Ann. Rev. Astron. Astrophys. 1986. 24: 205–53

THE PHYSICS OF SUPERNOVA EXPLOSIONS[1]

S. E. Woosley

Board of Studies in Astronomy and Astrophysics, Lick Observatory, University of California, Santa Cruz, California 95064

Thomas A. Weaver

Special Studies Group, Lawrence Livermore National Laboratory, Livermore, California 94550

1. INTRODUCTION

The modern study of supernovae involves many aspects: presupernova stellar evolution, the physics of the explosions themselves, observations at all wavelengths of the outbursts and their remnants, nucleosynthesis and the chemical evolution of galaxies, interaction with the interstellar medium, cosmic-ray acceleration, supernovae as distance indicators, and other potentially observable phenomena such as neutrino bursts, gravitational radiation, and the emissions of a white dwarf collapsing directly to a neutron star. In this review, although touching on a number of these topics, we are chiefly concerned with the physical processes currently held responsible for the explosion and radiation of Type I and II supernovae and the observable diagnostics of the models: energetics, nucleosynthesis, light curves, and spectra. Discussions of a broader nature appear elsewhere (Trimble 1982, 1983, Rees & Stoneham 1982, Branch 1986a, Helfand & Becker 1984). Here, if for no reasons other than space limitations, we focus on *recent* developments in our theoretical understanding of how supernovae work, especially insight achieved during the last very fruitful decade (see also Arnett 1978a, Sugimoto & Nomoto 1980, Wheeler 1981, 1982, Weaver & Woosley 1980a, Woosley & Weaver 1981, Chevalier 1981a, Brown et al. 1982, Imshennik & Nadëzhin 1983, Hillebrandt 1984, Nomoto 1985a, Bethe & Brown 1985), and, perhaps at the expense of

[1] The US Government has the right to retain a nonexclusive royalty-free license in and to any copyright covering this paper.

complete historical perspective, concentrate only upon the currently favored models. This is not to imply that our understanding of supernovae is now complete. One of the great appeals of the subject is that it is an area of rapid development and change, but we aim to give the reader perspective on the current state of the art.

We divide our discussions into sections on Type II supernovae and Type I's. For the theoretician these are almost totally distinct phenomena, the only relations being the approximate equality of the explosion energy ($\sim 10^{51}$ erg) and the fact that both can produce heavy elements. Type II's are generally believed to be the consequence of gravitational collapse in massive stars ($M \gtrsim 8\ M_{\odot}$) and are characterized by the presence of hydrogen lines in their spectra (Branch et al. 1981). Because of their association with massive stars, they are not seen in elliptical galaxies (Tammann 1974) and are found, although not uniquely, near the spiral arms of spiral galaxies (Maza & van den Bergh 1976). Type I supernovae, on the other hand, are a likely outcome of an accreting white dwarf (probably composed of carbon and oxygen) that is provoked into thermonuclear instability by the accumulation of a critical mass. This is consistent with the lack of hydrogen lines in their spectra and the fact that they occur in all varieties of galaxies, since it may take a Hubble time to accrete the critical mass. The fact that the kinetic energies are comparable in the two types of supernovae reflects the relative inefficiency with which a powerful energy source, gravitational collapse, is coupled to the explosion in Type II's and the efficient coupling of a weaker source, nuclear reactions, in Type I's. Presently, in our Galaxy, Type II supernovae are estimated to occur once every 44 years and Type I's once every 36 years (Tammann 1982), although the optical emissions of both are most often heavily obscured by dust.

2. TYPE II SUPERNOVAE

2.1 *Presupernova Evolution of Massive Stars*

The mass range for supernovae fitting our generic description of Type II is bounded on the lower end by the heaviest stars that can become white dwarfs and on the upper end by the most massive star that retains its hydrogen envelope at the time its core explodes. Stars having still greater mass exist (Humphreys 1984, Massey 1981) and may explode (Sections 2.6 and 2.7), but since they lack a hydrogen envelope, both their light curves and spectra would disqualify them for the label "Type II" (Chevalier 1976a, Woosley & Weaver 1982a, Filippenko & Sargent 1985). For single stars, the progenitor of the heaviest white dwarf has a mass on the main sequence that (depending on helium abundance, metallicity, and theory of convection) is near 8 $M_{\odot}$ (Iben & Renzini 1983). This value is consistent with statistical arguments on the occurrence of supernovae (Tammann 1982), the preferential location of Type II's in spiral arms (Maza & van den Bergh 1976), observations of white dwarfs (Romanishin & Angel 1980, Weidemann & Koester 1983), and theoretical models for white dwarf formation (Iben 1985a). Above 8 $M_{\odot}$, the star will ignite carbon burning nondegenerately and avoid the development of a thin helium-burning shell that may be instrumental in envelope ejection (Tuchman et al. 1979). We note in passing that if, contrary to current seasonal belief, it did prove possible for the degenerate carbon core of a star lighter than 8 $M_{\odot}$ to grow to the Chandrasekhar value while retaining its envelope, one would expect a carbon *deflagration* (Sections 2.4 and 3.2; see also Iben & Renzini 1983). The ensuing explosion would be of Type II, but characterized by an extended exponential tail on the light curve powered by radioactivity, and would leave no collapsed remnant.

The most massive star that dies while still in possession of its hydrogen envelope is uncertain and probably depends upon metallicity. Estimates range from about 20 $M_{\odot}$ (Chiosi 1981, Firmani 1982, Berteli et al. 1984) to more than 40 $M_{\odot}$ [Conti et al. (1983), although see Utrobin (1984) for a special exception], with a favored value around 40 $M_{\odot}$ (Schild & Maeder 1983, Maeder 1984). Such stars as η Car, S Dor, P Cyg, and the Hubble-Sandage variables may exemplify the transition to the Wolf-Rayet stage (Humphreys 1984, Lamers et al. 1983). Though of interest for their nucleosynthesis, for the properties of their collapsed remnants, and for the special optical properties their explosions may exhibit, stars more massive than this are relatively rare and would not contribute appreciably ($\lesssim 10\%$) to the present Type II supernova sample.

It is useful to segregate the remaining progenitors into two theoretical subclasses: 8 to 11 $M_{\odot}$, and everything else (Barkat et al. 1974). The former is a transitional region bounded on the lower end by stars that ignite carbon degenerately and on the upper end by those that ignite all six nuclear-burning stages (hydrogen, helium, carbon, neon, oxygen, and silicon) nondegenerately in their center. In between the structural evolution is complex, being frequently characterized by off-center ignition, a high degree of electron degeneracy, and sensitivity, even during neon and oxygen burning, to electron capture. Studies of stars in this mass region (Woosley et al. 1980, Miyaji et al. 1980, Nomoto 1982a, 1984a,b, 1985a,b, Woosley & Weaver 1985, Habets 1985) show that for helium cores between ~ 2.2 and ~ 2.5 $M_{\odot}$ (the helium core mass being approximately one fourth of the main-sequence mass for these stars) a degenerate neon-oxygen core develops following carbon burning. Depending upon details of the model, neon and oxygen burning may (Woosley & Weaver 1985) or may not (Nomoto 1984a,b, 1985a,b) ignite off center, but in either case the neon-oxygen composition is retained in the center until a density of 2.5×10^{10} g cm^{-3} is reached. Oxygen then ignites under extremely degenerate conditions and in a core that is already contracting rapidly owing to electron capture on ^{20}Ne and ^{24}Mg. Burning proceeds to nuclear statistical equilibrium, while rapid electron capture on iron-group nuclei leads to a pressure decrement that accelerates the collapse of the core to nearly free fall (Miyaji et al. 1980, Bruenn 1972). Thus, stable silicon burning and iron core formation are bypassed, and the core (mass 1.35–1.40 $M_\odot$) collapses to nuclear density while still containing unburned nuclear fuel in its outer regions. The continued evolution of such stars has been studied by Hillebrandt et al. (1984), Wilson et al. (1985), and Burrows & Lattimer (1985) and is discussed in Section 2.2.

For helium cores from $\sim$2.5 to $\sim$2.8 $M_\odot$, i.e. main-sequence stars in the roughly 10–11 $M_\odot$ range, an iron core in hydrostatic equilibrium is eventually formed following complicated stages of off-center burning and violent flashes that in some models (Woosley et al. 1980) lead to envelope ejection and a bright optical display (roughly 1% of a Type II supernova at peak luminosity) several years prior to core collapse. Collapse is triggered by a combination of photodisintegration and electron capture as in the more massive stars (see below), and an especially bright supernova results as a consequence of shock interaction with the ejected envelope (Section 2.4). The Crab Nebula is often associated with a progenitor star in this mass range (Arnett 1975, Woosley et al. 1980, Nomoto 1982a, 1984a,b,c, 1985a,b, Davidson et al. 1982, Nomoto et al. 1982) chiefly because such objects make neutron stars and eject helium contaminated by only a trace of heavier elements.

The advanced burning stages of stars heavier than 11 $M_\odot$ have been examined in numerous studies (e.g. Fowler & Hoyle 1964, Rakavy et al. 1967, Sugimoto 1970, Ikeuchi et al. 1971, 1972, Arnett 1972a,b, 1974a,b, 1975, 1978a, Barkat 1975, Barkat et al. 1975, Lamb et al. 1976, Sugimoto & Nomoto 1980, Imshennik & Nadëzhin 1983, Weaver et al. 1978, Woosley & Weaver 1985, Chiosi 1981, Maeder 1984, Habets 1985), the details of which will not be reviewed here. Beyond carbon ignition, energy losses are mainly a consequence of neutrino emission, both from thermal processes and weak interactions. Because the burning of each fuel is characterized by increasing Coulomb barriers, higher temperatures are required at each stage; and because neutrino losses scale as a high power of the temperature, the total power developed by the star increases very rapidly. At the same time, the specific energy per gram available from nuclear burning *decreases* with heavier fuels, so that the lifetimes of advanced burning stages are very short. By the time that carbon burning is underway, the outer layers of the star have assumed their final configuration, which, if mass loss has not removed the hydrogen envelope and if the star has a Population I composition, is typically a red supergiant. It is within this context, essentially as a point explosion of $\sim 10^{51}$ erg in the center, that the Type II supernova occurs (Section 2.4).

Properties of some presupernova models are given in Figure 1 and Table 1 (Woosley & Weaver 1985, 1986, Wilson et al. 1985). The relation between main-sequence mass, helium core mass, and final iron core mass depends on the initial helium abundance (table values were calculated for $Y = 0.21$; multiply "He Core Mass" by ~ 1.1 for given Main Sequence Mass if $Y = 0.28$); mass loss (Chiosi et al. 1978, Chiosi 1981, Brunish & Truran 1982a,b, Maeder 1984); convective overshoot (Doom 1982, 1983, Berteli et al. 1985); and, especially, the location of the massive star in a close binary system (Van den Heuvel 1984, Iben 1985a, Trimble 1982). The reader will also note a nonmonotonic dependence of iron core mass on main-sequence mass between 25 and 35 $M_\odot$. This occurs because the number of oxygen shell-burning episodes changes from two to one in that interval. The last three entries in Table 1 are discussed in Sections 2.2 and 2.5.

The presupernova structure, and especially the mass of the iron core, are best understood in terms of the evolution of the *entropy per baryon*, S, in the central regions of the star, a quantity to which both are sensitive. A massive star is born with a nearly constant entropy profile on the (convective) main sequence. For a 15-$M_\odot$ star, for example, we have $S/k \sim 23$, where k is Boltzmann's constant; for a 25-$M_\odot$ star, we have

Table 1 Presupernova models and explosions[a]

Main sequence mass	Helium core mass	Iron core mass	Explosion energy[b] (10^{50} erg)	Residual baryon mass[b]	Neutron star mass[b]	Heavies ejected ($Z \geq 6$)
11	2.4	—[c]	3.0	1.42	1.31	~ 0
12	3.1	1.31	3.8	1.35	1.26	0.96
15	4.2	1.33	2.0	1.42	1.31	1.24
20	6.2	1.70	—	—	—	2.53
25	8.5	2.05	4.0	2.44	1.96	4.31
35	14	1.80	—	—	—	9.88
50	23	2.45	—	—	—	17.7
75	36	—[d]	—	—	BH?	30?
100	45	~ 2.3[d]	$\gtrsim 4$	—	BH?	39?

[a] All masses given in units of $M_\odot$.
[b] All except for 100 $M_\odot$ determined by Wilson et al. (1985).
[c] Never developed iron core in hydrostatic equilibrium.
[d] Pulsational pair instability at oxygen ignition.

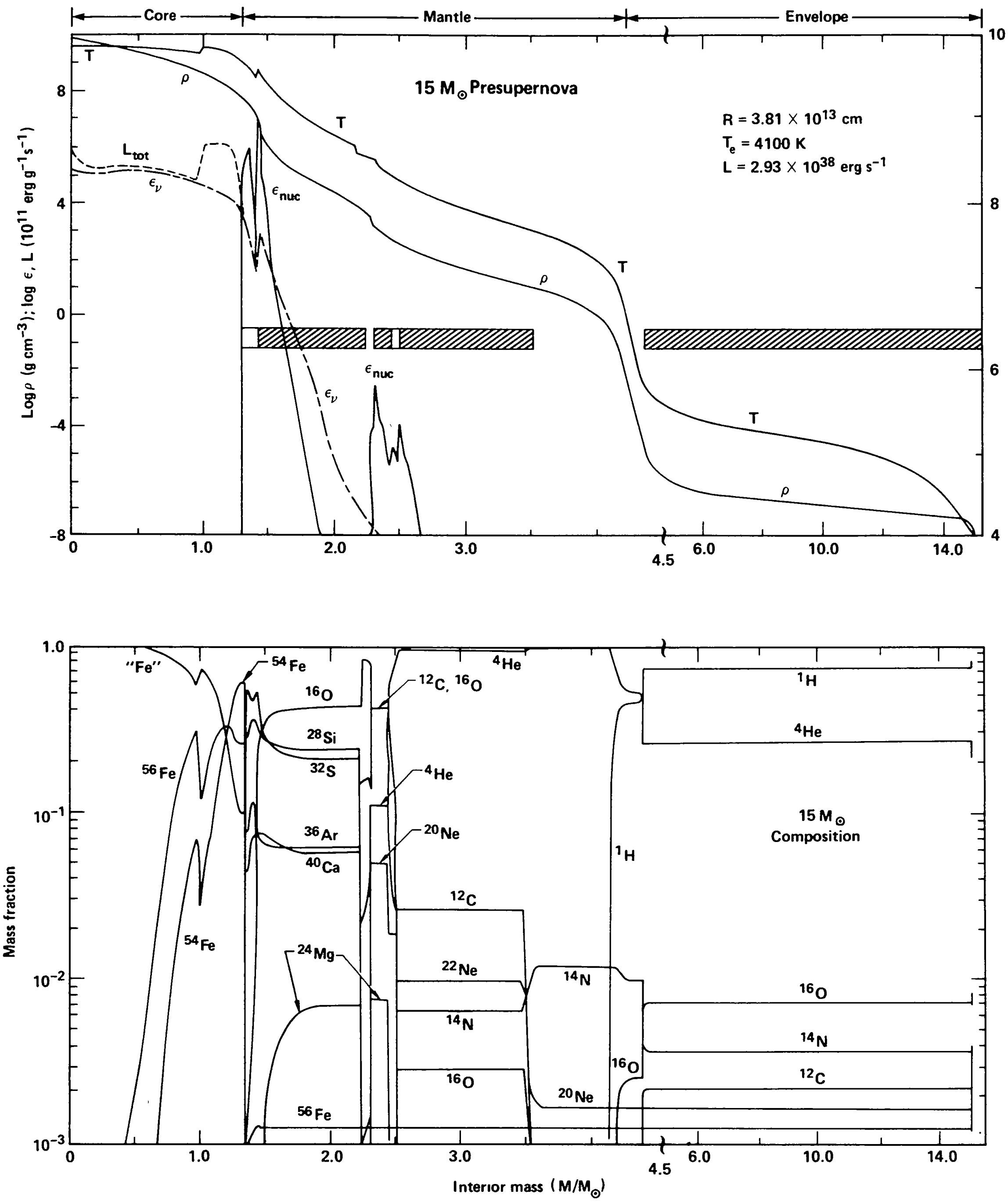


Figure 1 Structure and composition of a 15-$M_\odot$ presupernova star at a time when the edge of its iron core begins collapsing at 1000 km s^{-1}. Neutrino emission from electron capture (ε_ν) dominates photodisintegration in the total energy losses (L_{tot}) throughout most of the iron core. Central temperature here is 7.62×10^9 K and density is 9.95×10^9 g cm^{-3}. Spikes in the nuclear-energy generation rate (ε_{nuc}) show the location of active burning shells, while cross-hatched, blank, and open bars indicate regions that are convective, semiconvective, and radiative respectively. The species "Fe" includes all isotopes from $48 \lesssim A \lesssim 65$ having a neutron excess greater than ^{56}Fe. Note a scale break at 4.5 $M_\odot$. Figure adapted from Woosley & Weaver (1985).

$S/k \sim 27$. A lighter star begins with a lower entropy because, as the stellar structure equations demand, the temperature is less at a given density. This ordering persists on the average (though the quantitative ratio will vary) as photon losses and, later, neutrino losses reduce the entropy during advanced burning stages. Throughout this evolution the star is always subject to the convective stability criterion that entropy either be constant or increase radially outward. By the time the 15- and 25-$M_\odot$ stars ignite core carbon burning, radiation transport has decreased the entropies in their cores to $S/k \sim 3$ (of which the electronic entropy is roughly one half). From this point onward, entropy evolution is determined by neutrino losses. When the iron cores of the stars finally collapse, the central value of S/k in both stars has decreased to about one unit, whereas that in the envelope has increased to ~ 40, principally by radiation transport during red giant formation.

Loosely, then, one may picture the core of a massive star as digging itself into an "entropy hole," throwing the extra entropy out into the envelope or radiating it into space. The more efficient the losses, the lower the central entropy becomes and the steeper its radial gradient. It is the low value of central entropy that makes the core of the star sensitive to the Chandrasekhar limit and hence allows its convergence upon a particular iron core mass. It is also the entropy *gradients* that set the extent of convective burning shells that determine both the presupernova nucleosynthesis and core structure. This entropy distribution, which plays such an important role in determining the final structure of the star, is the product of all that went before and is sensitive to, among other things, the composition.

For stars more massive than about 20 $M_\odot$, with the actual value very sensitive to the reaction rate for $^{12}C(\alpha,\gamma)^{16}O$, so little carbon and neon (a carbon-burning product) are produced by helium burning that the carbon- and neon-burning stages of stellar evolution are essentially nonexistent (Woosley & Weaver 1985). The small abundances of these fuels that do burn do not liberate adequate energy to exceed the central neutrino losses; thus a convective core is not generated, the star is not supported, and the core may be considered (for thermodynamic purposes) as proceeding directly from helium to oxygen burning. Normally, most of the time that a star spends in evolutionary stages dominated by neutrino emission is spent, when they exist, in the carbon- and neon-burning stages. Lacking these stages, the entropy does not decline as much as it does in lower mass stars where they do occur, nor is the entropy decrease shared by as large a fraction of the core as it is when there is well-developed convection. Thus in the very last stages of stellar evolution—oxygen and silicon burning—the entropy is significantly higher in stars more massive than 20 $M_\odot$ than it is in lighter ones. Consequently, these stars end up with big iron cores (Table 1), not at all near the Chandrasekhar mass, and extended convective shells rich in heavy elements. Lighter stars, on the other hand, end up with iron cores near the Chandrasekhar mass and relatively thin convective shells.

One implication of this sensitivity of core structure to the entropy is that the model builder had best include accurate representations of all possible sources and sinks of entropy in the evolutionary calculation *and* use the proper rate for the reaction $^{12}C(\alpha, \gamma)^{16}O$. Revisions in weak rates (Fuller et al. 1982a,b) and "turning-on" weak interactions at an earlier stage in the evolution account, for example, for the downward revision of iron core mass in a 15-$M_\odot$ presupernova model from 1.56 $M_\odot$ (Weaver et al. 1978) to 1.35 $M_\odot$ (Table 1; Woosley & Weaver 1985). Similarly, recent inflation of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate (Kettner et al. 1982, Langanke & Koonin 1983, 1985) implies larger iron core masses in the bigger stars. A 25-$M_\odot$ model calculated with an earlier small value of $^{12}C(\alpha, \gamma)^{16}O$ (Fowler et al. 1975, Weaver et al. 1985) yielded an iron core mass of 1.35 $M_\odot$ and produced very little silicon through calcium, whereas the same model using the more recent rate (Caughlan et al. 1985, Woosley & Weaver 1985), about three times the old one, gave an iron core mass of 2.1 $M_\odot$ and abundant intermediate-mass nucleosynthesis (Table 1).

Once the iron core has reached a mass in excess of what the semidegenerate electrons can support, it begins to collapse. Two major instabilities are involved, often occurring simultaneously. For lower mass stars, especially $M \lesssim 15\ M_\odot$, electron capture on iron-group elements robs the core of electrons needed for support and emits neutrinos that remove entropy and facilitate collapse (Figure 1). This instability is supplemented in lower mass stars and is dominated in heavier ones ($M \gtrsim 20\ M_\odot$) by a pressure decrement from *photodisintegration* (Hoyle 1946, Burbidge et al. 1957, Fowler & Hoyle 1964). Contraction raises the temperature and density, but because a portion of the energy must go into stripping iron-group nuclei down to α-particles, the pressure does not increase as rapidly as gravity. Thus, on average, the structural adiabatic index Γ_1 decreases below 4/3. Once either of these instabilities is encountered, the core contracts very rapidly. Though never quite attaining free fall, the outer regions of the core do eventually reach supersonic velocity. What follows has remained one of the thornier problems in theoretical astrophysics for several decades.

2.2 *Core Collapse and Bounce*

As the iron core with the properties shown in Figure 1 collapses to high density, a large amount of gravitational potential energy is converted into heat and mechanical motion. For more than 50 years it has been realized (Baade & Zwicky 1934) that the coupling of even a small fraction of this energy to the comparatively loosely bound mantle and envelope (Figure 1) of the red giant star would lead to their vigorous ejection and explain the energies and luminosities of Type II supernovae. Unfortunately, the quest for this coupling mechanism has proved elusive, and its solution remains controversial.

The seminal works of Fowler and Hoyle (Hoyle & Fowler 1960, Fowler & Hoyle 1964) emphasized thermonuclear explosion as the mechanism for supernovae of *both* types, an idea that still persists in the modern Type I models but that is no longer accepted as an explanation for Type II's, at least in stars where the effects of rotation and magnetic fields can be neglected. Colgate & White (1966) first proposed the "neutrino transport model." A major fraction of the heat generated by the gravitational collapse of a massive stellar core was converted into neutrinos that interacted with the mantle, a process leading to its unbinding. The presupernova model structure, neutrino energy transport, and equation of state were handled very approximately in this first calculation, and subsequent work (Arnett 1966, 1967, 1968a, Wilson 1971) called the model into question, showing that the actual transport was too inefficient to power an explosion for iron cores having the large mass that was usually assumed at the time. In a study of a $1.25\text{-}M_\odot$ iron core, however, Wilson (1971), presaging somewhat the developments of later years, found a prompt, relatively low energy ($\sim 3 \times 10^{50}$ erg) explosion in which neutrino energy transport played no significant role, i.e. a purely hydrodynamical supernova.

A new twist was added to the neutrino transport model in the mid-1970s with the discovery of weak neutral currents. These had the interesting implication of giving the neutrino a much larger cross section for scattering on a heavy nucleus than for interacting with an electron or nucleon, with σ in fact going as $\sim A^2$ (Freedman 1974). Thus, for a totally dissociated core of nucleons and leptons with an overlying mantle of heavy elements, the neutrinos might lose a lesser amount of energy escaping from the former and deposit their momentum where it would do the most good, at the base of the mantle (Figure 1; Wilson 1974, Bruenn 1975, Schramm & Arnett 1975). Once again, however, calculations of increasing refinement and more accurate values of the weak interaction parameters refused to deliver explosions (Wilson et al. 1975, Bruenn et al. 1977). Too great a fraction of the neutrinos remained trapped in the core, in part because the high-energy neutrinos still had very short path lengths and those having lower energy became degenerate (Mazurek 1974, 1975, Sato 1975, Lamb & Pethick 1976, Wheeler 1981), which reduced their production and transport. Thus, inadequate impulse was developed to explode the star.

About this time, researchers returned to an earlier notion (Colgate & Johnson 1960, Figure 14 of Colgate & White 1966, Wilson 1971), that the *mechanical* energy of the core as transported by a shock wave might be a more promising mechanism for the elusive coupling (Bruenn 1975, Bruenn et al. 1977). More realistic presupernova models (Arnett 1974b, 1975, Barkat et al. 1975) having a denser core and less evolved envelope and, equally important, with the neutrinos more effectively trapped in the core by neutral current scattering now made this mechanism appear more attractive. Later it was also realized (Mazurek et al. 1979, Bethe et al. 1979) that owing to the large heat capacity of the nuclear-excited states of a heavy nucleus (Perdang 1966, Fowler et al. 1978), the collapsing core would remain much cooler than previously calculated. It would *not* halt and bounce at $\rho \sim 3 \times 10^{13}$ g cm^{-3} on the thermal pressure of hot nucleons from photodisintegrated matter (e.g. Wilson 1978) but would instead continue to densities beyond that of nuclear matter ($\rho_{\rm nuc} \approx 2.7 \times 10^{14}$ g cm^{-3} for matter having equal numbers of neutrons and protons; somewhat less for the neutron-rich material considered here). Furthermore, because of the lower temperature and larger partition function associated with the vast number of bound-excited states, heavy nuclei would persist until they touched and merged (Bethe et al. 1979). One consequence of the persistence of heavy nuclei was that neutrinos remained even more tightly locked in the core, a very unfavorable circumstance for the neutrino transport model, so that in its latter stages the collapse was very nearly isentropic. Bethe et al. also pointed out that the characteristic entropy of a collapsing supernova core starts and remains very small ($S/k \sim 1$).

Since 1980 our understanding of "prompt" explosions—those that occur within a few hydrodynamical crossing times of the collapsing iron core ($\sim$10 ms)—has developed within the framework outlined by Bethe et al. An enormous effort has been invested in determining the relevant nuclear physics, especially the weak interaction rates (Bethe et al. 1979, Fuller 1982, Fuller et al. 1982a,b, Cooperstein & Wambach 1984), the equation of state (Lattimer 1981, Bonche & Vautherin 1982, Bethe et al. 1979, 1983, Lamb et al. 1984, Hillebrandt et al. 1984, Cooperstein 1985, Baron et al. 1985c), and the neutrino interaction cross sections (Tubbs & Schramm 1975); incorporating this physics into hydrodynamic computer codes (e.g. Bowers & Wilson 1982a); and studying the continued evolution of realistic stellar models. The general properties of the solutions have been discussed in numerous reviews and papers (cf. Brown et al. 1982, Hillebrandt 1982a, 1984, Arnett 1980a, 1983, Mazurek et al. 1980b, 1982, Bowers & Wilson 1982a,b, Bruenn 1985, Lichtenstadt & Bludman 1984, Lattimer & Burrows 1984, Burrows & Lattimer 1985, Baron et al. 1985a,b, Bethe & Brown

1985, Wilson 1985, Bowers 1985, Wilson et al. 1985, Bethe & Wilson 1985), and the following summary is generally concurred.

Prior to achieving nuclear density, pressure comes predominantly from relativistic electrons, hence $\Gamma_1 \sim 4/3$. At a density $\rho \sim 10^{11}$ g cm^{-3}, depending somewhat on their energy, neutrinos become trapped within the collapsing core (that is, their diffusion time outward exceeds the collapse time scale of a few milliseconds). From this point on, the total number of neutrinos plus electrons does not vary greatly, although the two particles may exchange identity via the weak interaction. Typically the lepton number density is given by $n_l \approx 0.40\rho N_A$ cm^{-3} at trapping, where N_A is the Avogadro number. The dynamics of collapse naturally segregate the imploding core into two regions: an inner core that collapses homologously ($v \propto r$), with its outer extremity falling at about the sound speed, and an outer core, whose supersonic infall velocity ($v \propto r^{-1/2}$) is roughly one half of the free-fall velocity. At maximum, the collapse velocity reaches about 70,000 km s^{-1}. Homology can be preserved only in that inner portion that remains in sound communication. The mass of this inner core is sensitive to a variety of thermodynamic conditions (Yahil 1983)—the pressure decrement compared with that required for hydrostatic equilibrium, the adiabatic index of the gas, and how much electron capture has occurred—but for typical conditions it ranges from 0.6 to 0.8 $M_\odot$. As the central regions approach and exceed nuclear density, the equation of state suddenly stiffens (Γ_1 becomes much greater than 4/3), and that portion of the core that was collapsing homologously comes to an abrupt halt. Peak temperature here is $\sim$10–15 MeV and peak density is about $3\rho_{\rm nuc} \sim 8 \times 10^{14}$ g cm^{-3}. Pressure waves propagating outward accumulate where the Mach number equals one and build into a shock wave that begins to move out. Thus the shock is not born at the center of the star but out around 0.8–0.9 $M_\odot$, i.e. roughly 0.2 $M_\odot$ beyond the homologous core.

Analytic arguments (Yahil & Lattimer 1982, Lattimer et al. 1985) suggest that the shock wave is born with an energy approximately equal to the gravitational binding energy of the homologous (unshocked) core after it comes to rest, $\sim$4–7 $\times 10^{51}$ erg (as corrected for nuclear force and energy stored in the excited states of those nuclei that have not merged or evaporated). This energy would be ample to power the supernova if it could all be used, but unfortunately great degradation occurs as the shock now attempts to beat its way out through the remainder of the infalling core. Chief among the losses it suffers are neutrino emission, especially when it moves into a region where neutrinos from electron capture can diffuse ahead of the shock ($\rho \lesssim 10^{11}$ g cm^{-3}), and photodisintegration. The temperatures of the shocked material are so high that complete stripping of iron down to free nucleons is implied, with an energy $\sim 1.5 \times 10^{51}$ erg being required for each 0.1 $M_{\odot}$ so disintegrated. The shock cannot long endure such prodigious losses, and it will die unless it quickly reaches the edge of the dense core and moves into a region where the low density and high heat capacity give postshock temperatures too low to disintegrate iron and less efficient in producing neutrinos. Thus, an important criterion for the success of the core bounce mechanism is that the total mass of the collapsing iron core not be too large (Wilson 1971, Hillebrandt 1982a,b, Arnett 1983, Burrows & Lattimer 1983); one obvious limit is that the difference between the homologous and total core masses not be so great as to consume the entire shock in photodisintegration losses.

Many studies, both computer-based (Bowers & Wilson 1982b, Wilson et al. 1985, Arnett 1983, Hillebrandt 1982a,b, 1984, Cooperstein et al. 1984, Kahana et al. 1984, Burrow & Lattimer 1985) and semianalytic (Burrows & Lattimer 1983), have shown that for reasonable choices of the nuclear equation of state, upon which the initial shock energy is sensitive, the total mass of the iron core cannot exceed ~ 1.35 $M_{\odot}$ and still achieve a successful explosion powered by core bounce. Indeed, the currently favored values are $\lesssim 1.25$ $M_{\odot}$. Interestingly, this limit lies just at the lower extremity of what stellar evolution calculations actually provide (Table 1). Thus, while no one seriously believes that an iron core as large as 2.1 $M_{\odot}$ can explode by a hydrodynamical bounce, a smaller one (such as one that characterizes stars in the 8–15 $M_{\odot}$ range) might. Because such smaller cores are all marginal cases ($M_{\rm core} = 1.3$–1.4 $M_{\odot}$), the success or failure of the explosion in even this limited mass range of stars is quite sensitive to uncertain parameters and, unfortunately, to the codes used in their study. Thus, Baron et al. (1985a,b), using a "softer" nuclear equation of state than hitherto accepted, calculate prompt explosions of 12- and 15-$M_{\odot}$ models (Table 1), but Wilson et al. (1985), using a more standard equation of state, do not. [G. E. Brown and his collaborators (Baron et al. 1985c) find that the soft equation of state is what should be expected from nuclear theory, but this issue is still controversial within the nuclear physics community.] While Hillebrandt (1982b) obtains a marginal hydrodynamic explosion of a 10-$M_{\odot}$ model, Wilson et al. (1985), Bruenn (1985), and Burrows & Lattimer (1985) do not; and though Hillebrandt et al. (1984) get a strong explosion for an 8.8-$M_{\odot}$ star, Wilson & Mayle (1985) get a weak one, and Burrows & Lattimer (1985) get none at all.

More work is clearly needed, perhaps on the presupernova models as well. It is a curious quirk of nature (or is it of computers?) that the lower bound for the iron core mass from stellar evolution so marginally intersects the range for which shock-wave models would provide mass ejection.

2.3 *"Delayed" Explosions and Rotation*

If the supernova fails to explode promptly, as it almost certainly must for the larger masses in Table 1, one confronts a very interesting problem: a stellar core still containing more than 10^{53} erg of thermal and gravitational potential energy in its core, as well as a mantle and envelope that may contain too much angular momentum to collapse directly to a black hole. What is the continuing evolution of such an object? In particular, might it still produce a supernova?

In 1982, Wilson (1985), while running a 10-$M_\odot$ model (Woosley et al. 1980), noted interesting behavior developing behind the stalled (accretion) shock after all outward motion had ceased. Running the calculation further still, out to a time of several hundred milliseconds (most calculations were previously stopped at ~ 20 ms), a weak explosion developed (4×10^{50} erg) that would nevertheless be powerful enough to explain the light curve and total energetics of most Type II supernovae. Further analysis (Wilson 1985, Bethe & Wilson 1985, Wilson et al. 1985, Lattimer & Burrows 1984) showed that the energizing mechanism was, once again, *neutrino energy transport* but under different conditions and at a later time than in the original Colgate & White (1966) model. The later time is a consequence of the delayed neutrino diffusion out of the newly forming neutron star. The different conditions reflect the more extended structure of modern presupernova stars.

Following the failure of the shock, a nearly stationary "neutrinosphere" (surface of near unity optical depth for neutrinos) develops at about 40 km with a density $\rho \sim 10^{11}$ g cm^{-3} and an effective emission temperature ~ 5 MeV (somewhat of an oversimplification of the actual calculation; the neutrinos actually have an optical depth that depends on their energy, and the distribution function is never fully thermalized). The stalled shock, an *accretion shock* at this point, lies external to the neutrinosphere at ~ 100–300 km, where the density ($\sim 10^8$ g cm^{-3}) and postshock temperature (~ 1.5 MeV) are much smaller. Capture of a small fraction ($\lesssim 5\%$) of the $\sim 10^{53}$ erg s^{-1} neutrino luminosity on neutrons and protons (and, at later times, scattering on electron-positron pairs) behind the shock heats the matter, ultimately causing it to resume its outward course. The region of interest, just beneath the shock, is optically thin to neutrinos; but the small fraction of neutrinos that do interact deposit an energy per gram that does not greatly diminish as the material moves outward (suffering only $1/r^2$ geometrical dilution). Thus, the expansion is unstable, and a new equilibrium state is not attained. Instead, after the star accretes an amount that increases with the stellar mass considered (the difference between the "Iron core mass" and the "Residual baryon mass" in Table 1), explosive expansion resumes, and the mantle and envelope are ejected. The explosion is aided both by additional neutrino luminosity from the gravitational settling of freshly accreted matter and by an abrupt fall-off in its density (and hence in ram pressure ρv^2) that usually occurs at what had been the base of the oxygen-burning shell in the presupernova star (Figure 1). In cases where the density of the accreting matter does not abruptly decline, an oscillatory shock may exist (Figure 9 of Wilson et al. 1985) as the material first expands as a result of neutrino heating, is overcome by infalling matter, and falls back to release another burst of enhanced neutrino flux.

Wilson et al. (1985) have calculated explosions of this sort for a variety of stellar masses. The mechanism is apparently successful even for the very heavy iron cores of 25 and 50 $M_{\odot}$ stars. Interestingly, if this is the case, it now appears possible to obtain a supernova, with all its accompanying nucleosynthesis and optical display, in a situation that leaves behind a compact remnant so large that, upon cooling (~ 100 s), it becomes a black hole. In this case the upper end of the main sequence, $M \gtrsim 25\ M_{\odot}$, may leave black holes, whereas the lighter, more abundant stars leave neutron stars. Note that the difference between "Residual baryon mass" and "Neutron star mass" in Table 1 is the rest mass energy carried away by neutrinos as the compact remnant cools following the explosion. To this optimistic and fertile theme, however, must be added a note of caution. The validity of Wilson's "delayed mechanism" has not yet been verified by other theoreticians. Indeed, there are indications that the explosions are more marginal using the neutrino transport physics of other codes (Arnett 1985, Hillebrandt 1985).

On the other hand, at times as late as a few hundred milliseconds one must consider other variations upon the neutrino transport model. Our discussions thus far have been within the context of one-dimensional calculations, a condition that is doubtless overly restrictive. Epstein (1979) pointed out that *convection* should occur in a young supernova core owing to a buoyancy gradient resulting from density contrasts between matter near the surface that has lost its neutrinos and matter deeper inside where the neutrinos are still present. Subsequently, this idea was extended (Bruenn et al. 1979, Colgate & Petschek 1980) in speculative form to include a large scale Rayleigh-Taylor overturn of the core that would release a flood of neutrinos and power an explosion. This possibility was explored in two-dimensional calculations (Livio et al. 1980, Smarr et al. 1981) that were inconclusive. That *some* neutrino flux amplification was achieved on a prompt (~ 10 ms) time scale was agreed, but the calculations either did not employ a realistic stellar model (Livio et al. 1980) or were not followed to the late times now appropriate to "delayed explosions" to see if the larger fraction of neutrino energy trapped deep in the core might be released by overturn (Smarr et al. 1981). More recently, Wilson & Mayle (1985) and Mayle (1985), using a mixing-length theory of convection in a one-dimensional study, have found that a process of this sort (i.e. convection due to an unstable gradient in *composition*) may indeed amplify the energy of otherwise marginal "delayed" explosions by roughly 50%.

Arnett (1985) has also recently suggested an alternative form of delayed neutrino energy transport, one that relies on more traditional (Schwarzschild) convection occurring in the region just beneath the neutrinosphere. There an unstable entropy gradient comes to exist, in part because of the declining energy of the original bounce shock as it passes through the outer core, and in part because of diffusive neutrino losses from the edge of the core. The amplification of the neutrino flux would then, as in other convective schemes, lead to a more robust and energetic late-time explosion. So far, no models have been constructed to demonstrate this hypothesis. In general, the modeling of convection at late times in collapsed supernova cores is a difficult and controversial subject but one of great current interest.

Finally, one must consider the effect of rotation on the supernova model. Fowler & Hoyle (1964) speculated and Bodenheimer & Woosley (1983) calculated that a combination of rotation and nuclear burning in the *mantle* of a star (Figure 1) that has had the pressure removed from its central regions could provide enough energy to power the supernova. If so, supernova remnants having a pronounced equatorial anisotropy (e.g. N132 D in the Large Magellanic Cloud; Lasker 1980) may occur. Unfortunately, the initial angular momentum distribution is very poorly known and important to determining the success or failure of the mechanism. Moreover, the problem is computationally difficult because of the highly discrepant time scales associated with mantle evolution and the core accretion shock, which sets a critical inner boundary condition. More work is needed.

The possibility that rotation influences the dynamics of the collapsing *core* (Hoyle 1946, LeBlanc & Wilson 1970) is a recurrent idea. Present calculations (Müller & Hillebrandt 1981, Symbalisty et al. 1985) indicate that the effects of rotation on core bounce and neutrino transport are small, but this conclusion is again sensitive to assumptions regarding the unknown distribution of angular momentum in the presupernova star.

2.4 *Light Curves of Type II Supernovae*

Observationally, Type II supernovae have been divided by Barbon et al. (1979) into two main subclasses on the basis of their photometric light curves. One subclass, designated Type II-P, is characterized by a distinct plateau phase in the light curve and accounts for about two thirds of the well-observed supernovae. Perhaps the best-observed example of this fairly homogeneous subclass is SN 1969l (Kirshner et al. 1973, Ciatti et al. 1971, Kirshner & Kwan 1974, Schurmann et al. 1979), whose light curve is shown in Figure 2. The second subclass, designated Type II-L, comprises about one fourth of Barbon et al.'s sample of supernovae and exhibits a steady linear decline in magnitude after maximum light that changes slope to a less rapid rate of decline after about 100 days in a way qualitatively similar to Type I supernovae (Doggett & Branch 1985). The best-observed prototypes of this class are SN 1979c in M100 (de Vaucouleurs et al. 1981, Barbon et al. 1982, Balinskaya et al. 1980) and SN 1980k in NGC 6946 (Buta 1982, Barbon et al. 1982). In addition, a few peculiar Type II supernovae with bizarre, but highly structured, light curves have been observed (Zwicky 1964, Doggett & Branch 1985; see also Section 2.7) that defy any general classification and also show spectroscopic peculiarities. Finally, it can be inferred from remnants like Cas A (cf. van den Bergh & Kamper 1983, Ashworth 1980, Maran 1981) that at least some massive stars can explode without any very noticeable visual display.

During the last decade considerable progress has been made in understanding these various light curves. The key physical parameters that largely determine the observable display are (*a*) the total energy deposited by core processes in the overlying mantle, (*b*) the density distribution and composition of the presupernova star (including any previously ejected circumstellar material), and (*c*) the energy input from radioactive material produced and ejected in the explosion. Fortunately, owing to the very large differences in scale between the portion of the star that undergoes collapse (radius $\sim 10^8$ cm) and the radii of typical presupernova stars (10^{13} to 10^{14} cm), the still uncertain details of the core phenomena tend to be almost completely averaged out in the ensuing explosion. In most cases, it is an excellent approximation for the purposes of calculating light curves to treat the core as a point mass and energy source (cf. Zeldovich & Raizer 1966).

It has been realized for some time (Imshennik & Nadëzhin 1964, Grassberg et al. 1971, Falk & Arnett 1973, 1977, Arnett & Falk 1976, Chevalier 1976b, Arnett 1980b) that the response of simplified models of the envelopes of red giants to a central point explosion yields an optical display in reasonable agreement with many features of observed Type II supernova light curves, particularly those of Type II-P, provided that the envelope is sufficiently extended ($10^{13} \lesssim R \lesssim 10^{14}$ cm) and the total energy of the explosion is of the order of 10^{51} erg. Stellar evolution calculations by Lamb et al. (1976) and Weaver et al. (1978) that neglect mass loss have shown that 15- and 25-$M_{\odot}$ Population I stars should have such extended

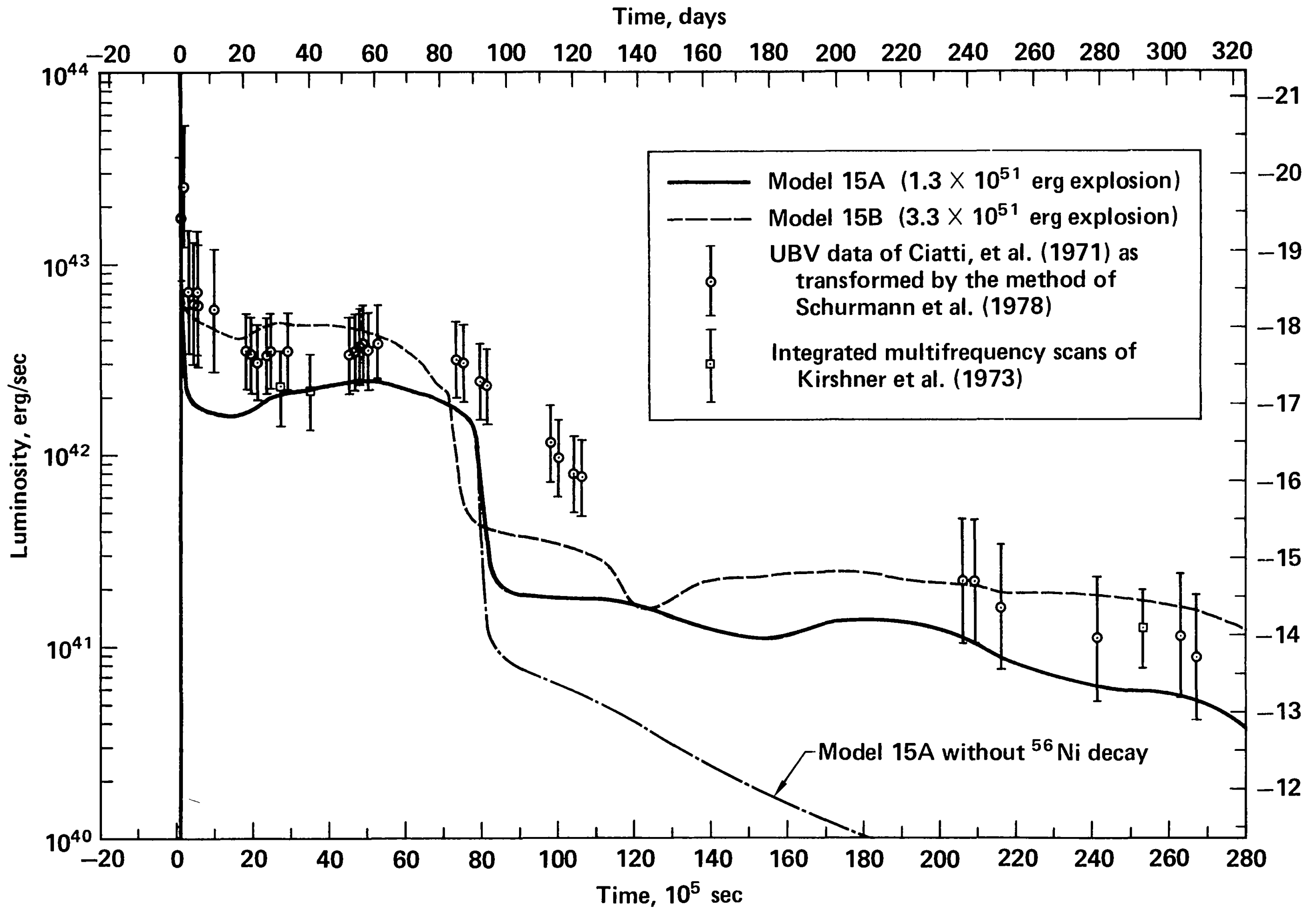


Figure 2 Light curve of a theoretically modeled 15-$M_{\odot}$ supernova as compared with observations of SN 1969l. Here M_b is the absolute bolometric magnitude of the supernova, and time is measured with respect to core bounce for the model and Julian date 2,440,560 for the observations. Note the existence of a distinctive plateau that occurs as a hydrogen recombination front eats into the expanding hydrogenic envelope. If ^{56}Ni is ejected, the Type II light curve will also have a radioactive tail as shown. Figure taken from Weaver & Woosley (1980a).

envelopes at the time their iron cores collapse. Weaver & Woosley (1980a) extended these calculations and found that the light curves (as well as the photospheric temperatures, radii, and velocities) resulting from the ensuing explosions were in excellent quantitative agreement with those of Type II-P supernovae as typified by SN 1969l (Figure 2). This agreement between theory and observation allows us to describe with some confidence the physical processes that produce such light curves.

Taking the case of the 15-$M_\odot$ star (Weaver & Woosley 1980a,b; Figure 2) as a representative example, we find that theoretical models indicate that the observable supernova event begins when the shock initiated in the core reaches the star's surface, which causes a soft X-ray pulse about 30 min long (Falk 1978, Klein & Chevalier 1978, Chevalier & Klein 1979, Lasher & Chan 1979, Epstein 1981). The supernova's luminosity then falls rapidly as its surface is cooled by expansion and radiative emission. Meanwhile, the rest of the star's material is cooled and accelerated by adiabatic expansion. The bulk of the star remains sufficiently optically thick during this acceleration that 99% of the total supernova energy is converted to kinetic energy in the expanding debris. Only about 1% (typically about 10^{49} erg) thus remains to be radiated when the star finally starts to become optically thin after expanding to about 10^{15} cm, or about 30 times its initial radius.

A two- to three-month-long plateau in emission then follows as a cooling wave associated with the transparency induced by hydrogen recombination propagates through the star's exploding envelope. During this period, the photospheric temperature is observed (Kirshner et al. 1973, Kirshner & Kwan 1974) to remain roughly fixed at 6000 K, the temperature at which hydrogen recombines at the typical envelope densities of 10^{-13} g cm^{-3}, while the absolute size of the photosphere remains approximately fixed at about 1.5×10^{15} cm (as a result of the near-cancellation of the expansion of the envelope and the inward motion of the photosphere relative to the envelope material as it follows the recombination wave). The resulting nearly constant luminosity phase persists until the recombination wave reaches the slowly moving ($\lesssim 1000$ km s^{-1}) mantle, which is relatively dense and very optically thick.

At later times, the luminosity of the 15-$M_\odot$ supernova results from the diffusion out of the mantle of thermalized radiation from the decay of explosively generated ^{56}Ni and its daughter ^{56}Co. As Figure 2 shows, models in which ^{56}Ni decay is turned off display a much more sharply falling luminosity tail, since the residual thermal energy in the mantle diffuses out over a characteristic time of only one to two months. In models containing energy input from radioactivity, temporary trapping of the decay energy in the optically thick mantle produces a luminosity decline somewhat slower than the 78-day half-life of ^{56}Co.

The physics and progenitors of Type II-L supernovae and Type II-peculiars are not currently so well understood. The Type II-L's may represent massive stars that have lost most, but not all, of their hydrogen envelopes (Chevalier 1984a) and thus exhibit only very short and difficult-to-observe plateau phases (Litvinova & Nadëzhin 1983). Alternatively or additionally, these supernovae may be powered mostly by the decay of ^{56}Ni (Doggett & Branch 1985, Iben & Renzini 1983), with the break in the rate of decline at 100 days being due to the transition from optically thick to optically thin emission, as is clearly seen in Type I supernovae. While no detailed stellar evolution calculations currently exist that match the II-L light curve, the 0.1–0.4 $M_{\odot}$ of ^{56}Ni calculated to be produced in the explosion of massive stars (see Section 2.5) is sufficient on energetic grounds to power the light curve, provided that the mass and/or opacity of the overlying layers is sufficiently small.

The interaction of an expanding supernova with previously ejected circumstellar material can have a variety of important effects, depending on the density structure of the ejecta. A few solar masses of material located at a radius of order 10^{15} cm, for instance, which might be ejected by neon or oxygen flashes late in a star's life (Woosley et al. 1980) or, less violently, as a stellar superwind, is very efficient at transforming the kinetic energy of the supernova into a bright optical display (Falk & Arnett 1977, Arnett 1980b, 1982b). Supernova 1983k in NGC 4699 (Niemela et al. 1985), which was extensively observed before maximum light, shows direct spectroscopic evidence for such a preexisting shell of ejecta, as well as the bright, extended light curve expected in this case. At the other extreme, Cas A appears to have resulted from the explosion of a very massive star ($\gtrsim 40\ M_{\odot}$?) that was very *underluminous* because it ejected its envelope to too great a distance for prompt interaction and left behind a core so compact that virtually all of its internal energy was transformed to kinetic energy by adiabatic expansion before it could be radiated (Chevalier 1976a). Other more complex density structures may account for the varied light curves of the Type II-peculiars referenced above. Finally, the recently observed prompt radio, infrared, and X-ray emission from certain Type II supernovae (Weiler et al. 1982, 1985, Pacini & Salvati 1981, Elias et al. 1981, Canizares et al. 1982) appears for the most part to be the natural result of the interaction of the exploding supernova with circumstellar material (Chevalier 1981b, 1982a,b, 1984a, Dwek 1983).

2.5 *Nucleosynthesis in Type II Supernovae*

It is a commonly accepted hypothesis that almost all of the elements heavier than helium have been synthesized in stars (Burbidge et al. 1957, Cameron 1957), a process in which Type II supernovae are expected to play a major role, especially for the intermediate-mass elements

($16 \lesssim A \lesssim 60$), the heavy *p*-process elements (Woosley & Howard 1978), probably the *r*-process elements (Hillebrandt 1978), and a portion of the *s*-process elements as well (Lamb et al. 1977). A thorough review of supernova nucleosynthesis is beyond the scope of this paper, but several important aspects of the problem should be noted before considering any quantitative results.

First, the more commonly occurring Type II supernovae are probably not those that have produced the bulk of the heavy elements (Arnett & Schramm 1973). The mass interior to the helium-burning shell at the time the supernova explodes but exterior to the expected compact remnant ("Heavies ejected" in Table 1) is approximately given by (Weaver & Woosley 1980a, Woosley & Weaver 1986) $M(Z)_{\rm ej} \approx M_* \,(0.4\text{–}4.2\, M_\odot/M_*)$, where M_* is the main-sequence mass of the presupernova star ($M_* \lesssim 60$ $M_\odot$). Toward the lower end of the mass range for Type II's, i.e. $M_* \sim 9$–12 $M_\odot$, almost no elements heavier than helium are ejected. Weighting this function with some estimate of the initial mass function (e.g. Miller & Scalo 1979) gives a typical mass for the supernovae that make the heavy elements of 20–30 $M_\odot$. Care must be taken in interpreting this, however, because the relative proportions of elements from different nucleosynthetic processes vary with the stellar mass considered. Thus ultimately one must do the entire integral over all masses, just as nature has.

Also, at least a portion of the nucleosynthesis is sensitive to the large uncertainty still inherent in the explosion mechanism. Since elements lighter than silicon are predominantly made in the outer portion of the mantle by nuclear burning in hydrostatic equilibrium and merely shoved off the star in the explosion, their synthesis is *not* greatly influenced by what makes the star explode (so long as it *does* blow up). The synthesis of silicon through calcium, on the other hand, comes partly from the presupernova evolution but is augmented by an important contribution from explosive oxygen burning in the shock (Weaver & Woosley 1980a). Thus it is sensitive to the explosion energy [although not extremely so, since the shock temperature goes as $\sim(3E_0/4\pi r^3 a)^{1/4}$, where E_0 is the explosion energy, r the preexplosive radius, and a the radiation density constant (Weaver & Woosley 1980a)] and especially to how much matter accretes onto the core before a delayed explosion finally occurs (Table 1; Wilson et al. 1985). Most of all, elements of the *iron* group are sensitive to the details of the explosion mechanism and where the "mass cut" ultimately develops. The evolution of iron in the Galaxy is further complicated by the contribution from Type I supernovae (Section 3.3), which probably dominates at the present time.

With these caveats, the reader may interpret the nucleosynthesis calculated for a 25-$M_\odot$ model (Figure 3) by Woosley & Weaver (1985) based upon a delayed explosion calculated by Wilson et al. (1985). A total of 4.31 $M_\odot$ of heavy elements was ejected by this explosion, sufficient to produce the present absolute abundance of oxygen in the Sun if one out of nine grams in our Galaxy had been through conditions like those in this 25 $M_\odot$ star. The agreement of the ejected abundances with the solar system abundance pattern (Cameron 1982) is striking; 34 out of the 61 species in this mass range are coproduced within a factor of two of their solar ratios compared with oxygen, and an additional 18 are within about a factor of 4. The agreement is all the more impressive when one considers that these same abundances span a range of 10^7 in abundance in the Sun and that many of the elements that are not produced here may have their origin in novae (^{15}N) or lower mass stars (^{12,13}C, ^{14}N). The generally low abundances of both carbon and its burning products (^{20}Ne, ^{23}Na, and ^{24,25,26}Mg) are direct consequences of the recent inflation of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate (Kettner et al. 1982, Langanke & Koonin 1983, 1985, Caughlan et al. 1985). So too, but indirectly because of adjustments to the stellar

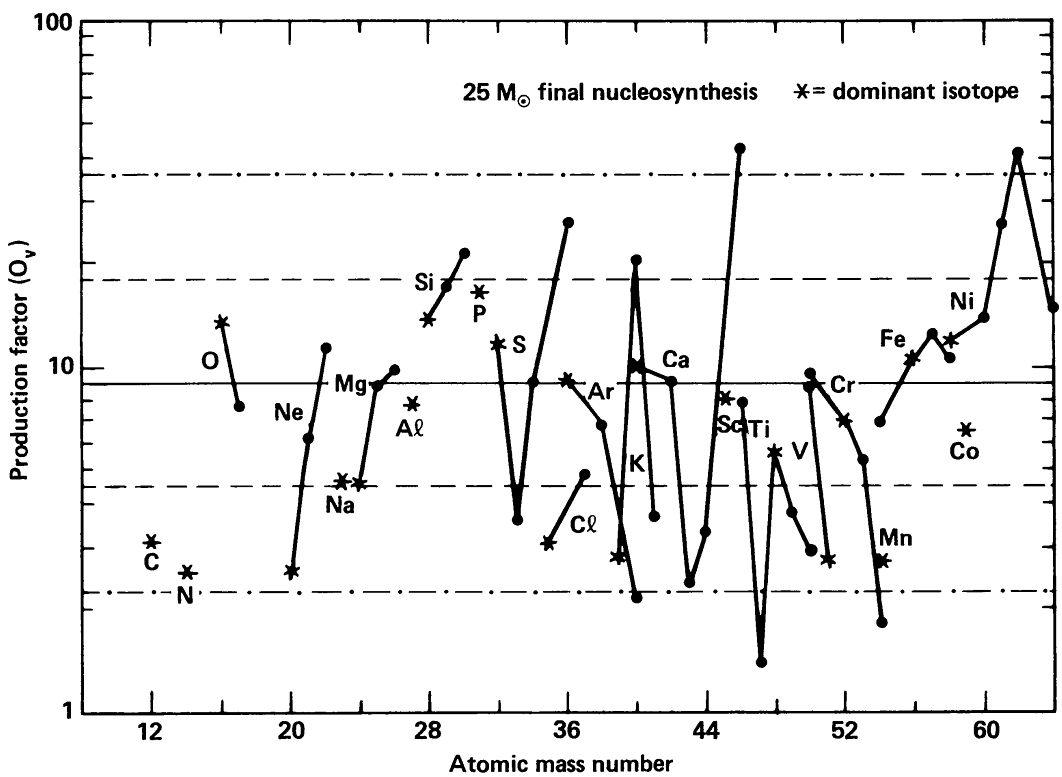


Figure 3 Isotopic nucleosynthesis in a 25-$M_\odot$ explosion. Final abundances in the ejecta are plotted for isotopes from ^{12}C to ^{64}Ni compared with their abundances in the Sun (Cameron 1982). An average production factor of nine characterizes the distribution. If one gram in nine of the matter in the Galaxy has experienced conditions like those in a 25-$M_\odot$ star, its metallicity will resemble the Sun with an abundance pattern as shown. Figure taken from Woosley & Weaver (1985).

structure, is the larger production of silicon through calcium (Woosley & Weaver 1982b, 1985). This same explosion also produces $7 \times 10^{-5}\ M_{\odot}$ of radioactive ^{26}Al, an important candidate for gamma-line astronomy (Mahoney et al. 1982, 1984). It is encouraging to see such good agreement between two samples, one totally the result of theory (and laboratory nuclear properties) and the other experimental. Whether this agreement will persist and even improve when explosions and isotopic nucleosynthesis have been properly calculated for the entire range of stellar masses remains to be seen. Nucleosynthesis studies in the *presupernova* models (Arnett 1978b, Arnett & Thielemann 1985, Thielemann & Arnett 1985, Woosley & Weaver 1986) suggest that it will.

2.6 *The Explosion of More Massive Stars*

Moving to the upper end of stars that are known to exist, $M \gtrsim 60\ M_{\odot}$, one encounters a different sort of evolution in the terminal stages. Following the exhaustion of helium, the central regions of the star contract, and since the amount of carbon and neon produced by helium burning is small ($\sim 5\%$ each by mass), the star goes directly to oxygen ignition. However, if the entropy of the central regions exceeds $S/k \sim 7$ (Bond et al. 1982, 1984, Woosley & Weaver 1986) or, for present values of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$, if the helium core mass exceeds about 32 $M_{\odot}$ (main-sequence mass $\gtrsim 65\ M_{\odot}$), oxygen burning is not ignited in a stable fashion. The instability, known as the "pair instability" (Fowler & Hoyle 1964, Barkat et al. 1967), occurs because a large portion of the energy from gravitational contraction goes, at temperatures around 2×10^9 K, into the creation of the rest mass of electrons and positrons. This temporarily reduces Γ_1 below 4/3 and triggers collapse. If the mass of the star is not too large, nuclear burning can give enough energy to reverse this collapse, which causes either a violent pulsational instability (Barkat et al. 1967, Woosley & Weaver 1986) or an explosion (Barkat et al. 1967, Arnett 1972b, 1973, 1978a, Fraley 1968, Wheeler 1977, Bond et al. 1982, 1984, Woosley & Weaver 1982a, Ober et al. 1983). The mass range for these occurrences is sensitive to $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ and to rotation (Stringfellow et al. 1983, in preparation, 1986; Glatzel et al. 1985), but it presently appears that pulsational instability, leading after a few pulses to core collapse (Woosley & Weaver 1986), will occur in stars having a main-sequence mass between about 65 and 120 $M_{\odot}$; the complete explosions will occur from 120 $M_{\odot}$ on up to about 300 $M_{\odot}$. Beyond this point, oxygen burning is unable to reverse even the first collapse, and since silicon burning is endoergic in stars of such high entropy, a black hole is formed (neglecting rotation) on a hydrodynamic time scale. The pulsating explosions may be especially interesting both because they occur for a mass range that may be significantly populated with stars and because they offer the possibility of an outburst having supernova-like energies but of longer duration. One explosion of a 45-$M_\odot$ helium core studied by Woosley & Weaver (1985, 1986) continued for two years and five oscillations before the bulk of the star finally collapsed. During this time, several solar masses of helium and helium-burning products were ejected with high velocity.

Providing that a portion of the extended hydrogen envelope is retained, a prospect that many regard as doubtful for such massive stars (Maeder 1984), the explosion of the core by the pair instability will still produce a supernova that would be optically designated Type II. Light curves for such supernovae have been calculated by Woosley & Weaver (1982a). The electromagnetic display of a pair instability supernova in a star that has lost its hydrogen envelope is an interesting problem, one that is as yet unattempted (although see Woosley & Weaver 1982a); its solution will depend sensitively upon whether even a small fraction of mass is ejected as radioactive ^{56}Ni. If so, these objects would be close cousins to Type I supernovae.

2.7 *Unusual Type II Supernovae*

Although the class of Type II supernovae is a diverse one, encompassing essentially all exploding objects with about 10^{51} erg of energy and hydrogen lines in their spectrum, there are some members that are obviously more extreme cases. Chief among these is SN 1961v (Wild 1961, Branch & Greenstein 1971, Chevalier 1981a), originally classified by Zwicky (1964) as Type V. An especially unique attribute of this supernova is that the presupernova star was actually seen for at least 37 years prior to the explosion (photographic magnitude $17^{\rm m}_{.}7$ to $18^{\rm m}_{.}2$; Zwicky 1964, Bertola 1963, Branch & Greenstein 1971, Utrobin 1984) and 8 years after maximum light (Bertola & Arp 1970). Reasonable estimates of the distance to NGC 1058 (11.1 Mpc) and interstellar extinction ($0^{\rm m}_{.}5$) imply a luminosity that for more than 23 years was $\gtrsim 5 \times 10^{40}$ erg s^{-1} (Utrobin 1984). This value and use of the Eddington luminosity limit suggest a star of *at least* several hundred solar masses (Chevalier 1981a). The abundance analysis by Branch & Greenstein indicated that the helium-to-hydrogen ratio was about 3 to 4 times the solar ratio and the spectral lines much narrower than in most Type II's. The light curve was also unique, with brilliant emission (a few percent peak, or $\sim 10^{41}$ erg s^{-1}) persisting for more than two years after maximum. Utrobin (1984) has modeled this supernova as the explosion of a 2000-$M_\odot$ star. Clearly the low velocity, enduring light curve, helium enhancement, and bright presupernova star are suggestive of a supermassive precursor. It should be noted, however, that not only are such stars rare (if they exist at all!), but that they lie well above the critical mass, 200 to 300 $M_\odot$, calculated by Woosley & Weaver (1982a) and Bond et al. (1982, 1984) for which nuclear burning is able to overcome the electron-positron pair instability and cause an explosion in a nonrotating star. Without rotation or catastrophic loss of a large fraction of its mass just prior to collapse, a 2000-$M_\odot$ star, or even a 500-$M_\odot$ star, would simply become a black hole. It is also most interesting that such a massive star should not have completely shed its hydrogen envelope by the time of its explosion. Apparently there may be exceptions to the "40-$M_\odot$ rule" discussed in Section 2.1. Cowan & Branch (1985) have just recently located what may be the radio remnant of SN 1961v, and Fesen (1985) has studied the H II region in which the remnant is embedded. The present magnitude of the supernova is dimmer than 21.

The progenitor of the Cas A supernova remnant is also generally regarded as having been unusual because, even though nearby, it was not unambiguously detected optically (Ashworth 1980, Maran 1981, van den Bergh & Kamper 1983). This may reflect the fact that the presupernova star had already lost its hydrogen envelope (Chevalier 1976a) and was thus lacking an optical amplifier at the time of its explosion. Indeed, such subluminous explosions may be common and selected against. Oxygen-rich supernova remnants similar to Cas A are now frequently discovered (Raymond 1984, Green 1984).

Peculiar too is a supernova recently discovered in NGC 4618 (Filippenko & Sargent 1985). Known presently as the "Filippenko-Sargent object" or SN 1985f, this stellar object, which is located in an H II region, displays very strong, broad emission lines of neutral oxygen. Weaker lines have been attributed to C I, Na I, Mg I, and Ca II, but there is no indication whatsoever of hydrogen or helium. The velocities (3000–5000 km s^{-1} at line half-maximum, 10,000–15,000 km s^{-1} near zero intensity), the absolute magnitude ($M \approx -14$ during February 1985; Filippenko & Sargent 1985), and the fact that this luminosity declined by roughly a factor of three between March and July 1985 (M. DeRobertis, private communication) are all indicative of a supernova, but the spectrum, and perhaps the light curve, is like nothing that has been seen before. Clearly the calculation of radiation transport in an explosion of a massive star that has lost its hydrogen envelope is needed. The ultimate power source may prove to be radioactive or hydrodynamical in origin, but the speculation is that this sort of phenomenon may have led to Cas A.

3. TYPE I SUPERNOVAE

A variety of mechanisms have been proposed to explain Type I supernovae. These include the hydrodynamical explosion of stellar cores (Lasher 1975, 1980, Lasher & Chan 1979, Arnett 1979, Colgate et al. 1980, Colgate & Petschek 1982), pulsar-driven explosions (Ostriker & Gunn 1969, Bodenheimer & Ostriker 1974, Shklovskii 1975, Nadëzhin & Utrobin 1977, Utrobin 1978), and the thermonuclear disruption of white dwarfs (Hoyle & Fowler 1960, Schatzman 1963, Arnett 1968b, 1969, Rose 1969, Paczynski 1970). Although (as we shall see) a number of outstanding issues still remain to be resolved, there has been a convergence in the last decade by most people working in the field upon the thermonuclear model to explain at least the majority of Type I events. The favored scenario involves an accreting white dwarf in a binary system that grows to a critical mass [Whelan & Iben (1973), although see also Truran & Cameron (1971) and Wheeler & Hansen (1971)], ignites carbon or helium under extremely degenerate conditions, and burns a substantial mass to nuclear statistical equilibrium. The energy from the burning disrupts the star at high velocity, although a portion of the white dwarf may, infrequently, stay behind if the ignition occurs off center. In general, no neutron star or black hole is expected in an event that would be called a Type I supernova [although see Wheeler & Levreault (1985) and Section 3.3]. The abundance peak in nuclear statistical equilibrium centers around ^{56}Ni (Truran et al. 1967), a terrestrially unstable nucleus, which by its decay ($\tau_{1/2} = 6.10$ days; average decay energy 1.72 MeV) and the decay of its daughter ^{56}Co ($\tau_{1/2} = 78.76$ days; average decay energy 3.58 MeV) provides the entire electromagnetic display associated with Type I supernovae (Pankey 1962, Colgate & McKee 1969, Colgate et al. 1980, Arnett 1979, 1982a,b, Chevalier 1981c, Weaver et al. 1980). The initial internal energy generated by nuclear fusion, $\sim 10^{51}$ erg, is degraded by a factor of roughly 10^6 as the supernova expands from its initial radius of $\sim 10^9$ cm to one of 10^{15} cm, where it becomes optically thin. As with Type II's, almost all of the explosion energy is kinetic. What we see in a Type I supernova, then, is nothing more than the fallout from a thermonuclear explosion.

This general scenario meshes well with a number of observational constraints. The low-mass progenitors can occur, although not exclusively, in very old populations such as exist in elliptical galaxies (Tammann 1974, 1977, 1978, 1982, but see also Oemler & Tinsley 1979) and need not be associated with the spiral arms of spiral galaxies (Maza & van den Bergh 1976). Exploding white dwarfs would plausibly lack hydrogen lines in their spectra, an essential condition to being called Type I, and would produce the large quantities of iron that are seen in the optical and infrared emissions, especially at late times (Kirshner & Oke 1975, Meyerott 1980, Axelrod 1980a,b, Graham et al. 1985); they would also produce the radioactive nucleus ^{56}Co, which is also identified in the optical spectrum at early (Branch 1984a,b, 1985a,b) and late (Axelrod 1980a,b) times. (The late-time identification is the much more solid of the two.) Increasing evidence is also mounting for the presence of several tenths of a solar mass of iron in the remnant of SN 1006 (Wu et al. 1983, Hamilton et al. 1985a) and other suspected Type I remnants (Hamilton et al. 1985b,c). We note that it is quite difficult for any but the most massive of stellar cores (helium core mass $\gtrsim 8\ M_{\odot}$) to produce 0.3 $M_{\odot}$ of iron in a hydrodynamical or neutrino-energized explosion (Weaver & Woosley 1980a, Wilson et al. 1985). The coincidence that this same quantity of iron, i.e. ~ 0.3 to ~ 1.0 $M_{\odot}$, implies a sufficient energy release to provide the observed kinetic energy starting from a white dwarf configuration and the fact that, if initially present in the form of ^{56}Ni as the model predicts, it would also give the correct total *optical* energy and time history of the light curve (Colgate & McKee 1969, Colgate et al. 1980, Arnett 1979, 1982a,b, Chevalier 1981c, Weaver et al. 1980) as well as the late-time spectrum (Axelrod 1980a,b) add to the compelling aspects of the thermonuclear model. Finally, the class of Type I supernovae is very regular. With few exceptions (Section 3.6) one Type I supernova looks very much like any other. This similarity would be a natural consequence of a uniform starting configuration, e.g. a carbon-oxygen (CO) white dwarf igniting a thermonuclear runaway in its center after almost achieving the Chandrasekhar mass.

3.1 *General Thermonuclear Models*

Within the thermonuclear umbrella there can be considerable variation (Figure 4), and it is an important unresolved issue just how nature selects from among various theoretical possibilities to give the common event (Branch 1985a). One may have either *detonations*, in which the thermonuclear burning propagates as a supersonic front, with density and pressure both increasing as matter passes through the wave (Courant & Friedrichs 1948), or *deflagrations* (sometimes referred to as "combustion waves" or simply "flames"; Zeldovich et al. 1985), in which the burning proceeds subsonically and pressure and density both decrease just behind the burning front. The combusting fuel may be carbon (detonation or deflagration) or helium (detonation). Burning may ignite centrally or off center, and, at least in the case of helium detonations, there may be considerable variation in the critical mass of the white dwarf at the time it explodes.

The original calculation of Arnett (1968b, 1969, 1971) that served to stimulate a great deal of work that followed was a *carbon detonation*. Much has been written since then (Buchler et al. 1971, 1974, Mazurek et al. 1974, 1977, Nomoto et al. 1976, Sugimoto & Nomoto 1980, Bruenn 1971, Mazurek & Wheeler 1980, Ivanova et al. 1974, Buchler & Mazurek 1975, Kudryashov et al. 1979, Woosley & Weaver 1986) concerning such issues as whether a detonation wave will form in a region experiencing a degenerate carbon runaway; if it forms will it survive; and whether it is possible to implode to a neutron star. There is now a consensus that a centrally ignited carbon detonation (or deflagration, for that matter) will not lead to neutron star formation unless the initial carbon abundance is unreasonably small (although see Canal & Schatzman 1976, Canal & Isern 1979, Isern et al. 1983), but the other two issues remain controversial and are sensitive to the initial conditions assumed in various studies. For example, Mazurek et al. (1977) calculate that a supersonic burning front *will* form for the adiabatic temperature gradient that should be present at the time of runaway owing to the convective stage that precedes the final incineration (Arnett 1969). Essentially, it is easier to start a detonation in hot material near the center of the star that is already on the verge of exploding than in cold material having a low initial internal energy (Mazurek et al. 1974). Nomoto et al. (1976), on the other hand, using very fine mass zoning ($\sim 10^{-5}$ $M_{\odot}$ in the central zone) and including time-

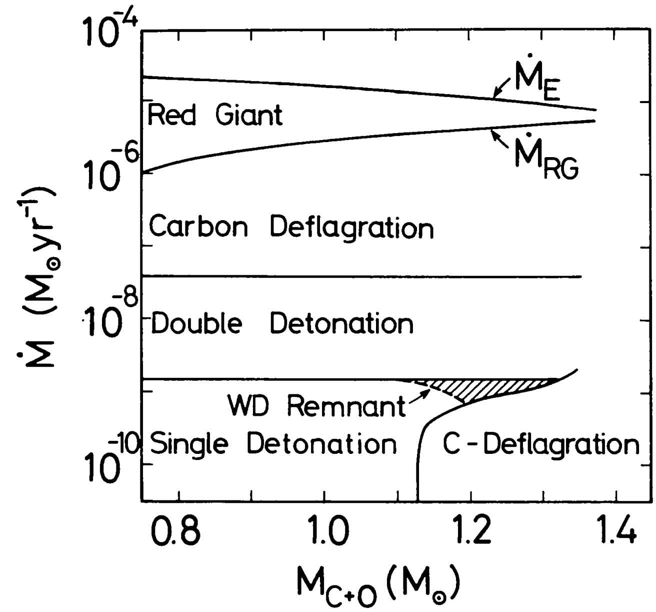


Figure 4 The type of thermonuclear explosion expected from an accreting CO white dwarf of a given mass and accretion rate. Here $\dot{M}_E$ denotes the Eddington limit. For accretion more rapid than $\dot{M}_{RG}$, a red giant–like envelope is formed (Nomoto et al. 1979b). For 4×10^{-8} $M_{\odot}$ yr$^{-1} \lesssim \dot{M} \lesssim \dot{M}_{RG}$ accretion leads to weak helium-shell flashes that gradually increase the core mass until deflagration is ignited in the center. In double detonation models the flash of accreted helium is strong enough to induce both helium and carbon detonation. For $\dot{M} \lesssim 1.5 \times 10^{-9}$ $M_{\odot}$ yr^{-1} the outcome is sensitive to the initial mass of the white dwarf. For larger masses carbon is centrally ignited prior to any helium-shell flash. For smaller masses helium detonates prior to carbon ignition and fails to form a carbon detonation wave. The single detonation either disrupts the star completely or leaves a white dwarf remnant (shaded region). Figure taken from Nomoto et al. (1985).

dependent convection, do not find a supersonic burning front occurring in an appreciable fraction of the mass. Our own recent calculations (Woosley & Weaver 1986) suggest that both solutions are mathematically possible and that the outcome is critically dependent upon both the mass zoning and *especially* the temperature at which one relinquishes a mixing-length approximation to the energy transport preceding the runaway. In particular, if an adiabatic gradient is maintained over a large fraction of the core up to the point where the central temperature exceeds $\sim 1.0 \times 10^9$ K, then the initiation of a supersonic burning front is very likely; but for somewhat cooler cores, $T \lesssim 8 \times 10^8$ K, supersonic burning does not occur in a large fraction of the mass. This is also consistent with the calculations of Müller & Arnett (1982, 1985), who found that initiation of the detonation requires a critical mass of material to run away as a unit. Once born, it is also controversial whether the detonation will incinerate the entire star (Arnett 1969, Müller & Arnett 1982, 1985) or die in the decreasing temperature gradient (Mazurek et al. 1977, Woosley & Weaver 1986). In the latter case, the burning front presumably continues for a time as a deflagration wave, although no calculations have been carried out. As we see in Section 3.2, the observational data, especially the presence of silicon and calcium lines in the spectrum taken at peak light, suggest that a detonation wave has *not* propagated through the *entire* star in the common event.

No such uncertainties surround the fate of a degenerate *helium* runaway, either in a helium dwarf (Mazurek 1973, 1980, Nomoto & Sugimoto 1977, Woosley et al. 1986) or at the base of a thick helium layer accreted onto a CO or oxygen-neon-magnesium (ONeMg) white dwarf (Weaver & Woosley 1980b, Woosley et al. 1980, Nomoto 1980a,b, 1982b,c, Sutherland & Wheeler 1984, Woosley et al. 1986). The result is always detonation. Helium burning to iron releases more energy than carbon and oxygen and, more importantly, ignites at lower densities, where the Fermi pressure is not so large and the thermal overpressure from nuclear burning is correspondingly greater. Earlier studies focused upon the central ignition of helium in an accreting *helium* white dwarf. The critical mass for the helium white dwarf to detonate may, depending upon accretion rate, be as small as $\sim 0.65\ M_{\odot}$ (Woosley et al. 1986), since gravitational compression and the relatively low ignition temperature of helium could allow an explosion to occur long before the Chandrasekhar mass is reached. Iben & Tutukov (1984) estimated that the frequency of helium detonations, either in systems consisting of two helium dwarfs merging by gravitational radiation or a single helium dwarf accreting from a low-mass main-sequence star, is adequate to explain a substantial fraction of all Type I events. Later, Iben & Tutukov (1985) revised this estimate downward, especially for the merger of two helium dwarfs, but the possibility remains that a minority of events may originate in this fashion. One may also ignite a helium detonation off center at the base of a layer accreted on a CO white dwarf [Figure 4; Weaver & Woosley (1980b), Nomoto (1980a,b, 1982b,c), Woosley et al. (1980, 1986), Sutherland & Wheeler (1984), Iben & Tutukov (1984), although see Iben & Tutukov (1985), who claim that a more likely outcome is a R Cr B star, not a supernova]. If the strength of the helium detonation is sufficient, a detonation wave will also move into the carbon core, leading to the complete incineration of the star [the so called "double detonation model" (Weaver & Woosley 1980b, Woosley et al. 1980; Figure 4)]. Otherwise, the helium (converted mostly to ^{56}Ni) and a portion of unburned carbon and oxygen substrate are ejected and a hot, violently oscillating white dwarf is left behind.

In general, the light curves and nucleosynthesis of helium detonation models (of all varieties, helium dwarfs and otherwise) are in good agreement with observations on the one hand, and solar system abundances on the other, provided that $\gtrsim 0.3\ M_{\odot}$ of ^{56}Ni is synthesized (Axelrod 1980a,b, Weaver et al. 1980, Sutherland & Wheeler 1984, Woosley et al. 1986). A lesser amount of ^{56}Ni gives an optical display that is too brief and too dim. Severe difficulty is encountered, however, when one examines the spectrum. Because of the large energy released by helium burning to iron, the fact that the detonation wave burns almost all of the ejected layer, and the lower gravitational binding energies associated with the smaller white dwarfs that experience helium detonation, the result is that the kinetic energy per gram (i.e. the terminal velocity) is too large. Thus, line features are overly broad in both the early- (Branch et al. 1982, 1983, Branch 1984a) and late-time (Axelrod 1980b, Woosley et al. 1984) spectrum. Moreover, as mentioned previously, helium detonations suffer from a severe deficiency of intermediate-mass elements in the ejecta. For a detonation wave there are essentially only two states for the matter—unburned or nuclear statistical equilibrium. Only a tiny fraction of a helium (or helium-capped) star exists at such low density that its heat capacity allows substantial burning without the temperature rising above 5×10^9 K, a value that guarantees the complete burning (even of silicon) on a hydrodynamic time scale. Absorption lines of silicon, sulfur, and calcium are prominent in a spectrum taken at peak light (Branch et al. 1982, 1983, Branch 1984a, 1985a,b) and are generally regarded as evidence that Type I supernovae powered by helium detonation do not comprise a large fraction of the present sample, although Branch & Doggett (1985) speculate that SN 1957a may have been a helium detonation event.

3.2 *The Standard Model*

If a detonation wave does not form in a CO core experiencing a degenerate runaway, or if the detonation wave does form but dies shortly thereafter, then a *deflagration* results. The ensuing explosion turns out to have properties in remarkable agreement with what is observed and warrants, at least temporarily, the designation "standard model." We summarize the salient aspects of this model as developed in a number of independent works. No single calculation thus far has included *all* the relevant physics.

As a CO white dwarf grows by accretion, its central density increases. Early on, energy loss by neutrino emission, principally from plasmon decay, and energy generation by gravitational compression dominate the evolution of the central regions. Since the rate for the neutrino losses initially increases with density, a temperature inversion develops. When the mass of the white dwarf reaches about 1.40 $M_\odot$, the exact value depending upon specific choices of composition, entropy, and post-Newtonian corrections to gravity, the central density is near 2×10^9 g cm^{-3}. At such a high density, the neutrino losses begin to decline owing to the increasing difficulty of creating a high-energy plasmon from the thermal bath. At the same time nuclear energy generation, enhanced by a very large electron screening correction, increases to the point that it finally exceeds these neutrino losses. The runaway commences (Arnett 1969, 1971).

Initially nuclear reactions are slow, and it makes some sense to employ conventional (mixing-length) convection theory. Calculations show that neutrino losses from both convective and stationary URCA processes become important at this stage and briefly act to stabilize the runaway (Tsuruta & Cameron 1970, 1976, Bruenn 1973, Paczynski 1972, 1973a,b, Ergma & Paczynski 1974, Couch & Arnett 1974, 1975, Iben 1978a,b, 1982). The central density rises to $\sim 4 \times 10^9$ g cm^{-3}, the carbon mass fraction decreases by 5 to 10%, and the temperature slightly off center rises to about 3.5×10^8 K. Past this time URCA losses are less efficient in stabilizing the runaway, and nuclear burning accelerates rapidly. It is important that the runaway does *not* begin at the center of the star (Iben 1978a,b, 1982). Because of the operation of the ^{21}Ne-^{21}F URCA pair at a threshold density of 3.9×10^9 g cm^{-3}, very efficient cooling decreases the central temperature in the inner 0.02 $M_\odot$ to about 10^8 K. This cooling disconnects a small central region above this critical density from the overlying convective shell, and it is at the base of this convective shell that the nuclear runaway commences. Since it is impossible for a spherical shell to ignite all at once, the runaway will start at one point, or more likely many points, located on a spherical surface about 100 km out from the center of the star.

Once carbon is burning at a sufficient rate that losses are negligible, the temperature rises about 10^8 K for each 10^{15} erg g^{-1} liberated at constant density, or for each 0.3% by mass of carbon that burns. By the time the temperature reaches 7×10^8 K, the time scale for heating by nuclear reactions is comparable to the reciprocal of the Brunt-Väisälä frequency, very roughly 100 s (Mihalas & Mihalas 1984, Spiegel 1972), and it no longer makes sense to speak of convection in any traditional sense (Nomoto et al. 1984b). A short time later, by the time $T \approx 10^9$ K, nuclear reactions are occurring on a time that is short even compared with the sound-crossing time for a pressure scale height ($\sim$0.01 s). Again, provided that a detonation does not form at this stage, a flame front (or fronts) commence that are initially propagated by electron conduction (Mazurek et al. 1980a, Woosley & Weaver 1985, 1986). The steady velocity of this flame is about $v_{\rm cond} \sim (cl_{\rm mfp}/\tau_{\rm nuc})^{1/2} \sim 50$ km s^{-1} in the absence of turbulence and instabilities. Here $v_{\rm cond}$ is the flame velocity as propagated by conduction, $l_{\rm mfp}$ is the electron mean free path, and $\tau_{\rm nuc}$ is the life time of carbon against carbon-burning at a temperature where nuclear energy release dominates conduction ($\sim 4.5 \times 10^9$ K).

Actually the low density and high temperature behind the flame front guarantee instability, and as the burning region becomes larger, longer wavelength Rayleigh-Taylor modes will begin to grow rapidly (Müller & Arnett 1982, 1985). Dimensional analysis suggests then that $v_{\rm turb} \propto R$, the radius of the flame front (Mazurek et al. 1980a, Woosley & Weaver 1986), with a proportionality constant k such that turbulent propagation will dominate for radii greater than about 100 km ($k \sim 1$ s^{-1}). It is a curious coincidence that this is about the same size as the radius where the runaway begins. Thus the conductive phase may be expected to lead to the coalescence of various diverse burning regions and perhaps to the combustion of the cold central knot of 0.02 $M_\odot$ before switching to a turbulent mode of propagation that in the terminal stages is limited only by the sound speed of the expanding burned material. One also expects and calculates (Müller & Arnett 1982, 1985) large-scale angular inhomogeneity in the composition that is finally ejected.

Several groups (Nomoto et al. 1976, Buchler & Mazurek 1975, Nomoto 1980a,b, 1981, 1984d,e, Nomoto et al. 1984b, Woosley et al. 1984, Sutherland & Wheeler 1984) have simulated the complicated, inherently multidimensional nature of the flame front using modified theories of time-dependent convection in one-dimensional stellar evolution codes. In such calculations, ignorance of the real nature of the turbulent flame is parameterized as the time- or radius-dependent velocity of a burning front whose angular dependence is ignored. Since by definition in a deflagration the flame must proceed at subsonic speeds, a pressure wave moves ahead of the front, accelerating the outer regions of the star and expanding them ahead of the burning wave. This marks an important distinction from detonations. Some material far out in the white dwarf may escape the star, having never experienced nuclear burning, while intermediately situated material undergoes incomplete nuclear burning as the flame dies out in the expanding star. Eventually the heat capacity of the expanding gas becomes so large that burning carbon or oxygen does not raise the temperature sufficiently to ignite silicon burning ($T \gtrsim 5 \times 10^9$ K). Thus intermediate-mass elements as well as unburned fuel get ejected. This has important implications for the spectroscopic properties of the model as well as for its energetics, and it is the principal reason the deflagration model is presently so highly regarded.

As a representative case, we consider a CO white dwarf of 1.0 $M_\odot$ accreting at 4×10^{-8} $M_\odot$ yr^{-1} (Model W7 of Nomoto et al. 1984b). If we ignore the complications brought about by the URCA process, the runaway ignites at a central density of 2.9×10^9 and a mass of 1.378 $M_\odot$. The deflagration front moves through the star at an accelerating velocity, reaching a terminal speed of about 30% of the sound speed in the outer layers. A total mass of 0.86 $M_\odot$ of iron-group elements is synthesized, of which 0.58 $M_\odot$ is initially in the form of ^{56}Ni, and an excess energy (over and above the initial white dwarf binding energy) of 1.3×10^{51} erg is released. This goes mainly into the kinetic energy of the supernova. In addition, 0.27 $M_\odot$ of silicon through calcium are synthesized as the flame dies out in the expanding star (Figure 5).

For this review, we have calculated the light curve expected from a model quite similar to Nomoto's "W7" (Model 2 of Woosley & Weaver 1986) following the prescription of Weaver et al. (1980), and it is compared with experimental data in Figure 6. The agreement with observations is very good. Branch et al. (1985) have also calculated the *spectrum* expected from Nomoto's Model W7 at peak light, and the comparison to SN 1981b is excellent (Figure 7). Note especially absorption features attributable to silicon and calcium, a distinctive signature of a deflagration (as opposed to detonation) model. It is noteworthy that to obtain the good agreement displayed in Figure 7, it was necessary to artificially mix the material external to $v = 10^4$ km s^{-1} (Figure 5). Otherwise, absorption lines of specific elements, such as calcium, occur at an overly narrow range of velocities. The physical mechanism that gives this mixing in the star is not clear, but it should be remembered that in the true multidimensional case, matter at a given radius in the star, and hence at a given asymptotic velocity, would not have the same composition along different angular rays. Such symmetry is an artifact of the one-dimensional calculation. The turbulence and Rayleigh-Taylor "fingers" associated with the flame front in its final stages (Müller & Arnett 1982, 1985) may provide a natural mechanism for spreading out the composition in "velocity space."

Figure 8 shows the *late*-time spectrum of Model 5 of Woosley et al. (1984), another CO deflagration model similar to Nomoto's W7, compared with the spectrum of Type I SN 1972e (which at maximum was a neartwin, spectroscopically, of SN 1981b). At such late times as 264 days, the emission comes from an optically thin nebula and is composed almost entirely of emission lines of iron-group elements, particularly ^{56}Fe and *radioactive* ^{56}Co in the first and second ionization stages. The agreement with observations is again striking, confirming among other things the presence of freshly synthesized iron and cobalt in the supernova. It is important to note that the late-time spectrum is much more restrictive upon the models than the light curve or nucleosynthesis. Not only must one get the composition right, but also, especially at late times, the dominant ionization stages come from a balance of heating by radioactive energy deposition in the form of gamma rays and positrons and of cooling by collisional excitation of forbidden lines (Axelrod 1980a,b). The ionization stages are quite sensitive to the *density* structure as a function of time and location in the young supernova; along with the widths of various spectral features, they greatly constrain the velocity structure allowed for the asymptotic model. Helium detonations, for example, are apparently disallowed for the common event (Woosley et al. 1984).

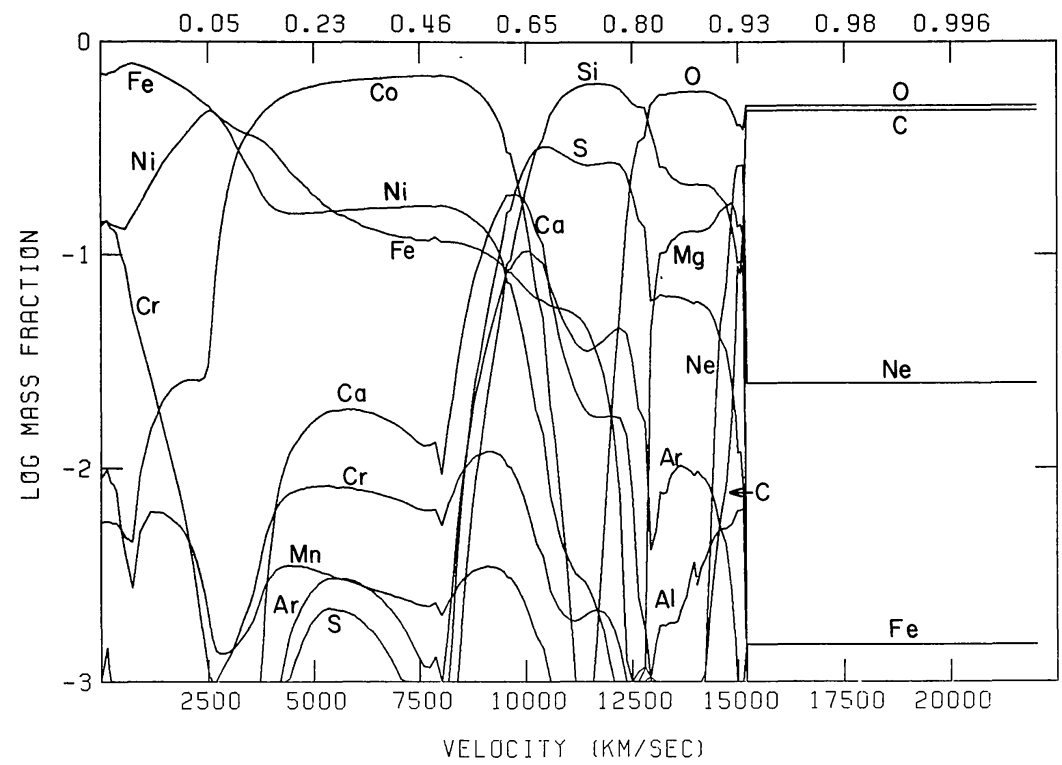
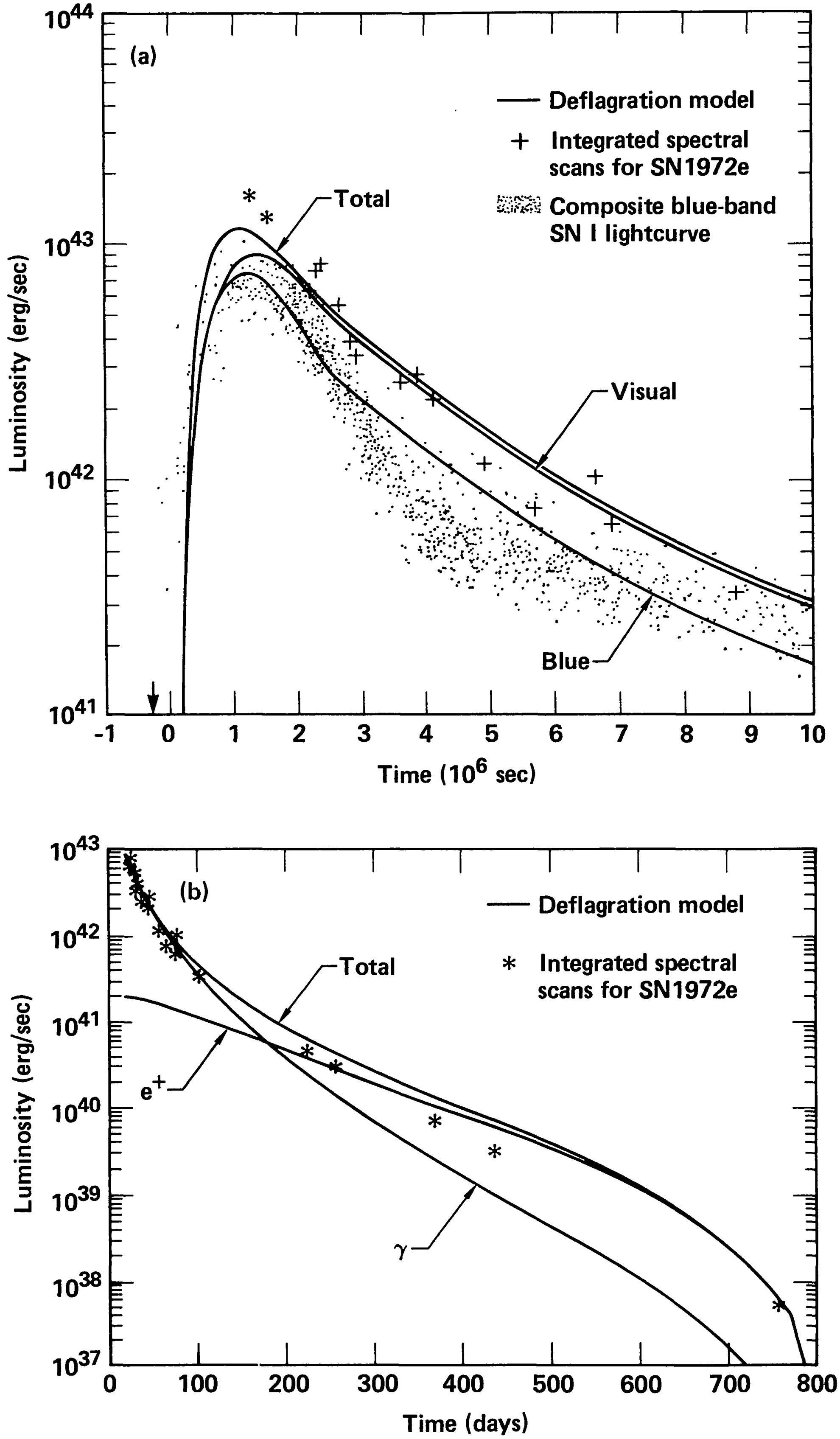


Figure 5 Composition of a carbon deflagration model for Type I supernovae (Model W7 of Nomoto et al. 1984b) as a function of interior mass in solar masses (top of figure) and asymptotic expansion velocity (bottom of figure). The composition is sampled at a time near maximum light (15 days). All of the cobalt shown will later decay to ^{56}Fe. Figure taken from Branch et al. (1985).



(a)
Deflagration model
Integrated spectral scans for SN1972e
Composite blue-band SN I lightcurve
Total
Visual
Blue
Luminosity (erg/sec)
Time (10^6 sec)
(b)
Deflagration model
Integrated spectral scans for SN1972e
Total
e^+
γ
Luminosity (erg/sec)
Time (days)

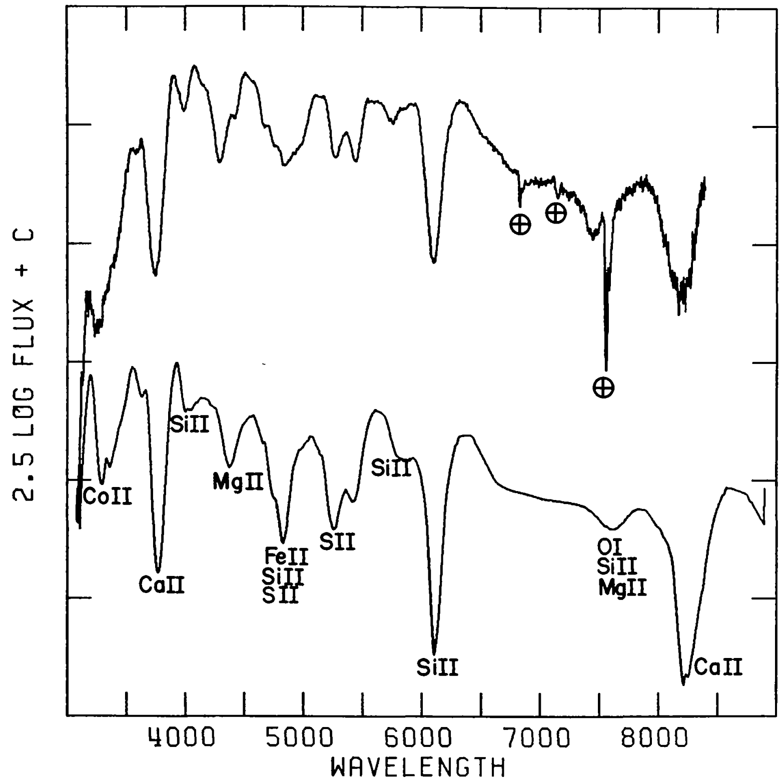


Figure 7 The March 7 (maximum light) spectrum (top) of SN 1981b (Branch et al. 1983) is compared with a synthetic spectrum (below) for deflagration model W7 (Nomoto et al. 1984b). In order to obtain the good agreement shown, it was necessary to mix the composition in Figure 5 external to 0.65 $M_\odot$ ($v \sim 10^4$ km s^{-1}). Terrestrial absorption features in the observed spectrum (circled crosses) are indicated. Figure taken from Branch et al. (1985).

Figure 6 Theoretical total, visual, and blue-band light curves calculated for a carbon deflagration supernova using the technique of Weaver et al. (1980) compared with observations. The supernova model employed is Model 2 of Woosley & Weaver (1986), an explosion of a 1.41-$M_\odot$ CO dwarf (final kinetic energy of 1.1×10^{51} erg) that ejected 0.86 $M_\odot$ of iron-group isotopes, 0.58 $M_\odot$ of which was initially ^{56}Ni. Here the calculated curve is shown compared with data for SN 1972e for times near peak light (upper frame) and far out on the tail (lower frame) under the assumptions of an explosion date of JD 2441428 and a distance of 3.2 Mpc to NGC 5253. In the upper frame, integrated spectral scans of Kirshner et al. (1973) are shown as crosses, asterisks are from Austin (1972) as is the downward-pointing arrow indicating a prediscovery upper bound, and dots are the composite blue-band light curve of many Type I supernovae (Barbon et al. 1973) shifted in magnitude and time so as to provide the best fit. At late times the optical emission is pumped partly by gamma rays but chiefly by the kinetic energy of positrons emitted during the decay of radioactive ^{56}Co. Asterisks in the lower frame are unreddened, integrated spectral scans from Kirshner et al. (1973) and Kirshner & Oke (1975).

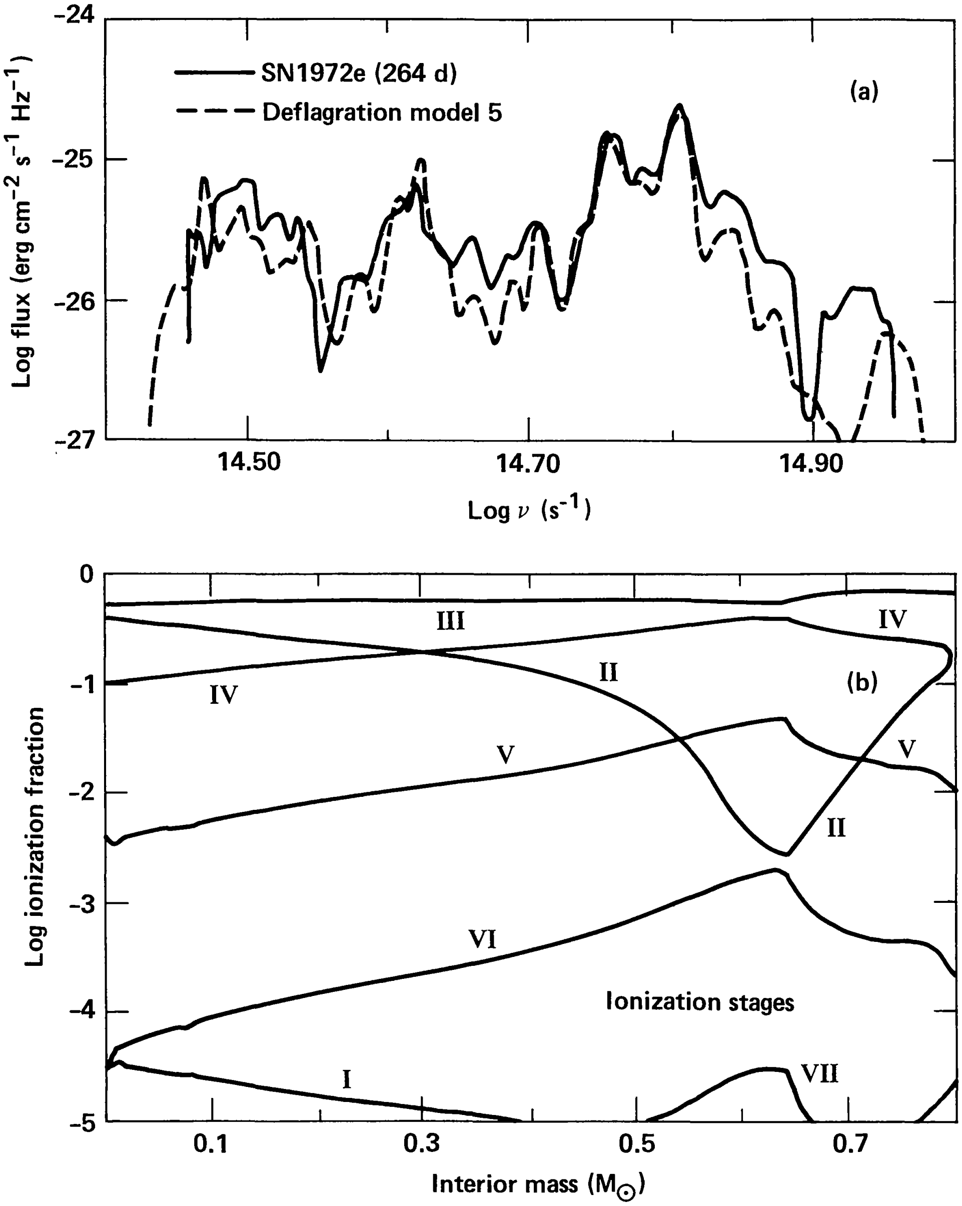


Figure 8 Optical spectrum of a carbon deflagration model supernova (Model 5 of Woosley et al. 1984) compared with that observed for SN 1972e (Kirshner et al. 1973) at a time 264 days after its explosion. At this point the entire supernova is transparent, and the spectrum is, for the most part, a composite of emission lines, chiefly Fe II, Fe III, and Co III (radioactive). A narrow absorption feature in the observations at log $\nu \approx 14.90$ is due to calcium, which was not included in the model calculation. The lower frame shows the distribution of ionization fractions for cobalt and iron as a function of interior mass.

3.3 *Nucleosynthesis in the Standard Model*

The nucleosynthesis expected from the standard model has been calculated by several groups (Woosley et al. 1984, Nomoto et al. 1984b, Thielemann et al. 1985). The dominant product is iron peak nuclei (Figure 5), but important minor synthesis of lighter elements also occurs. Normalizing to ^{56}Fe, Thielemann et al. find about one half of the silicon, sulfur, argon, and calcium in the solar system could be produced by Type I supernovae (see also Nomoto et al. 1984a). Woosley et al. (1984) find a value about one half as much as that of Thielemann et al. with the discrepancy attributable to different prescriptions for the flame velocity, which is a rather uncertain quantity, as our previous discussions indicate. A faster flame in the final stages of the explosion allows more material to experience the intermediate temperatures (especially 3–4×10^9 K) appropriate to explosive oxygen burning, and hence more intermediate-mass elements are produced (Woosley et al. 1973). Unfortunately the isotopic ratios of iron and the nickel-to-iron elemental ratio in these calculations are distinctly nonsolar (Woosley et al. 1984, Thielemann et al. 1985). In the work of Thielemann et al. the ratio ^{54}Fe/^{56}Fe is 2.4 times the solar value and Ni/Fe is 5 times the solar value. Since in any nucleosynthesis calculation one must properly normalize to the greatest overproduction, the synthesis of silicon through calcium is rendered trivial. Unless these overproductions can be explained away, Type I supernovae would be the source in nature of the element nickel and little else!

The cause of these overproductions can be traced to the large amount of electron capture experienced during the explosion, especially in the central regions. Reasonable adjustments in the capture rates (Fuller et al. 1982a,b) do not substantially alleviate the problem (Thielemann et al. 1985), although making the initial metallicity smaller by presuming a Population II origin for the white dwarf does help a little (Thielemann et al. 1985). It should be noted, however, that the model employed in these studies (Nomoto's W7) neglects the URCA process and thus uses a central ignition density of 2.9×10^9 g cm^{-3} rather than the correct value of 4×10^9 g cm^{-3} (Iben 1982). Weak rates scale with a high power of the density, and thus the problem is, in fact, even worse than it appears. We have suggested (Woosley et al. 1984, Woosley & Weaver 1985, 1986) that the unacceptable nucleosynthesis is again a consequence of our uncertain knowledge about how the flame propagates, especially during the first few hundred kilometers. In particular, if the flame begins very slowly, the energy release from the burning of only a few hundredths of a solar mass of carbon could "preexpand" the star so that later, when the flame begins to go very rapidly (Rayleigh-Taylor regime), the density would not be so high and electron capture would be correspondingly reduced. Alternatively, the "deflagration" might begin as a *detonation* with very rapid expansion of the core at early times (Section 3.1) and subsequently evolve into a subsonic flame in the decreasing temperature gradient. This is an area where our understanding is in a rapid state of evolution, and the reader should follow the literature for future developments.

The fact that each Type I supernova must produce $\sim 0.5\ M_\odot$ of iron in order to explain its light curve (as well as the fact that this is what the standard model gives) has historically been a point of concern in galactic chemical evolution models and was once used as an argument against the thermonuclear model (Arnett 1974c, Ostriker et al. 1974). The fact that the predicted synthesis has declined from $1.4\ M_\odot$ to $\sim 0.5\ M_\odot$ has helped somewhat, but there is still roughly a factor of 5 overproduction in the interstellar medium during the last 5 Gyr, when standard values of Type I rate and interstellar medium (ISM) mass are employed (Woosley et al. 1986). Suggested resolutions to this dilemma are (*a*) that a large fraction of the iron ejected in Type I supernovae actually leaves the Galaxy (Wheeler 1982, 1985, Nomoto et al. 1984a, Woosley et al. 1986); (*b*) that the mass of the ISM is not constant, i.e. there is infall (Tinsley 1980a,b, Twarog & Wheeler 1982, Woosley et al. 1986); (*c*) that the Type I supernova rate in our Galaxy is more like one per century or so than one per 36 years as frequently employed (Nomoto et al. 1984a, Tammann 1982); and (*d*) various uncertainties in the mass exchange rate between stars and the ISM and in the interstellar iron abundance (Tinsley 1980a,b). Given these possibilities (and any combination thereof), the iron poisoning of the ISM is no longer regarded as a lethal objection to the thermonuclear model, although, of course, one should keep it in mind.

Another important subsidiary issue to the nucleosynthesis is the amount of gamma radioactivities produced that might some day be observable to missions such as the *Gamma-Ray Observatory*. The principal isotope of interest is ^{56}Ni, since the synthesis here is adequate that a Type I supernova would be marginally detectable even in the Virgo cluster by the Oriented Scintillator Spectroscopy Experiment (Woosley et al. 1981, 1986, Kurfess et al. 1983). Another isotope of interest, ^{44}Ti ($\tau_{1/2} = 54.2$ yr), is also produced in substantial quantities [$\sim 10^{-4}\ M_\odot$ in the standard model (Nomoto et al. 1984b, Woosley et al. 1984) and even larger amounts, up to $10^{-2}\ M_\odot$, in more unusual models (e.g. detonating helium dwarfs) that experience explosive helium burning (Woosley et al. 1986)]. The species ^{22}Na and ^{26}Al, the latter of which was recently detected in the interstellar medium by Mahoney et al. (1984), are not substantially produced in Type I supernovae.

3.4 *Type I Supernovae and the Hubble Constant*

As many have noted (Branch & Bettis 1978, Colgate 1979, Elias et al. 1981, Arnett 1982a,b,c, Tammann 1982, Branch 1982, 1985b, Sandage 1985, Sandage & Tammann 1982), the regularity and brilliance of Type I supernovae make them excellent "standard candles" for determining the Hubble constant. Most recently, Arnett et al. (1985) have estimated on the basis of reasonable restrictions on the thermonuclear model that $H_0 = 39$–$71\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, with a best value of $58\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. A similar analysis by Woosley et al. (1986) gives $H_0 = 50$–$70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. Van den Bergh (1985) claims that these determinations are sensitive to the radiation transport model and points out that the transport of energy deposited as gamma rays and positrons in a rapidly and differentially expanding atmosphere with temperature and density gradients is a difficult problem. Much of this complexity affects the spectrum far more than the bolometric light curve, however, and as Figures 6, 7, and 8 illustrate, substantial progress in solving the full transport problem has already occurred. More work is needed but we and most people working in the area feel that Type I supernovae of the standard variety offer the best hope for a "standard candle" in the near and intermediate future.

3.5 *Evolution Leading to Type I Supernovae*

Despite the major successes that strongly suggest our interpretation of common Type I supernova events such as the deflagration of CO white dwarfs is largely correct, the precise evolutionary scenario leading to the outburst remains very uncertain. A number of scenarios have been discussed recently by Iben & Tutukov (1984). Somewhat surprisingly, the traditionally most attractive system, a degenerate CO white dwarf paired with a red supergiant filling its Roche lobe, does not fare at all well. Limitations on the initial white dwarf mass, which must be large ($\gtrsim 1.3\ M_\odot$), the primordial separation of the system components, and their mass ratio severely limit the expected supernova rate to a small fraction of what is observed. These restrictions are eased somewhat by considering the companion to be a red supergiant that is *not* filling its Roche lobe (here the accretion is provided by the capture of the stellar wind) or a "cataclysmic" close binary in which the companion is a low-mass main-sequence star that does fill its Roche lobe. The difficulty, however, in *any* system where hydrogen-rich material is being accreted is the complexity introduced by the nova instability. Evidence exists, both observational and theoretical, that novae eject most of the matter accreted between flashes and perhaps a portion of the accreting dwarf as well (Nariai et al. 1980, Sugimoto & Miyaji 1981, Fujimoto & Taam 1982, Fujimoto & Sugimoto 1982, Fujimoto 1982a,b, Prialnik et al. 1982, MacDonald 1983, 1984). Thus it is not at all well determined for what accretion rates and white dwarf masses, if any, the dwarf will *increase* its mass to the critical value.

In part to counter these objections, considerable attention has been given in recent years (Tutukov & Yungelson 1979, Webbink 1979, 1984, Iben & Tutukov 1984) to the possibility that Type I supernovae result from the merger, accomplished at the end by gravitational radiation, of two white dwarf stars (the so-called double degenerate model). This hypothesis has the attractive feature of providing the rapid accretion of nonhydrogenic material (helium or carbon) in a system that may be realized with adequate frequency to explain Type I statistics. The requisite orbital shrinkage by gravitational radiation provides a built-in time delay that, by reasonable adjustment of initial orbital parameters, may be as long as the Hubble time or as short as 10^8 yr. Unfortunately, this model too has its difficulties. The accretion rate in the terminal stages of the merger of two white dwarfs, probably accomplished by the shearing of the lighter one into a massive accretion disk, is both very difficult to calculate and at the same time a critical parameter of the model. Too rapid an accretion rate, $\dot{M} \gtrsim 3 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, leads to off-center carbon ignition (Saio & Nomoto 1985, Nomoto & Iben 1985, Woosley & Weaver 1985) and the conversion, accomplished in hydrostatic equilibrium on a conduction time scale, of the CO dwarf to an ONeMg dwarf that collapses without substantial optical display to a neutron star (Nomoto et al. 1979a, Nomoto 1984e). This itself, of course, has very interesting implications for creating X-ray sources and for its own particular transient emissions (Colgate & Petsheck 1979) but does not explain Type I supernovae. Only if the net accretion rate of the CO dwarf can be reduced below $\sim 3 \times 10^{-6}$ $M_\odot\ \mathrm{yr}^{-1}$ will the standard carbon deflagration occur. Further work is obviously needed, but the problem is multidimensional, involves details of angular momentum transport and mass loss, and is clearly difficult.

Within the double degenerate scenario, other interesting combinations of composition also come to mind involving hybrid mixtures (Iben & Tutukov 1985, Cameron & Iben 1985): a helium-capped CO dwarf mating with a naked CO core; the merger of a CO core with a ONeMg dwarf; and so on. The explosion of these stars could be distinctly different than in the standard model. The presence of a helium "sandwich" in a CO dwarf approaching the Chandrasekhar limit, for example, might grossly alter the manner of its combustion, producing a "double detonation" event in what would otherwise have been a deflagration. Carbon burning ignited on a neon substrate might be more likely to leave a white dwarf remnant, and so on. Though probably not an explanation for common Type I supernovae, such possibilities should be kept in mind when considering rare nonstandard events.

3.6 *Peculiar Type I's*

Over the last several years increasing evidence, principally spectroscopic in nature, has mounted that Type I supernovae may not be quite so regular and homogeneous a class as they were once considered. At present there is a tendency in the community to refer to all exceptions to "usual" Type I (i.e. those that comprise the bulk of our present observed set) as *peculiar*. Here, however, we follow the notation suggested by Elias et al. (1985) and Branch (1986b) and segregate the known Type I's into *three* classes: Type Ia, the brighter, more common events ($\sim 80\%$, although observational selection is probably a major effect; Branch 1986b); Type Ib ($\sim 10\%$), a dimmer subgroup sharing common spectral properties; and Type Ip, the remainder that fit into neither class and are therefore truly "peculiar." It is the Type Ia events that the "standard" model has thus far addressed. They are defined by Figures 6, 7, and 8. The signature of Type Ib is absence of the $\lambda 6130$ absorption feature in the spectrum taken at peak light—a feature generally attributed to Si II (Figure 7)—and the presence instead of an unidentified "doublet" at $\lambda 6300$ and $\lambda 6500$ (Bertola 1964, Bertola et al. 1965, Kirshner et al. 1976, Richtler & Sadler 1983, Uomoto & Kirshner 1985, Wheeler & Levreault 1985). At present, this class includes four certain members: SN 1962l, SN 1964l, SN 1983n, and SN 1984l. In general, the spectrum at peak light of the Type Ib supernovae resembles that of Type Ia supernovae taken at a time roughly 2 months after maximum. Thus the statement is sometimes made that these objects appear to have been "born old." Characteristics of the class include, in addition to the spectral features, a light curve that is at maximum roughly a factor of 4 dimmer than a Type Ia supernova while having a width not less than average (and perhaps slightly slower than average on the rise; Richtler & Sadler 1983, Wheeler & Levreault 1985, Panagia et al. 1985). Also at least one member of the Type Ib class, SN 1984l, is located in an H II region, and another member, SN 1983n, was the first Type I supernova to be detected in radio (Sramek et al. 1984). Thus, there is some indication that, unlike ordinary Type Ia supernovae, Type Ib supernovae *might* be associated with massive stars (Wheeler & Levreault 1985, although see Chevalier 1984b).

Though the observational distinction has only recently been realized, theoreticians have been quick to offer plausible explanations for the Type Ib class (Wheeler 1985, Wheeler & Levreault 1985, Iben 1985b, Cameron & Iben 1985). Absorption lines of intermediate-mass elements, still prominent in their early spectrum, and the velocities inferred from line widths, which are not much larger than those seen in ordinary Type I supernovae, again argue against helium detonation models (Woosley et al. 1980, 1986, Nomoto 1982a,b); however, the similarities in spectrum, light curve, and velocity with their classical relatives suggest that the radioactive model is still a good starting point. The dimmer light curve would then imply a smaller amount of ^{56}Ni ejected in the explosion, one fourth as much in the simplest interpretation, or about 0.15 $M_{\odot}$. This is not too different from the value suggested by Colgate et al. (Colgate et al. 1980, Colgate & Petschek 1982), who claim that all Type I's result from the collapse of a white dwarf to a neutron star with the hydrodynamical synthesis and ejection of 0.25 $M_{\odot}$ of ^{56}Ni; however, calculations to accurately determine the ^{56}Ni synthesis in a collapsing ONeMg white dwarf are lacking. Observations of a strong infrared line of [Fe II] (1.644 μm) by Graham et al. (1985) have been analyzed and suggest an iron mass of roughly 0.3 $M_{\odot}$ for SN 1983n. Given the uncertainties in the distance to M83 and especially in the radiative model employed both for the light curve and for the infrared emission, this is consistent with the above theoretical estimates.

Wheeler (1985) and Wheeler & Levreault (1985) suggest a model for Type Ib similar to that of Colgate et al. but utilizing a massive stellar core (helium core mass of 2–4 $M_{\odot}$) that has lost its hydrogen envelope, a requisite condition if the supernova is to be considered Type I. The ^{56}Ni is then produced by shock wave–heating and explosive nucleosynthesis, just as in Type II's. Too large a core mass must be avoided, however, so that the light curve does not become overly broad. This may pose a difficulty, since helium core masses in this range, typical of main-sequence masses of 10–15 $M_{\odot}$, have steep density gradients near the collapsing iron core at the time of the supernova explosion. Synthesis of even 0.1 $M_{\odot}$ of ^{56}Ni in helium cores with mass $\lesssim 6$ $M_{\odot}$ may be difficult (Wilson et al. 1985). On the other hand, both the radiation transport in such a novel environment and the Type II supernova explosion mechanism itself still need much work.

Since most of the distinguishing characteristics are spectroscopic and since Type Ib really does closely resemble Type Ia at peak light, one should not rule out the possibility that the Type Ib mechanism may be only slightly different from that of Type Ia [e.g. ignition of carbon farther off center than in the standard model either because of accretion on a refractory NeOMg core (Iben 1985b, Cameron & Iben 1985) or because of the situation of a critical URCA shell (^{21}Ne?) farther out in the star, or variations in the flame velocity in the standard model]. The spectrum, much more than the light curve, is sensitive not only to the composition, but also to the preexplosive structure of the white dwarf and the flame velocity (Axelrod 1980a,b, Woosley et al. 1984).

The truly peculiar Type I's—the Type Ip's—which may also include SN 1885a, SN 1954a, SN 1957a, SN 1980i, and SN 1983v (Branch 1986b), have various distinguishing spectral and photometric properties. Frequently they are dimmer than Type Ia supernovae and may have been selected against (doubly so, since being dimmer they are less likely to have their spectrum taken). At least a portion of Type Ip's may be helium detonation events (Branch & Doggett 1985).

We note in passing that the existence of a peculiar subclass(es) complicates the use of Type I supernovae as standard candles for obtaining H_0. Types Ib and Ip may be distinguished (and, for the time being, excluded from the sample) on the basis of their spectra (Branch 1986b), but this implies that photometric measurements of the light curve alone will not suffice. The Hubble Telescope will be useful in this regard for obtaining the spectrum of very distant Type I explosions.

ACKNOWLEDGMENTS

The authors are indebted to Dave Arnett, Hans Bethe, David Branch, Gerry Brown, Adam Burrows, Stirling Colgate, Icko Iben, Ken Nomoto, Friedel Thielemann, Craig Wheeler, and Jim Wilson for instructive conversations and comments on earlier drafts of this review. This work has been supported by the National Science Foundation (AST-84-18185) and, at Livermore, by the Department of Energy (W-7405-ENG-48).

Literature Cited

Arnett, W. D. 1966. *Can. J. Phys.* 44: 2553
Arnett, W. D. 1967. *Can. J. Phys.* 45: 1621
Arnett, W. D. 1968a. *Ap. J.* 153: 341
Arnett W. D. 1968b. *Nature* 219: 1344
Arnett, W. D. 1969. *Astrophys. Space Sci.* 5: 180
Arnett, W. D. 1971. *Ap. J.* 169: 113
Arnett, W. D. 1972a. *Ap. J.* 176: 681
Arnett, W. D. 1972b. *Ap. J.* 176: 699
Arnett, W. D. 1973. In *Explosive Nucleosynthesis*, ed. D. N. Schramm, W. D. Arnett, p. 236. Austin: Univ. Texas Press
Arnett, W. D. 1974a. *Ap. J.* 193: 169
Arnett, W. D. 1974b. *Ap. J.* 194: 373
Arnett, W. D. 1974c. *Ap. J.* 191: 727
Arnett, W. D. 1975. *Ap. J.* 195: 727
Arnett, W. D. 1978a. In *Physics and Astrophysics of Neutron Stars and Black Holes, Enrico Fermi Course 35*, ed. R. Giaconni, R. Ruffini, p. 356. Amsterdam: North-Holland
Arnett, W. D. 1978b. *Ap. J.* 219: 1008
Arnett, W. D. 1979. *Ap. J. Lett.* 230: L37
Arnett, W. D. 1980a. *Ann. NY Acad. Sci.* 336: 366
Arnett, W. D. 1980b. *Ap. J.* 237: 541
Arnett, W. D. 1982a. See Rees & Stoneham 1982, p. 221
Arnett, W. D. 1982b. *Ap. J.* 253: 785
Arnett, W. D. 1982c. *Ap. J.* 254: 1
Arnett, W. D. 1983. *Ap. J. Lett.* 263: L55
Arnett, W. D. 1985. Submitted for publication
Arnett, W. D., Schramm, D. N. 1973. *Ap. J. Lett.* 184: L47
Arnett, W. D., Falk, S. W. 1976. *Ap. J.* 210: 733
Arnett, W. D., Branch, D., Wheeler, J. C. 1985. *Nature* 314: 337
Arnett, W. D., Thielemann, F.-K. 1985. *Ap. J.* 295: 589
Ashworth, W. 1980. *J. Hist. Astron.* 11: 1
Austin, R. R. D. 1972. *IAU Circ. No. 2421*
Axelrod, T. S. 1980a. PhD thesis. Univ. Calif., Santa Cruz (available as UCRL Preprint 52994 from Lawrence Livermore Natl. Lab.)
Axelrod, T. S. 1980b. In *Type I Supernovae*, ed. J. C. Wheeler, p. 80. Austin: Univ. Texas

Baade, W., Zwicky F. 1934. *Phys. Rev.* 45: 138
Balinskaya, I. S., Bychkov, K. V., Neizvestny, S. I. 1980. *Astron. Astrophys.* 85: L19
Barbon, R., Ciatti, F., Rosino, L. 1973. *Astron. Astrophys.* 25: 241
Barbon, R., Ciatti, F., Rosino, L. 1979. *Astron. Astrophys.* 72: 287
Barbon, R., Ciatti, F., Rosino, L. 1982. *Astron. Astrophys.* 116: 35
Barkat, Z. 1975. *Ann. Rev. Astron. Astrophys.* 13: 45
Barkat, Z., Rakavy, G., Sack, N. 1967. *Phys. Rev. Lett.* 19: 379
Barkat, Z., Reiss, Y., Rakavy, G. 1974. *Ap. J. Lett.* 193: L21
Barkat, Z., Rakavy, G., Reiss, Y., Wilson, J. R. 1975. *Ap. J.* 196: 633
Baron, E., Cooperstein, J., Kahana, S. 1985a. *Phys. Rev. Lett.* 55: 126
Baron, E., Cooperstein, J., Kahana, S. 1985b. *Nucl. Phys. A* 440: 744
Baron, E., Brown, G. E., Cooperstein, J., Prakash, M. 1985c. Preprint
Berteli, G., Bressan, A. G., Chiosi, C. 1984. *Astron. Astrophys.* 130: 279
Berteli, G., Bressan, A. G., Chiosi, C. 1985. *Astron. Astrophys.* 150: 33
Bertola, F. 1963. *Contrib. Asiago Obs. No. 142*
Bertola, F. 1964. *Ann. Astrophys.* 27: 319
Bertola, F., Mammano, A., Perrinotto, M. 1965. *Contrib. Asiago Obs. No. 174*
Bertola, F., Arp, H. 1970. *Publ. Astron. Soc. Pac.* 82: 894
Bethe, H. A., Brown, G. E., Applegate, J., Lattimer, J. 1979. *Nucl. Phys. A* 324: 487
Bethe, H. A., Brown, G. E., Cooperstein, J., Wilson, J. R. 1983. *Nucl. Phys. A* 403: 625
Bethe, H. A., Brown, G. 1985. *Sci. Am.* 252: 60
Bethe, H. A., Wilson, J. R. 1985. *Ap. J.* 295: 14
Bodenheimer, P., Ostriker, J. P. 1974. *Ap. J.* 191: 465
Bodenheimer, P., Woosley, S. E. 1983. *Ap. J.* 269: 281
Bonche, P., Vautherin, D. 1982. *Astron. Astrophys.* 112: 268
Bond, J. R., Arnett, W. D., Carr, B. J. 1982. See Rees & Stoneham 1982, p. 303
Bond, J. R., Arnett, W. D., Carr, B. J. 1984. *Ap. J.* 280: 825
Bowers, R. L. 1985. In *Numerical Astrophysics*, ed. J. Centrella, J. LeBlanc, R. Bowers, p. 403. Boston: Jones & Bartlett
Bowers, R. L., Wilson, J. R. 1982a. *Ap. J. Suppl.* 50: 115
Bowers, R. L., Wilson, J. R. 1982b. *Ap. J.* 263: 366
Branch, D. 1982. *Ap. J.* 258: 35
Branch, D. 1984a. *Ann. NY Acad. Sci.* 422: 186
Branch, D. 1984b. In *Stellar Nucleosynthesis*, ed. C. Chiosi, A. Renzini, p. 19. Dordrecht: Reidel
Branch, D. 1985a. In *Challanges and New Developments in Nucleosynthesis*, ed. W. D. Arnett, J. W. Truran. Chicago: Univ. Chicago Press. In press
Branch, D. 1985b. In *Supernovae as Distance Indicators*, ed. N. Bartel. Berlin: Springer-Verlag
Branch, D. 1986a. In preparation
Branch, D. 1986b. *Ap. J. Lett.* In press
Branch, D., Greenstein, J. L. 1971. *Ap. J.* 167: 89
Branch, D., Bettis, C. 1978. *Astron. J.* 83: 224
Branch, D., Falk, S. W., McCall, M. L., Rybski, P., Uomoto, A. K., Wills, B. J. 1981. *Ap. J.* 244: 780
Branch, D., Buta, R., Falk, S. W., McCall, M. L., Sutherland, P. G., et al. 1982. *Ap. J. Lett.* 252: L61
Branch, D., Lacy, C. H., McCall, M. L., Sutherland, P. G., Uomoto, A., et al. 1983. *Ap. J.* 270: 123
Branch, D., Doggett, J. B. 1985. *Ap. J.* In press
Branch, D., Doggett, J. B., Nomoto, K., Thielemann, F.-K. 1985. *Ap. J.* 294: 619
Brown, G. E., Bethe, H. A., Baym, G. 1982. *Nucl. Phys. A* 375: 481
Bruenn, S. W. 1971. *Ap. J.* 168: 203
Bruenn, S. W. 1972. *Ap. J. Suppl.* 24: 283
Bruenn, S. W. 1973. *Ap. J. Lett.* 183: L125
Bruenn, S. W. 1975. *Ann. NY Acad. Sci.* 262: 80
Bruenn, S. W. 1985. *Ap. J. Suppl.* 58: 771
Bruenn, S. W., Arnett, W. D., Schramm, D. N. 1977. *Ap. J.* 213: 213
Bruenn, S. W., Buchler, R. J., Livio, M. 1979. *Ap. J. Lett.* 234: L183
Brunish, W. M., Truran, J. W. 1982a. *Ap. J.* 256: 247
Brunish, W. M., Truran, J. W. 1982b. *Ap. J. Suppl.* 49: 447
Buchler, J. R., Wheeler, J. C., Barkat, Z. 1971. *Ap. J.* 167: 465
Buchler, J. R., Mazurek, T. J., Truran, J. W. 1974. *Comments Astrophys. Space Sci.* 6: 45
Buchler, J. R., Mazurek, T. J. 1975. *Mem. Soc. R. Sci. Liège 6ᵉ Ser.* 8: 435
Burbidge, E. M., Burbidge, G. R., Fowler, W. A., Hoyle, F. 1957. *Rev. Mod. Phys.* 29: 547
Burrows, A., Lattimer, J. M. 1983. *Ap. J.* 270: 735
Burrows, A., Lattimer, J. M. 1985. *Ap. J. Lett.* 299: L19
Buta, R. J. 1982. *Publ. Astron. Soc. Pac.* 94: 578

Cameron, A. G. W. 1957. *Chalk River Rep. CRL-41*

Cameron, A. G. W. 1982. In *Essays in Nuclear Astrophysics*, ed. C. Barnes, D. Clayton, D. Schramm, p. 23. Cambridge: Cambridge Univ. Press

Cameron, A. G. W., Iben, I. Jr. 1985. Preprint

Canal, R., Schatzman, E. 1976. *Astron. Astrophys.* 46: 229

Canal, R., Isern, J. 1979. In *White Dwarfs and Variable Degenerate Stars, IAU Colloq. No. 53*, ed. H. M. Van Horn, V. Weidemann, p. 52. Rochester, NY: Univ. Rochester

Canizares, C. R., Kriss, G. A., Feigelson, E. D. 1982. *Ap. J. Lett.* 253: L17

Caughlan, G. R., Fowler, W. A., Harris, M. J., Zimmerman, B. A. 1985. *At. Data Nucl. Data Tables* 32: 197

Chevalier, R. A. 1976a. *Ap. J.* 208: 826

Chevalier, R. A. 1976b. *Ap. J.* 207: 872

Chevalier, R. A. 1981a. *Fundam. Cosmic Phys.* 7: 1

Chevalier, R. A. 1981b. *Ap. J.* 251: 25

Chevalier, R. A. 1981c. *Ap. J.* 246: 267

Chevalier, R. A. 1982a. *Ap. J.* 258: 790

Chevalier, R. A. 1982b. *Ap. J.* 259: 302

Chevalier, R. A. 1984a. *Ann. NY Acad. Sci.* 422: 215

Chevalier, R. A. 1984b. *Ap. J. Lett.* 285: L63

Chevalier, R. A., Klein, R. I. 1979. *Ap. J.* 234: 597

Chiosi, C. 1981. In *The Most Massive Stars*, ed. S. D'Odorico, D. Baade, K. Kjär, p. 27. Garching: ESO

Chiosi, C., Nasi, E., Sreenivason, S. R. 1978. *Astron. Astrophys.* 63: 103

Ciatti, F., Rosino, L., Bertola, F. 1971. *Mem. Soc. Astron. Ital.* 42: 163

Colgate, S. A. 1979. *Ap. J.* 232: 404

Colgate, S. A., Johnson, H. J. 1960. *Phys. Rev. Lett.* 5: 235

Colgate, S. A., White, R. H. 1966. *Ap. J.* 143: 626

Colgate, S. A., McKee, C. 1969. *Ap. J.* 157: 623

Colgate, S. A., Petschek, A. G. 1979. *Ap. J.* 229: 682

Colgate, S. A., Petschek, A. G. 1980. *Ap. J. Lett.* 236: L115

Colgate, S. A., Petschek, A. G., Kriese, J. T. 1980. *Ap. J. Lett.* 237: L81

Colgate, S. A., Petschek, A. G. 1982. *Nature* 296: 804

Conti, P. S., Leep, E. M., Perry, D. N. 1983. *Ap. J.* 268: 228

Cooperstein, J. 1985. *Nucl. Phys. A.* 438: 722

Cooperstein, J., Wambach, J. 1984. *Nucl. Phys. A* 420: 591

Cooperstein, J., Bethe, H. A., Brown, G. E. 1985. *Nucl. Phys. A* 429: 527

Couch, R. G., Arnett, W. D. 1974. *Ap. J.* 194: 537

Couch, R. G., Arnett, W. D. 1975. *Ap. J.* 196: 791

Courant, R., Friedrichs, K. O. 1948. *Supersonic Flow and Shock Waves*, p. 204. New York: Interscience. 464 pp.

Cowan, J. J., Branch, D. 1985. Submitted for publication

Davidson, K., Gull, T. R., Maran, S. P., Stecher, T. P., Fesen, R. A., et al. 1982. *Ap. J.* 253: 696

de Vaucouleurs, G., de Vaucouleurs, A., Buta, R., Ables, H. D., Hewitt, A. V. 1981. *Publ. Astron. Soc. Pac.* 93: 36

Doggett, J. B., Branch, D. 1985. Submitted for publication

Doom, C. 1982. *Astron. Astrophys.* 116: 303, 308

Doom, C. 1983. PhD thesis. Vrije Univ., Brussels

Dwek, E. 1983. *Ap. J.* 275: 175

Elias, J. H., Frogel, J. A., Hackwell, J. A., Persson, S. E. 1981. *Ap. J. Lett.* 251: L13

Elias, J. H., Mathews, K., Neugebauer, G., Persson, S. E. 1985. Preprint

Epstein, R. 1979. *MNRAS* 188: 305

Epstein, R. 1981. *Ap. J. Lett.* 244: L89

Ergma, E., Paczynski, B. 1974. *Acta Astron.* 24: 1

Falk, S. W. 1978. *Ap. J. Lett.* 225: L133

Falk, S. W., Arnett, W. D. 1973. *Ap. J. Lett.* 180: L65

Falk, S. W., Arnett, W. D. 1977. *Ap. J. Suppl.* 33: 515

Fesen, R. A. 1985. *Ap. J. Lett.* 297: L29

Filippenko, A. V., Sargent, W. L. W. 1985. *Nature* 316: 407

Firmani, C. 1982. In *WR Stars: Observations, Physics, and Evolution, IAU Colloq. No. 99*, ed. C. deLoore, A. J. Willis, p. 499

Fowler, W. A., Hoyle, F. 1964. *Ap. J. Suppl.* 9: 201

Fowler, W. A., Caughlan, G. R., Zimmerman, B. A. 1975. *Ann. Rev. Astron. Astrophys.* 13: 69

Fowler, W. A., Englebrecht, C. A., Woosley, S. E. 1978. *Ap. J.* 226: 984

Fraley, G. 1968. *Astrophys. Space Sci.* 2: 96

Freedman, D. Z. 1974. *Phys. Rev. D* 9: 1389

Fujimoto, M. Y. 1982a. *Ap. J.* 257: 752

Fujimoto, M. Y. 1982b. *Ap. J.* 257: 767

Fujimoto, M. Y., Sugimoto, D. 1982. *Ap. J.* 257: 291

Fujimoto, M. Y., Taam, R. E. 1982. *Ap. J.* 260: 249

Fuller, G. M. 1982. *Ap. J.* 252: 741

Fuller, G. M., Fowler, W. A., Newman, M. J. 1982a. *Ap. J. Suppl.* 48: 279

Fuller, G. M., Fowler, W. A., Newman, M. J. 1982b. *Ap. J.* 252: 715
Glatzel, W., El Eid, M. F., Fricke, K. J. 1985. *Astron. Astrophys.* 149: 413
Graham, J. R., Meikle, W. P. S., Allen, D. A., Longmore, A. J., Williams, P. M. 1985. *MNRAS*. In press
Grassberg, E. K., Imshennik, V. S., Nadëzhin, D. K. 1971. *Astrophys. Space Sci.* 10: 28
Green, D. A. 1984. *MNRAS* 209: 449
Habets, G. M. H. J. 1985. PhD thesis. Univ. Amsterdam
Hamilton, A. J. S., Sarazin, C. L., Szymkowiak, A. E. 1985a. Submitted for publication
Hamilton, A. J. S., Sarazin, C. L., Szymkowiak, A. E. 1985b. Submitted for publication
Hamilton, A. J. S., Sarazin, C. L., Szymkowiak, A. E., Vartanian, M. H. 1985c. Submitted for publication
Helfand, D. J., Becker, R. H. 1984. *Nature* 307: 215
Hillebrandt, W. 1978. *Space Sci. Rev.* 21: 639
Hillebrandt, W. 1982a. See Rees & Stoneham 1982, p. 123
Hillebrandt, W. 1982b. *Astron. Astrophys.* 110: L3
Hillebrandt, W. 1984. *Ann. NY Acad. Sci.* 422: 197
Hillebrandt, W. 1985. In *Cosmogonical Processes, Proc. A. G. W. Cameron's 60th Birthday Symp., Boulder, Colo.* In press
Hillebrandt, W., Nomoto, K., Wolff, R. G. 1984. *Astron. Astrophys.* 133: 175
Hoyle, F. 1946. *MNRAS* 106: 343
Hoyle, F., Fowler, W. A. 1960. *Ap. J.* 132: 565
Humphreys, R. M. 1984. In *Observational Tests of Stellar Evolution Theory, IAU Symp. No. 105*, ed. A. Maeder, A. Renzini, p. 279. Dordrecht: Reidel
Iben, I. 1978a. *Ap. J.* 219: 213
Iben, I. 1978b. *Ap. J.* 226: 996
Iben, I. 1982. *Ap. J.* 253: 248
Iben, I. 1985a. *Q. J. R. Astron. Soc.* 26: 1
Iben, I. 1985b. *Ap. J.* In press
Iben, I. Jr., Renzini, A. 1983. *Ann. Rev. Astron. Astrophys.* 21: 271
Iben, I. Jr., Tutukov, A. V. 1984. *Ap. J. Suppl.* 54: 335
Iben, I. Jr., Tutukov, A. V. 1985. *Ap. J. Suppl.* 58: 661
Ikeuchi, S., Nakazawa, K., Murai, T., Hoshi, R., Hayashi, C. 1971. *Prog. Theor. Phys. Kyoto* 46: 1713
Ikeuchi, S., Nakazawa, K., Murai, T., Hoshi, R., Hayashi, C. 1972. *Prog. Theor. Phys. Kyoto* 48: 1890
Imshennik, V. S., Nadëzhin, D. K. 1964. *Astron. Zh.* 41: 829
Imshennik, V. S., Nadëzhin, D. K. 1983. *Astrophys. Space Phys. Rev.* (*Sov. Sci. Rev.*) 2: 75
Isern, J., Labay, J., Hernanz, M., Canal, R. 1983. *Ap. J.* 273: 320
Ivanova, L. N., Imshennik, V. S., Chechetkin, V. M. 1974. *Astrophys. Space Sci.* 31: 497
Kahana, S., Baron, E., Cooperstein, J. 1984. In *Problems of Collapse and Numerical Relativity*, ed. D. Bancel, M. Signore, p. 163. Dordrecht: Reidel
Kettner, K. U., Becker, H. W., Buchmann, L., Görres, J., Kräwainkel, H., et al. 1982. *Z. Phys. A* 308: 73
Kirshner, R. P., Oke, J. B., Penston, M. V., Searle, L. 1973. *Ap. J.* 185: 303
Kirshner, R. P., Kwan, J. 1974. *Ap. J.* 193: 27
Kirshner, R. P., Oke, J. B. 1975. *Ap. J.* 200: 574
Kirshner, R. P., Arp, H. C., Dunlap, J. R. 1976. *Ap. J.* 207: 44
Klein, R. I., Chevalier, R. A. 1978. *Ap. J. Lett.* 223: L109
Kudryashov, A. D., Shcherbatyuk, V. A., Ergma, E. V. 1979. *Astrophys. Space Sci.* 66: 391
Kurfess, J. D., Johnson, W. N., Kinzer, R. L., Share, G. H., Strickman, M. S., et al. 1983. *Adv. Space Res.* 3: 109
Lamb, D. Q., Pethick, C. J. 1976. *Ap. J. Lett.* 209: L77
Lamb, D. Q., Lattimer, J. M., Pethick, C. J., Ravenhall, D. G. 1984. Univ. Ill. Preprint ILL-(TH)-84-11; see also *Nucl. Phys. A* 411: 449 (1983)
Lamb, S. A., Iben, I. Jr., Howard, W. M. 1976. *Ap. J.* 207: 209
Lamb, S. A., Howard, W. M., Truran, J. W., Iben, I. Jr. 1977. *Ap. J.* 217: 213
Lamers, H. J., De Groot, M., Cassatella, A. 1983. *Astron. Astrophys.* 123: L8
Langanke, K., Koonin, S. E. 1983. *Nucl. Phys. A* 410: 334
Langanke, K., Koonin, S. E. 1985. *Nucl. Phys. A*. In press
Lasher, G. 1975. *Ap. J.* 201: 194
Lasher, G. 1980. In *Supernova Spectra, AIP Conf. Proc. No. 63*, ed. R. E. Meyerott, G. H. Gillespie, p. 1. New York: Am. Inst. Phys.
Lasher, G. J., Chan, K. L. 1979. *Ap. J.* 230: 742
Lasker, B. M. 1980. *Ap. J.* 237: 765
Lattimer, J. M. 1981. *Ann. Rev. Nucl. Part. Sci.* 31: 337
Lattimer, J. M., Burrows, A. 1984. In *Problems of Collapse and Numerical Relativity*, ed. D. Bancel, M. Signore, p. 147. Dordrecht: Reidel
Lattimer, J. M., Burrows, A., Yahil, A. 1985. *Ap. J.* 288: 644

LeBlanc, J. M., Wilson, J. R. 1970. *Ap. J.* 161: 541
Lichtenstadt, I., Bludman, S. A. 1984. *Ap. J.* 276: 246
Litvinova, I. Yu., Nadëzhin, D. K. 1983. *Astrophys. Space Sci.* 89: 89
Livio, M. J. R., Buchler, R. J., Colgate, S. A. 1980. *Ap. J. Lett.* 238: L139
MacDonald, J. 1983. *Ap. J.* 267: 732
MacDonald, J. 1984. *Ap. J.* 283: 241
Maeder, A. 1984. In *Observational Tests of Stellar Evolution Theory, IAU Symp. No. 105*, ed. A. Maeder, A. Renzini, p. 299. Dordrecht: Reidel
Mahoney, W. A., Ling, J. C., Jacobson, A. S., Lingenfelter, R. E. 1982. *Ap. J.* 262: 742
Mahoney, W. A., Ling, J. C., Wheaton, W. A., Jacobson, A. S. 1984. *Ap. J.* 286: 578
Maran, S. P. 1981. *Nat. Hist.* 90(5): 1
Massey, P. 1981. *Ap. J.* 246: 153
Mayle, R. 1985. PhD thesis. Univ. Calif., Berkeley
Maza, J., van den Bergh, S. 1976. *Ap. J.* 204: 519
Mazurek, T. J. 1973. *Astrophys. Space Sci.* 23: 365
Mazurek, T. J. 1974. *Nature* 252: 287
Mazurek, T. J. 1975. *Astrophys. Space Sci.* 35: 117
Mazurek, T. J. 1980. In *Type I Supernovae*, ed. J. C. Wheeler, p. 182. Austin: Univ. Texas
Mazurek, T. J., Truran, J. W., Cameron, A. G. W. 1974. *Astrophys. Space Sci.* 27: 261
Mazurek, T. J., Meier, D. L., Wheeler, J. C. 1977. *Ap. J.* 213: 518
Mazurek, T. J., Lattimer, J. M., Brown, G. E. 1979. *Ap. J.* 229: 713
Mazurek, T., Colgate, S. A., Buchler, J. R. 1980a. *J. Phys. Colloq.* C2: 159
Mazurek, T. J., Cooperstein, J., Kahana, S. 1980b. *DUMAND-80*, ed. V. J. Stenger, p. 142. Honolulu: Univ. Hawaii
Mazurek, T. J., Wheeler, J. C. 1980. *Fundam. Cosmic Phys.* 5: L193
Mazurek, T. J., Cooperstein, J., Kahana, S. 1982. See Rees & Stoneham 1982, p. 71
Meyerott, R. E. 1980. *Ap. J.* 239: 257
Mihalas, D., Mihalas, B. W. 1984. *Radiation Transport and Hydrodynamics*, p. 185. New York: Oxford Univ. Press. 718 pp.
Miller, G. E., Scalo, J. M. 1979. *Ap. J. Suppl.* 41: 513
Miyaji, S., Nomoto, K., Yokoi, K., Sugimoto, D. 1980. *Publ. Astron. Soc. Jpn.* 32: 303
Müller, E., Hillebrandt, W. 1981. *Astron. Astrophys.* 103: 358
Müller, E., Arnett, W. D. 1982. *Ap. J. Lett.* 261: L109
Müller, E., Arnett, W. D. 1985. *Ap. J.* In press
Nadëzhin, D. K., Utrobin, V. P. 1977. *Astron. Zh.* 54: 96 (*Sov. Astron. AJ* 21: 564)
Nariai, K., Nomoto, K., Sugimoto, D. 1980. *Publ. Astron. Soc. Jpn.* 32: 473
Niemela, V. S., Ruiz, M. T., Phillips, M. M. 1985. *Ap. J.* 289: 52
Nomoto, K. 1980a. In *Type I Supernovae*, ed. J. C. Wheeler, p. 164. Austin: Univ. Texas
Nomoto, K. 1980b. *Space Sci. Rev.* 27: 563
Nomoto, K. 1981. In *Fundamental Problems in the Theory of Stellar Evolution, IAU Symp. 93*, ed. D. Sugimoto, D. Q. Lamb, D. N. Schramm, p. 295. Dordrecht: Reidel
Nomoto, K. 1982a. See Rees & Stoneham 1982, p. 205
Nomoto, K. 1982b. *Ap. J.* 253: 798
Nomoto, K. 1982c. *Ap. J.* 257: 780
Nomoto, K. 1984a. In *Stellar Nucleosynthesis*, ed. C. Chiosi, A. Renzini, p. 239. Dordrecht: Reidel
Nomoto, K. 1984b. *Ap. J.* 277: 791
Nomoto, K. 1984c. In *The Crab Nebula and Related Supernova Remnants*, ed. M. Kafatos, R. B. C. Henry, p. 97. Cambridge: Cambridge Univ. Press
Nomoto, K. 1984d. In *Stellar Nucleosynthesis*, ed. C. Chiosi, A. Renzini, p. 205. Dordrecht: Reidel
Nomoto, K. 1984e. In *Problems of Collapse and Numerical Relativity*, ed. D. Bancel, M. Signore, p. 89. Dordrecht: Reidel
Nomoto, K. 1985a. *Proc. Texas Symp. Relativ. Astrophys., 12th, Ann. NY Acad. Sci.* In press
Nomoto, K. 1985b. In *Challenges and New Developments in Nucleosynthesis*, ed. W. D. Arnett, J. W. Truran, p. 202. Chicago: Univ. Chicago Press
Nomoto, K., Sugimoto, D., Neo, S. 1976. *Astrophys. Space Sci.* 39: L37
Nomoto, K., Sugimoto, D. 1977. *Publ. Astron. Soc. Jpn.* 29: 765
Nomoto, K., Miyaji, S., Yokoi, K., Sugimoto, D. S. 1979a. In *White Dwarfs and Variable Degenerate Stars, IAU Colloq. No. 53*, ed. H. M. Van Horn, V. Weidemann, p. 56. Rochester, NY: Univ. Rochester
Nomoto, K., Nariai, K., Sugimoto, D. 1979b. *Publ. Astron. Soc. Jpn.* 31: 287
Nomoto, K., Sparks, W. M., Fesen, R. A., Gull, T. R., Miyaji, S., Sugimoto, D. 1982. *Nature* 299: 803
Nomoto, K., Thielemann, F.-K., Wheeler, J. C. 1984a. *Ap. J. Lett.* 279: L23
Nomoto, K., Thielemann, F.-K., Yokoi, K. 1984b. *Ap. J.* 286: 644
Nomoto, K., Iben, I. 1985. *Ap. J.* 297: 531
Nomoto, K., Thielemann, F.-K., Miyaji, S. 1985. *Astron. Astrophys.* 149: 239

Ober, W. W., El Eid, M. F., Fricke, K. J. 1983. *Astron. Astrophys.* 119: 61
Oemler, A., Tinsley, B. M. 1979. *Astron. J.* 84: 985
Ostriker, J. P., Gunn, J. E. 1969. *Ap. J.* 157: 1395
Ostriker, J. P., Richstone, D. O., Thuan, T. X. 1974. *Ap. J. Lett.* 188: L87
Pacini, F., Salvati, M. 1981. *Ap. J. Lett.* 245: L107
Paczynski, B. 1970. *Acta Astron.* 20: 47
Paczynski, B. 1972. *Astrophys. Lett.* 11: 53
Paczynski, B. 1973a. *Acta Astron.* 23: 1
Paczynski, B. 1973b. *Astrophys. Lett.* 15: 147
Panagia, N., et al. 1985. Preprint
Pankey, T. 1962. PhD thesis. Howard Univ., Washington, DC. (*Diss. Abstr.* 23: 4)
Perdang, J. 1966. *Bull. R. Soc. Liège* 35: 369
Prialnik, D., Livio, M., Shaviv, G., Kovetz, A. 1982. *Ap. J.* 257: 312
Rakavy, G., Shaviv, G., Zinamon, Z. 1967. *Ap. J.* 150: 131
Raymond, J. C. 1984. *Ann. Rev. Astron. Astrophys.* 22: 75
Rees, M. J., Stoneham, R. J., eds. 1982. *Supernovae: A Survey of Current Research.* Dordrecht: Reidel
Richter, T., Sadler, E. M. 1983. *Astron. Astrophys.* 128: L3
Romanishin, W., Angel, J. R. P. 1980. *Ap. J.* 235: 992
Rose, W. K. 1969. *Ap. J.* 155: 491
Saio, H., Nomoto, K. 1985. *Astron. Astrophys.* 150: In press
Sandage, A. R. 1985. In *Supernovae as Distance Indicators*, ed. N. Bartel. Berlin: Springer-Verlag
Sandage, A. R., Tammann, G. A. 1982. *Ap. J.* 256: 339
Sato, K. 1975. *Prog. Theor. Phys.* 53: 595, 54: 1325
Schatzman, E. 1963. In *Star Evolution, Enrico Fermi Course 28*, ed. L. Gratton, p. 389. New York: Academic
Schild, R., Maeder, A. 1983. *Astron. Astrophys.* 130: 237
Schramm, D. N., Arnett, W. D. 1975. *Ap. J.* 198: 629
Schurmann, S. R., Arnett, W. D., Falk, S. W. 1979. *Ap. J.* 230: 11
Shklovskii, I. S. 1975. *Astron. Zh.* 52: 911 (*Sov. Astron. Astrophys.* 19: 554)
Smarr, L., Wilson, J. R., Barton, R. T., Bowers, R. L. 1981. *Ap. J.* 246: 515
Spiegel, E. A. 1972. In *Stellar Evolution*, ed. H. Y. Chui, A. Muriel, p. 512. Cambridge, Mass: MIT Press
Sramek, R. A., Panagia, N., Weiler, K. W. 1984. *Ap. J. Lett.* 285: L63
Stringfellow, G. M., Woosley, S. E., Bodenheimer, P. B. 1983. *Bull. Am. Astron. Soc.* 15: 955
Sugimoto, D. 1970. *Prog. Theor. Phys. Kyoto* 44: 599
Sugimoto, D., Miyaji, S. 1981. In *Fundamental Problems in the Theory of Stellar Evolution, IAU Symp. No. 93*, ed. D. Sugimoto, D. Q. Lamb, D. N. Schramm, p. 191. Dordrecht: Reidel
Sugimoto, D., Nomoto, K. 1980. *Space Sci. Rev.* 25: 155
Sutherland, P., Wheeler, J. C. 1984. *Ap. J.* 280: 282
Symbalisty, E. M. D., Schramm, D. N., Wilson, J. R. 1985. *Ap. J. Lett.* 291: L11
Tammann, G. A. 1974. In *Supernovae and Supernova Remnants*, ed. C. B. Cosmovici, p. 155. Dordrecht: Reidel
Tammann, G. A. 1977. In *Supernovae, IAU Symp. No. 66*, ed. D. N. Schramm, p. 95. Dordrecht: Reidel
Tammann, G. A. 1978. *Mem. Soc. Astron. Ital.* 49: 315
Tammann, G. A. 1982. See Rees & Stoneham 1982, p. 371
Thielemann, F.-K., Arnett, W. D. 1985. *Ap. J.* 295: 604
Thielemann, F.-K., Nomoto, K., Yokoi, K. 1985. *Astron. Astrophys.* In press
Tinsley, B. M. 1980a. In *Type I Supernovae*, ed. J. C. Wheeler, p. 196. Austin: Univ. Texas
Tinsley, B. M. 1980b. *Fundam. Cosmic Phys.* 5: 287
Trimble, V. 1982. *Rev. Mod. Phys.* 54: 118
Trimble, V. 1983. *Rev. Mod. Phys.* 55: 511
Truran, J. W., Arnett, D., Cameron, A. G. W. 1967. *Can. J. Phys.* 45: 2315
Truran, J. W., Cameron, A. G. W. 1971. *Astrophys. Space Sci.* 14: 179
Tsuruta, S., Cameron, A. G. W. 1970. *Astrophys. Space Sci.* 7: 374
Tsuruta, S., Cameron, A. G. W. 1976. *Astrophys. Space Sci.* 39: 397
Tubbs, D. L., Schramm, D. N. 1975. *Ap. J.* 201: 467
Tuchman, Y., Sack, N., Barkat, Z. 1979. *Ap. J.* 234: 217
Tutukov, A. V., Yungelson, L. R. 1979. *Acta. Astron.* 23: 665
Twarog, B. A., Wheeler, J. C. 1982. *Ap. J.* 261: 636
Uomoto, A. K., Kirshner, R. P. 1985. *Astron. Astrophys.* 149: L7
Utrobin, V. P. 1978. *Astrophys. Space Sci.* 55: 441
Utrobin, V. P. 1984. *Astrophys. Space Sci.* 98: 115
van den Bergh, S. 1985. *Nature* 314: 320
van den Bergh, S., Kamper, K. W. 1983. *Ap. J.* 268: 129
Van den Heuvel, E. P. J. 1984. In *Accretion Driven Stellar X-Ray Sources*, ed. W. H. G. Lewin, E. P. J. Van den Heuvel, p. 303. Cambridge: Cambridge Univ. Press
Weaver, T. A., Zimmerman, G. B., Woosley, S. E. 1978. *Ap. J.* 225: 1021
Weaver, T. A., Axelrod, T. S., Woosley, S.

E. 1980. In *Type I Supernovae*, ed. J. C. Wheeler, p. 113. Austin: Univ. Texas
Weaver, T. A., Woosley, S. E. 1980a. *Ann. NY Acad. Sci.* 336: 335
Weaver, T. A., Woosley, S. E. 1980b. In *Supernova Spectra, AIP Conf. Proc. No. 63*, ed. R. E. Meyerott, G. H. Gillespie, p. 15
Weaver, T. A., Woosley, S. E., Fuller, G. M. 1985. In *Numerical Astrophysics*, ed. J. Centrella, J. LeBlanc, R. Bowers, p. 374. Boston: Jones & Bartlett
Webbink, R. F. 1979. In *White Dwarfs and Variable Degenerate Stars, IAU Colloq. No. 53*, ed. H. M. Van Horn, V. Weidemann, p. 426. Rochester, NY: Univ. Rochester
Webbink, R. F. 1984. *Ap. J.* 277: 355
Weidemann, V., Koester, D. 1983. *Astron. Astrophys.* 121: 77
Weiler, K. W., Sramek, R. A., van der Hulst, J. M., Panagia, N. 1982. See Rees & Stoneham 1982, p. 281
Weiler, K. W., Sramek, R. A., Panagia, N., van der Hulst, J. M., Salvati, M. 1985. Preprint
Wheeler, J. C. 1977. *Astrophys. Space Sci.* 50: 125
Wheeler, J. C. 1981. *Rep. Prog. Phys.* 44: 88
Wheeler, J. C. 1982. See Rees & Stoneham 1982, p. 167
Wheeler, J. C. 1985. In *Nucleosynthesis and its Implications on Nuclear and Particle Physics, Proc. Moriand Astrophys. Workshop*. In press
Wheeler, J. C., Hansen, C. J. 1971. *Astrophys. Space Sci.* 11: 373
Wheeler, J. C., Levreault, R. 1985. *Ap. J. Lett.* 294: L17
Whelan, J. C., Iben, I. Jr. 1973. *Ap. J.* 186: 1007
Wild, P. 1961. *IAU Circ. No. 1764*
Wilson, J. R. 1971. *Ap. J.* 163: 209
Wilson, J. R. 1974. *Phys. Rev. Lett.* 32: 849
Wilson, J. R. 1978. *Proc. Int. Sch. Phys. "Enrico Fermi,"* ed. R. Giaconni, R. Ruffini, 65: 644. Amsterdam: North-Holland (also known as "Varenna Lectures," 1975)
Wilson, J. R. 1985. In *Numerical Astrophysics*, ed. J. M. Centrella, J. M. LeBlanc, R. L. Bowers, p. 422. Boston: Jones & Bartlett
Wilson, J. R., Couch, R., Cochran, S., LeBlanc, J., Barkat, Z. 1975. *Ann. NY Acad. Sci.* 262: 54
Wilson, J. R., Mayle, R. 1985. Private communication (also talk presented at 1985 Aspen Supernova Conf.)
Wilson, J. R., Mayle, R., Woosley, S. E., Weaver, T. A. 1985. *Proc. Texas Symp. Relative. Astrophys., 12th Ann. NY Acad. Sci.* In press
Woosley, S. E., Arnett, W. D., Clayton, D. D. 1973. *Ap. J. Suppl.* 26: 231
Woosley, S. E., Howard, W. M. 1978. *Ap. J. Suppl.* 36: 285
Woosley, S. E., Weaver, T. A., Taam, R. E. 1980. In *Type I Supernovae*, ed. J. C. Wheeler, p. 96. Austin: Univ. Texas
Woosley, S. E., Axelrod, T. S., Weaver, T. A. 1981. *Comments Nucl. Part. Phys.* 9: 185
Woosley, S. E., Weaver, T. A. 1981. *Ann. NY Acad. Sci.* 375: 357
Woosley, S. E., Weaver, T. A. 1982a. See Rees & Stoneham 1982, p. 79
Woosley, S. E., Weaver, T. A. 1982b. In *Essays in Nuclear Astrophysics*, eds. C. A. Barnes, D. D. Clayton, D. N. Schramm, p. 377. Cambridge: Cambridge Univ. Press
Woosley, S. E., Axelrod, T. S., Weaver, T. A. 1984. In *Stellar Nucleosynthesis*, ed. C. Chiosi, A. Renzini, p. 263. Dordrecht: Reidel
Woosley, S. E., Weaver, T. A. 1985. *Nucleosynthesis and Its Implications On Nuclear and Particle Physics, Proc. Moriand Astrophys. Conf., 5th*, ed. J. Audouze, T. van Thuan. Dordrecht: Reidel. In press
Woosley, S. E., Taam, R. E., Weaver, T. A. 1986. *Ap. J.* 301: 601
Woosley, S. E., Weaver, T. A. 1986. In *Radiation Transport and Hydrodynamics, IAU Colloq. No. 89*, ed. D. Mihalas, K. H. Winkler. Dordrecht: Reidel. In press
Wu, C.-C., Leventhal, M., Sarazin, C. L., Gull, T. R. 1983. *Ap. J. Lett.* 269: L5
Yahil, A. 1983. *Ap. J.* 265: 1047
Yahil, A., Lattimer, J. M. 1982. See Rees & Stoneham 1982, p. 53
Zeldovich, Ya. B., Raizer, Yu. P. 1966. *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena*, p. 93. New York: Academic
Zeldovich, Ya. B., Barenblatt, G. I., Librovich, V. B., Makhviladze, G. M. 1985. *The Mathematical Theory of Combustion and Explosions*. New York: Plenum. 597 pp.
Zwicky, F. 1964. *Ap. J.* 139: 514