gradient ($\rho \propto r^{-n}$) and its relevance for "fall back" in Type II supernovae.

In general, an adiabatic shock passing through a medium with n less than 3, (i.e., increasing ρr^3) must decelerate. One place where ρr^3 increases dramatically is at the interface between the helium core and the hydrogen envelope (Fig. 7), This increase is largely responsible for the formation of the "reverse shock" that gives rise to the RT instability referenced above (Bethe 1990). Because it occurs in a region behind and out of sonic communication with the outgoing shock, the deceleration propagates inwards (in Lagrangian coordinate) as a shock wave.

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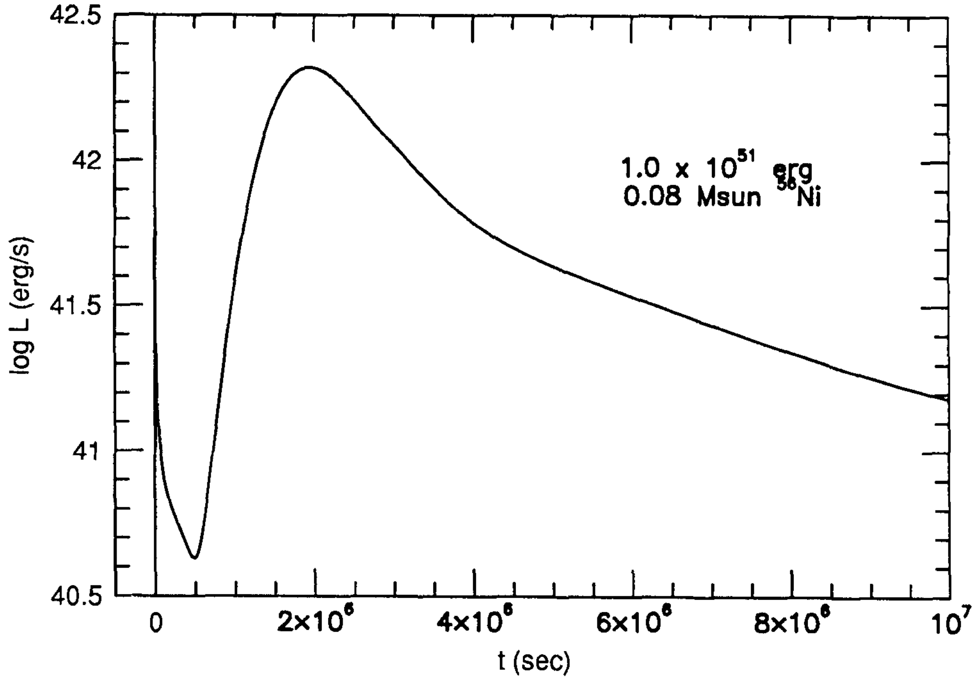

FIGURE 6. Approximate bolometric light curve when the model in Fig.5 is exploded with a piston at 1.60 $M_\odot$.

As Fig. 7 shows, however, there is another important region of increasing ρr^3 especially prominent in the mantles of the more massive stars (e.g., between 3 and 8 $M_\odot$ in the 35 $M_\odot$ model). The outgoing shock also slows in these regions, but because the sound speed is still high, deceleration of the outgoing material occurs smoothly - there is no reverse shock. Nevertheless this deceleration can lead to significant amounts of material falling back into the collapsed remnant. This has some interesting implications for the formation of black holes.

Fig. 8 shows the final mass of the collapsed remnant for a series of simulated explosions in presupernova models of various masses and metallicities (Weaver & Woosley 1994). In each case the piston was located at the Y_e discontinuity (Fig. 1) and given sufficient velocity such that the final kinetic energy at infinity of all ejecta was 1.2×10^{51} erg. *In all cases the entire hydrogen envelope was ejected with high velocity and (for all red supergiants) a normal Type II-p light curve was produced.* However, a variable amount of mass fell back onto the (stationary) piston well after the explosion had been launched. In a 25 $M_\odot$ star with a Y_e jump and piston at 1.78 $M_\odot$ for example, the fall back mass was 0.29 $M_\odot$ which included most, but not all of the 0.39 $M_\odot$ of ^{56}Ni produced in the explosion (0.12 $M_\odot$ of ^{56}Ni was still ejected). In the 30 $M_\odot$ model the piston was at 1.83 $M_\odot$ but the final remnant mass was 4.24 $M_\odot$. All of the ^{56}Ni fell back along with most of the freshly synthesized heavy elements. However, there was still a brilliant Type II-p display which lacked, of course, the radioactive tail. By turning up the explosion energy one can force the ejection of all material external to the piston. For an explosion energy of 2.0×10^{51} erg, the remnant mass in the 30 $M_\odot$ (Pop I) model is decreased to 1.94 $M_\odot$, but this way of counting the energy (KE at infinity) can be misleading. The binding energy of the mantle of the 30 $M_\odot$ presupernova star (beyond 10^9 cm in the

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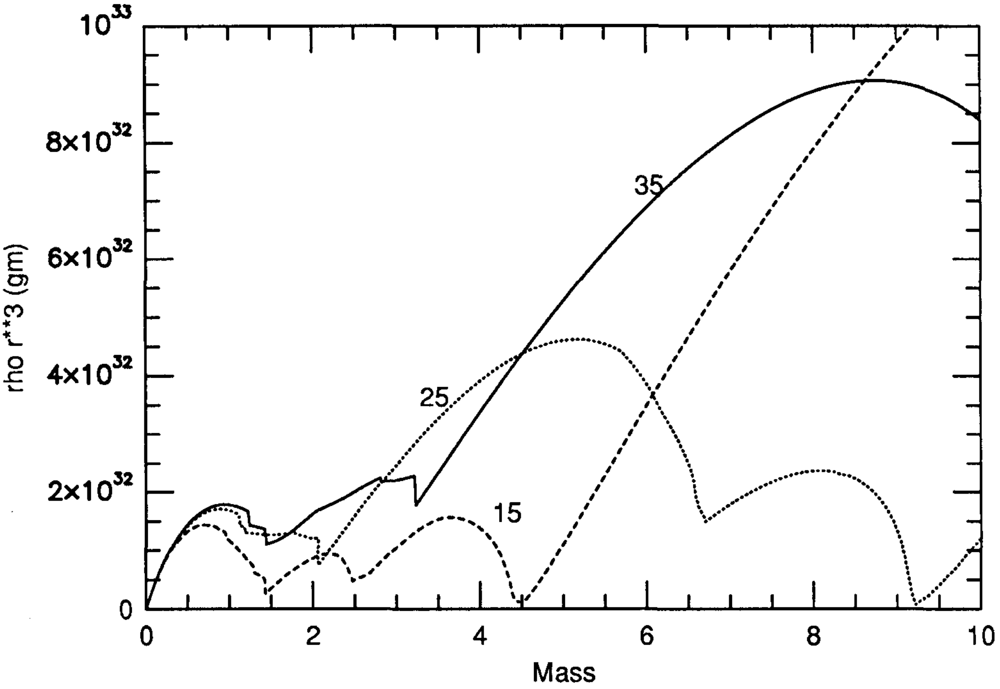

FIGURE 7. The product of density times radius cubed in presupernova stars of several masses. Where ρr^3 decreases a Sedov shock will accelerate; where it increases the shock will slow down. The helium core masses for these stars are 4.2, 9.2, and 14.2 $M_\odot$ for the 15, 25, and 35 $M_\odot$ models respectively.

presupernova model) is also 2.0×10^{51} erg. So the explosion mechanism would actually have to generate 4.0×10^{51} erg, much larger than the inferred explosion energy for SN 1987A. A 35 $M_\odot$ star would have to generate about 4.4×10^{51} erg to leave a remnant of 2.0 $M_\odot$. Whether the explosion energy available from neutrino deposition scales upwards as one moves to stars of larger mass is an interesting question in need of study. Perhaps by providing more ram pressure during the infall stage the inner mantle sets up conditions that extract a larger fraction of the available neutrino energy. Maybe the larger cores provide larger neutrino luminosities. Maybe not.

If not then there should be a mass, perhaps somewhere around 30 $M_\odot$, which separates Type II supernovae that leave neutron stars from those that leave black holes. This would have many important implications for the number of black holes in our galaxy, for galactic chemical evolution, for the late time light curves of some supernovae, and for the formation of accreting x-ray sources in binaries. For now, we want only to leave the reader with this clear message - it is quite possible to produce brilliant optical displays and copious mass ejection (mainly envelope) in supernovae that leave behind as their collapsed remnant black holes of substantial mass.

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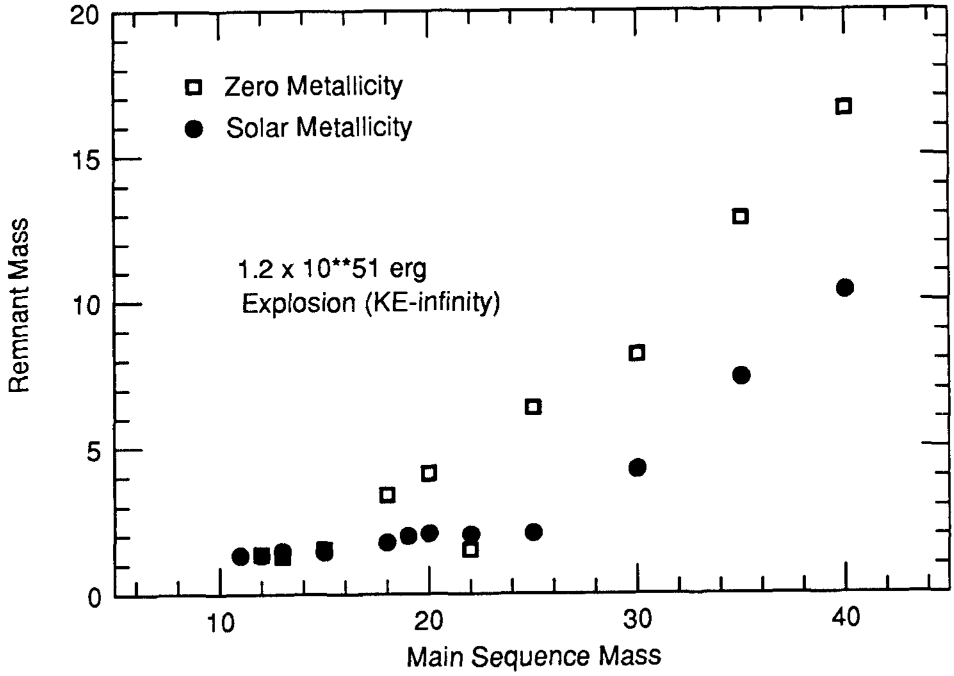

FIGURE 8. Final remnant mass for a series of supernova models that employed pistons at the edge of their iron core which communicated to their ejecta a final kinetic energy at infinity of approximately 1.3 $\times 10^{51}$ erg. All were brilliant Type II-p optical events (Weaver & Woosley 1994).

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