UCRL- 89841
PREPRINT

CONF-8304155--1

CONF-8304155--1

NUCLEOSYNTHESIS IN STELLAR EXPLOSIONS

CONF-8304155--1

S. E. Woosley
Timothy S. Axelrod
Thomas A. Weaver

This paper was prepared for inclusion in
the Proceedings of the Erice Conference
on Nucleosynthesis
Erice, ITALY

September 9, 1983

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NUCLEOSYNTHESIS IN STELLAR EXPLOSIONS

S. E. Woosley

Board of Studies in Astronomy and Astrophysics

University of California, Santa Cruz 95064,

and

Special Studies Group, Lawrence Livermore National Laboratory

University of California, Livermore CA 94550,

Timothy S. Axelrod

T-Division, Lawrence Livermore National Laboratory

University of California, Livermore CA 94550,

and

Thomas A. Weaver

Special Studies Group, Lawrence Livermore National Laboratory

University of California, Livermore CA 94550

ABSTRACT

The final evolution and explosion of stars from $10 M_{\odot}$ to $10^6 M_{\odot}$ are reviewed with emphasis on factors affecting the expected nucleosynthesis. We order our paper in a sequence of decreasing mass. If, as many suspect, the stellar birth function was peaked towards larger masses at earlier times (see e.g., Silk 1977; but also see Palla, Salpeter, and Stahler 1983), this sequence of masses might also be regarded as a temporal sequence. At each stage of Galactic chemical evolution stars form from the ashes of preceding generations which typically had greater mass. A wide variety of Type I supernova models, most based upon accreting white dwarf stars, are also explored using the expected light curves, spectra, and nucleosynthesis as diagnostics. No clearly favored Type I model emerges that is capable of simultaneously satisfying all three constraints.

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.

It has been reproduced from the best available copy to permit the broadest possible availability.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EAB

1. SUPERMASSIVE STARS ($M > 10^5 M_\odot$)

The most massive stars to form early in the Universe might have had masses on the order of the Jeans' mass at the time of radiation decoupling, $\sim 10^5$ to $10^6 M_\odot$, coincidentally the mass of a typical globular cluster (Dicke and Peebles 1968). Alternatively such supermassive objects might have formed at a later time, and with a greater metallicity, from the relaxation of a dense stellar cluster (Sanders 1970). Stars having such great mass are *general relativistically unstable* (Iben 1963; Fowler 1966). After spending only a few thousand years contracting as gravity provides the radiation leaving their surface (Kelvin-Helmholtz stage), the stars reach a critical radius, $\lesssim 10^{14}$ cm for a star of $5 \times 10^5 M_\odot$, where the first order relativistic corrections to Newtonian gravity render the star, which has γ very nearly equal to $4/3$, unstable to continuing collapse. Were it not for the presence of unburned nuclear fuel this collapse would continue indefinitely until the star became a black hole. Because the star *does* contain hydrogen, however, it is possible for nuclear reactions during the implosion to release sufficient energy to power a gigantic explosion.

Figure 1. Thermodynamic conditions and final expansion velocity in a supermassive stellar explosion. Peak values of central temperature (in units of 10^8 K) and density (g cm^{-3}) are indicated. The velocity curve is dashed in the outermost layers where the mass zoning was not adequate for an exact calculation. The kinetic energy is given at infinity.

Fuller, Woosley, and Weaver (1982,1983) have recently constructed numerical models of supermassive stars in the range 10^5 to $10^6 M_{\odot}$ using a one-dimensional implicit hydrodynamics code (KEPLER; Weaver, Zimmerman, and Woosley 1978) revised to include first order post-Newtonian corrections to gravity and nuclear burning by the *rp*-process (Wallace and Woosley 1981). They find, similar to Fricke (1973, 1974); Appenzeller and Fricke (1972); and Appenzeller and Tscharnuter (1973), but contrary to Ober (1981), that non-rotating stars in this mass range will collapse to black holes with no reversal of implosion unless the initial metallicity of the star is already a substantial fraction of solar (i.e., $Z \gtrsim 0.005$). The results are quite sensitive to the metallicity since the rate of hydrogen burning is proportional to the abundances of catalytic nuclei in the CNO group. Lower burning rates do not release sufficient energy during the infall to reverse the implosion. Supermassive stars having mass 1×10^5 ($Z = 0$), 2.5×10^5 ($Z = 0$), 5×10^5 ($Z = 0$, 0.002, 0.005, 0.01), and 10×10^5 ($Z = 0$, 0.006, 0.01) solar masses were studied. The $10^5 M_{\odot}$ star burned hydrogen in a stable fashion, i.e., it did not experience the general relativistic instability prior to hydrogen depletion in the center of the star and it did not collapse. All other models with the exception of three produced black holes. The three exceptions were two $5 \times 10^5 M_{\odot}$ stars with metallicity 0.005 and 0.01, and one $10^6 M_{\odot}$ star with metallicity 0.01. These models completely disrupted with kinetic energies of $\sim 10^{56}$ to 10^{57} erg. The central temperature and density history during the implosion/explosion of one $5 \times 10^5 M_{\odot}$ model is shown in Figure 1. In the $10^6 M_{\odot}$ explosion the luminosity, which during the Kelvin-Helmholtz stage was near 10^{44} erg s $^{-1}$, i.e., the Eddington value, rises to $\gtrsim 10^{46}$ erg s $^{-1}$ and stays that bright for approximately 10 years. Apparently if such gigantic stars ever do form they will make their presence known!

The chief nucleosynthetic consequences of these explosions are the production of helium from hydrogen and trace amounts of ^{16}N and ^7Li (Wallace and Woosley 1981; Norgaard and Fricke 1976). The helium mass fraction in both $5 \times 10^5 M_{\odot}$ explosions rises by 3% and in the $10^6 M_{\odot}$ explosion, it rises by 16%. One should keep in mind, however, that were it not for a near solar concentration of heavy elements these stars would never have exploded in the first place. Thus *non-rotating* supermassive stars (heavier than $10^5 M_{\odot}$) played absolutely no role in producing pre-Galactic helium.

Quite different results may be expected if these stars are endowed with rotation (Fowler 1966; Fricke 1974). In particular, higher central temperatures may be reached by objects that have lower initial metallicity (zero ?) yet succeed in exploding because of the centrifugal potential. At these higher temperatures the *rp*-process can produce heavy elements up to the iron group and beyond (Wallace and Woosley 1981). Fuller *et al* intend to model rotating supermassive stars during the forthcoming year by introducing a one-dimensional "pseudo-rotational" potential into the same KEPLER code used to study the non-rotating models. Full two-dimensional calculations should eventually be attempted.

2. VERY MASSIVE STARS ("HYPERNOVAE")

Stars forming with initial masses in the range roughly 100 to 300 $M_{\odot}$ (without rotation) experience an instability that bears certain similarities to the supermassive stars discussed above. Following stages of relatively stable hydrogen and helium burning (during which *pulsational* instabilities exist that may drive rapid mass loss, Stothers and Simon 1970; Talbot 1971; Papaloizou 1973) the stellar core enters a thermodynamic regime that favors the creation of large quantities of electron-positron pairs. Creation of these pairs takes energy that might otherwise have provided pressure support and thus the star collapses (Barkat, Rakavy, and Sack 1967), again with γ close to 4/3. Nuclear fusion during the collapse liberates energy from carbon, neon, and oxygen burning, but silicon burning *requires energy*. This is because, at the low densities characteristic of such massive stars, silicon burning produces $^{54}\text{Fe} + 2p$, not ^{56}Ni , and the net reaction sequence is *endoergic*. If sufficient energy is liberated during the collapse by carbon, neon, and oxygen burning then the star blows up; but if the implosion continues well into silicon burning (and rotation is negligible), a black hole forms. Consequently, non-rotating stars having mass greater than about 300 $M_{\odot}$ (and less than $10^6 M_{\odot}$) end up as black holes. Below 100 $M_{\odot}$ the pair instability is not encountered and the star undergoes stable carbon, neon, oxygen, and silicon burning, culminating in iron core collapse (see next Section).

In the range 100 to 300 $M_{\odot}$ (these being rough estimates of the mass of the star *at its birth on the main sequence* prior to mass loss), stars end their lives in gigantic explosions called "hypernovae". Such stars have been recently modeled by Woosley and Weaver (1982a); Bond, Arnett, and Carr (1982, 1983; see also Bond, this volume); and Ober, El Eid, and Fricke (1983). The evolution of a 200 $M_{\odot}$, Pop III (i.e. $Z = 0$) star studied by Woosley and Weaver is typical. This star burns hydrogen at a central temperature of $\sim 1.2 \times 10^8$ K and density $\sim 20 \text{ g cm}^{-3}$ for ~ 2.5 million years (note that the main sequence lifetimes of stars in this mass range are approximately constant owing to the Eddington limitation on their luminosities and the fact that they are convective throughout most of their mass). The luminosity of the 200 $M_{\odot}$ star on the main sequence is $\sim 2.0 \times 10^{40} \text{ erg s}^{-1}$ and the effective emission temperature (neglecting mass loss) is 80,000 K. Because the luminosity is so close to Eddington and the core pulsationally unstable, extensive mass loss may well modify the surface properties leading to softer, perhaps even infra-red emission. It is interesting that hydrogen burning in this star is mediated by the CNO-cycle despite the fact that the star was born with no metals. Prior to hydrogen ignition the star contracts, heats up and actually burns a trace of helium to nitrogen ($\gtrsim 10^{-9}$ by mass) before igniting hydrogen burning (see also Ezer and Cameron 1971). At one-half hydrogen depletion the nitrogen mass fraction is $\sim 10^{-8}$.

Following hydrogen exhaustion, the 200 $M_{\odot}$ star burns helium for 265,000 years at a central temperature near 2.5×10^8 K and density 250 g cm^{-3} . During this time the radius of the star

expands greatly to $\sim 10^{14}$ cm. At the end of helium burning, the inner $112 M_{\odot}$ is comprised of oxygen and carbon in a roughly 3 to 1 ratio with traces of neon and magnesium. As the star contracts and heats in its center to $\sim 10^9$ K, seeking to ignite the $^{12}\text{C} + ^{12}\text{C}$ reaction, it encounters the pair instability and begins to collapse rapidly (although not super-sonically and not in free fall). The central temperature rises to 3.9×10^9 K and density to 2.2×10^6 g cm $^{-3}$ as carbon burns in the inner $\sim 80 M_{\odot}$, neon in the inner $\sim 70 M_{\odot}$, and oxygen in the inner $\sim 20 M_{\odot}$. The energy released by this burning is adequate to explode the star with total kinetic energy 2.6×10^{52} erg. For 140 days the light output of this hypernova is $\sim 10^{44}$ erg s $^{-1}$, or about 10 times that of a typical Type II supernova (see Woosley and Weaver 1982a for light curve).

The nucleosynthesis from this explosion is summarized in Table 1 with results normalized to solar system abundances (Cameroa 1973) relative to ^{16}O , an abundant product of the explosion. The lack of iron production is a common trait of this class of models owing to the endoergic nature of silicon burning. It is interesting that these explosions are such efficient producers of heavy elements (more than 1/2 of the initial mass ends up in elements heavier than helium) that the explosion of only one or two could account for the abundances of elements from carbon through calcium found in a typical globular cluster of stars ($10^6 M_{\odot}$, $Z \sim 10^{-4}$). Ten thousand such explosions could produce a metallicity *throughout the Galaxy* comparable to that observed in the most metal-deficient stars (eg. CD-38°-245, Bessel and Norris 1981; see also Bond 1981). If this did in fact occur at very early times, one might expect to find, in the most metal deficient stars, large overabundances of the elements from carbon through calcium relative to iron (compared to the sun). Observations indicate that such a correlation may indeed exist (Snedden, Lambert, and Whitaker 1979; Butler, Dickens and Epps 1978; Bessel and Norris 1981). Unless some unforeseen circumstance prohibited star formation in this mass range or led to dispersal of the star prior to the pair instability, it is hard to see how the nucleosynthetic contribution from stars in this mass range could have been anything other than very important.

Table 1: Nucleosynthesis in a $200 M_{\odot}$ Pop III Star

Species	^4He	^{12}C	^{16}O	^{20}Ne	^{24}Mg
Mass ejected ($M_{\odot}$)	70	11	57	4.5	5.5
Compared to sun	0.03	0.45	1	0.44	1.7
Species	^{28}Si	^{32}S	^{36}Ar	^{40}Ca	^{56}Fe
Mass ejected ($M_{\odot}$)	20	6.8	0.85	0.66	0.08
Compared to sun	4.6	2.7	1.4	1.4	0.01

Other important implications for stars in the mass range $> 100 M_{\odot}$, especially for providing "missing mass", helium synthesis, and microwave background are discussed by Bond elsewhere in this volume (see also Bond, Arnett, and Carr 1982, 1983). We would only briefly comment on work in progress by Stringfellow, Woosley, and Bodenheimer regarding the evolution of very massive stars *including rotation*. As noted above the fate of non-rotating stars having main sequence mass greater than $\sim 300 M_{\odot}$ is a black hole. Stringfellow recently examined a $300 M_{\odot}$ helium core (corresponding to a main sequence mass of $\geq 500 M_{\odot}$) using a two-dimensional explicit hydrodynamics code (Bodenheimer and Woosley 1983). The $300 M_{\odot}$ core was first evolved to the point of pair instability using a one-dimensional *implicit* hydrodynamics code (KEPLER) then remapped onto the two-dimensional grid at a time when its central temperature had reached 2×10^9 K. Continued evolution in one dimension led to the formation of a black hole. This same evolution to black hole was replicated in the 2-D code if the star was not rotating. Stringfellow found, however, that the implosive evolution is greatly modified by the introduction of only a small amount of rotation. A rotational energy corresponding to 0.4% of the gravitational binding energy at the beginning of the calculation (i.e., when the central temperature was 2×10^9 K and the binding energy 7.4×10^{53} erg), or a ratio of centrifugal force to gravity of only 1%, leads to a reversal of the implosion and a gigantic explosion. During this explosion matter at the center of the star reaches 12 billion degrees and the central density rises to 4×10^7 g cm $^{-3}$, much greater than in any of the one-dimensional calculations. A similar calculation employing 5 times as much rotational energy also explodes but reaches a somewhat lower temperature (5.9×10^9 K). Unfortunately the nuclear physics included in these two-dimensional calculations (only oxygen burning) is not adequate for such extreme thermodynamic conditions. In particular, photodisintegration, a very important endoergic process that can diminish the prospects for an explosion, was left out. Stringfellow is currently rewriting his program to include photodisintegration and electron capture and we should have reliable results in the near future. An interesting possibility is mass "bifurcation", i.e., the central portions of the star may continue to collapse while outer layers are ejected by a combination of nuclear burning and rotation (see also Bodenheimer and Woosley 1983). Important implications loom for both nucleosynthesis and the "missing mass" problem. The higher explosion temperatures accessible with the inclusion of rotation may allow iron group nuclei to be synthesized and ejected. Ejection of only a small fraction of the stars mass as heavy elements could eliminate the residual black hole as an important component of the missing mass.

3. MASSIVE STARS (10 to $100 M_{\odot}$)

Stars in the range 10 to $\sim 100 M_{\odot}$ end their lives by producing iron cores of roughly a Chandrasekhar mass which collapse owing to a combination of photodisintegration reactions (induced by the high core temperature) and electron capture (resulting from both the high core

temperature and density). In the limited, although numerically significant mass range 8 to 10 $M_{\odot}$, the late evolution may be diverse and complex. This results, in part, from an inverted temperature gradient set up by efficient neutrino cooling in a star whose central pressure is only marginally sensitive to temperature and, in part, from the semi-degenerate nature of the nuclear burning itself (Weaver and Woosley 1979; Woosley, Weaver, and Taam 1980; Miyaji *et al* 1980; Nomoto, 1980a, 1981, 1983, this volume; Hillebrandt 1982a). Here we will restrict our attention to the (comparatively) simpler evolution of more massive stars.

Much has been written about the evolution of stars in this mass range and, especially, the core bounce/neutrino transport mechanism which may (or may not, depending seemingly upon the year in which one lives!) lead to their explosion. We shall not, in this limited space, even attempt to review the extensive literature dealing with this subject. The interested reader may consult reviews by Arnett (1980); Trimble (1982); Wheeler (1981); Hillebrandt (1982b, 1983); Bowers and Wilson (1982ab); and Brown, Bethe, and Baym (1982). Here we will briefly discuss some recent results from our ongoing attempt to numerically simulate the complete evolution of a grid of stellar masses 10, 15, 20, 35, 50, and 100 $M_{\odot}$ (of constant mass) from birth on the main sequence through their death as Type II supernovae.

In 1978 Weaver, Zimmerman, and Woosley published presupernova models of 15 and 25 $M_{\odot}$ stars. These were subsequently followed through simulated core bounce and explosion (Weaver and Woosley 1980a) and yielded luminosity, radius, and effective temperature histories in good agreement with observations of typical Type II supernovae. Furthermore, the nucleosynthesis calculated by Weaver and Woosley (1980a) and, subsequently in greater detail by Woosley and Weaver (1982b), for the 25 $M_{\odot}$ star agreed reasonably well with solar system proportions of isotopes from ^{12}C to ^{60}Ni . There were notable deficiencies, however, as noted by the authors. The abundances of species in the silicon to titanium range were too small by roughly a factor of 5 compared to other important isotopes such as ^{16}O ; ^{23}Na was *overabundant* by roughly the same factor; and several interesting species: ^{13}C , $^{14,16}\text{N}$, ^{19}F , ^{48}Ca , and ^{47}Ti , were hardly produced at all. Some of these deficient productions were not particularly worrisome, eg. ^{13}C and ^{14}N can probably be produced adequately in lower mass stars, ^{16}N by novae, ^{48}Ca by the occasional ejection of highly neutronized core material, etc., but others, eg. the deficient production of silicon through titanium, all of which are *explosively* synthesized during shock wave passage, led us to suggest that solar abundance set requires a component of nucleosynthesis from stars *more massive than 25 $M_{\odot}$* . This is a proposition to which we still adhere for several reasons. First, as discussed in the previous section, stars of mass $\geq 100 M_{\odot}$ are copious producers of silicon through calcium (Table 1). Unless nature has purposefully avoided their creation, hypernovae should form an important component of the nucleosynthetic matrix. Second, as one goes to higher mass stars the density gradient around the core becomes less steep. A shallower density gradient implies that

the shock wave generated by core bounce (in stars less massive than $100 M_{\odot}$ but more massive than $25 M_{\odot}$) will heat more matter to peak temperatures in the range 3 to 4 billion degrees, i.e., the requisite range for explosive oxygen burning, and produce proportionately greater amounts of silicon through calcium. Finally, it is unrealistic to expect the nucleosynthesis of all stars in the 10 to $100 M_{\odot}$ range to be so similar that element production in any one mass (eg. $25 M_{\odot}$) is anything other than an extremely qualitative representation of the entire ensemble. An accurate calculation of *iron group* synthesis, for example, is an especially difficult problem as it relies on knowing both the strength of the shock and the location of the "mass cut" (last stellar zone to fall back onto the neutron star) in stars of different total mass. Therefore, quantitative predictions of iron synthesis are likely to remain highly uncertain for some time to come.

During the last several years we have computed the evolution of a number of other massive stars up to the point of silicon ignition. These include, in addition to the $15 M_{\odot}$ and $25 M_{\odot}$ models of Weaver, Zimmerman and Woosley (1978), stars of mass 10, 20, 35, 50, and $100 M_{\odot}$. We stopped these calculations at silicon ignition because the nuclear physics in the code at that time, especially the rates for and coupling of hydrostatic neutronization processes to the calculation, was not wholly adequate for an accurate representation of the final evolutionary stages (the same goes for the 15 and $25 M_{\odot}$ stars that we *did* publish; see below). Even so, we were able to determine several interesting quantities that are not expected to be greatly modified during silicon core burning or by the ejection process. These include the helium core mass at the end of the stars life; the mass of heavy ($Z > 2$) elements in the core (from which we can subtract roughly $1.5 M_{\odot}$ to obtain a rough estimate of the total mass of heavy elements ejected by the star); and the nucleosynthesis of light isotopes ($Z \leq 12$). Given the helium abundance dredged up by convection into the envelope, one can also estimate $\Delta Y / \Delta Z$, the change in helium mass fraction divided by the change in metallicity, for these stars. The nucleosynthesis of light isotopes was reported in Woosley and Weaver (1982a). The remaining quantities are summarized in Table 2. The metallicity, i.e., that fraction of the initial stellar mass finally ejected in the form of elements heavier than helium, can be approximated in the mass range 15 to $100 M_{\odot}$ by $Z = 0.5 - 6.3 M_{\odot} / M$.

Table 2: Bulk Nucleosynthesis in Massive Stars

Mass ($M_{\odot}$)	Helium Core ($M_{\odot}$)	Metal Core ($M_{\odot}$)	Y_{env}^*	$\Delta Y/\Delta Z$
10	2.6	1.5	0.30	large
15	4.5	3.0	0.33	0.70
20	7.4	5.0	0.36	0.40
25	9.5	7.1	0.40	0.30
35	17.0	13.0	0.41	0.08
50	24.0	21.0	0.51	0.14
100	47.0	47.0	0.57	0.05

*Initially the helium mass fraction in envelope was 0.28

More recently Weaver, Woosley, and Fuller (1982, 1983; WWF) have revised the stellar evolution code so that the electron capture processes that commence during oxygen and silicon burning are properly modeled. Modifications include weak interaction rates from Fuller, Fowler, and Newman (1982ab); a new treatment of quasiequilibrium and "cluster equilibrium" (Woosley, Arnett, and Clayton 1973) that calculates the rate of neutronization (principally due to electron capture) during core and shell oxygen burning as well as during silicon burning and core collapse; new sequences of nuclear reactions for silicon burning in a composition that has already become so neutron-rich that ^{30}Si is a major constituent; minor corrections to nuclear screening factors; initial abundances from Cameron (1973) rather than Cox and Stewart (1970ab); and finer time step and zoning criteria (roughly a factor of 2 in each). Using the improved code, WWF have calculated new pre-supernova models of 20 and 25 $M_{\odot}$ stars. Other masses, eg. 10, 11, 15, 50, and 100 $M_{\odot}$, are in progress.

The chief differences in the new pre-supernova models (Figures 2 and 3) are smaller iron cores at the time of collapse; smaller values of Y_e , the electron mole number; and lower values of entropy (see WWF for plots of Y_e and entropy in the new models). In 20 and 25 $M_{\odot}$ pre-supernova models the iron core masses are now 1.41 and 1.35 $M_{\odot}$ (as opposed to a value of 1.61 $M_{\odot}$ in the old 25 $M_{\odot}$ star); central values of Y_e are 0.422 and 0.423; and central values of entropy are 0.69 and 0.73 respectively. The smaller cores and lower entropies should favor the prospects for explosion by the core bounce mechanism (eg. Hillebrandt 1982b; 1983). Additionally, the density gradients surrounding the iron cores of the new models are less steep. This implies, all else being equal, improved nucleosynthesis of elements from silicon through calcium. We plan to follow the (continued) explosive evolution of these new models in the near future.

Figure 2. Abundances in the new $25 M_{\odot}$ pre-supernova star (WWF). The composition is sampled at a time when the collapse velocity has first reached a value of 1000 km s^{-1} in any zone. Note the smaller iron core mass as compared to earlier calculations. Horizontal abundance lines are, in general, indicative of regions that are, or once were, convective. An exception is the curve labeled "Fe" which is the sum of the mass fractions of all iron group species more neutron-rich than ^{56}Fe .

Figure 3. Thermodynamic conditions in the new $25 M_{\odot}$ presupernova star (WWF). In the region external to the iron core the nuclear energy generation rate is positive and the neutrino loss rate negative. Internal to the core both are negative, with neutrino losses primarily coming from electron capture. Collapse here (at the same time as Figure 2) is a consequence of both photodisintegration and electron capture. Cross-hatched and open rectangles denote regions of convective and semi-convective instability respectively. Hydrogen and helium shells are burning at rates that are off-scale as indicated by arrows. Curves for ρ and T are parallel in regions where the density scales as T^3 . The stellar radius, effective emission temperature, and photon luminosity are also given.

Perhaps the most exciting recent development in studies of massive star evolution are the calculations of Wilson (1983) showing the *delayed* explosion of the collapsed core following a long period of shock stagnation. *All the models Wilson has calculated now explode when the calculation is continued to sufficiently late times.* These include the "old" $10 M_{\odot}$ star (see also Hillebrandt 1982a); the new $25 M_{\odot}$ star (WWF); and *the old $15 M_{\odot}$ star* (Weaver, Zimmerman, and Woosley 1978). Explosions occur at time ranging from 0.25 s ($10 M_{\odot}$) to 0.55 s ($25 M_{\odot}$); produce total explosion energies of from 1.8 to 4.5×10^{50} erg; and leave neutron star masses (not corrected for neutrino losses) of $1.48 M_{\odot}$ ($10 M_{\odot}$), $1.76 M_{\odot}$ ($15 M_{\odot}$), and $1.66 M_{\odot}$ ($25 M_{\odot}$). Note that the $25 M_{\odot}$ core accretes roughly $0.3 M_{\odot}$ before finally exploding. The mechanism for these explosions involves the slow diffusion of neutrinos out of the core which capture on free nucleons behind an almost stationary accretion shock. The heating from this capture plus the diminished ram pressure as regions of decreasing density pass through the accretion shock (and the scattering of neutrinos on pairs produced as the temperature rises and density drops, a lesser effect) ultimately combine to change the standing accretion shock into an outwardly propagating wave capable of ejecting the stellar mantle and envelope. Considerable numerical uncertainty exists in these calculations owing to the necessity of running thousands of time steps using explicit hydrodynamics and continuous mass rezoning. It will be very interesting to see the results of future calculations, perhaps employing implicit hydrodynamics and mixed Eulerian/LaGrangian mass zoning. Also interesting are the implications this all has for "leptonic convection" (Epstein 1979) at these late times and the possibility of core overturn (Colgate and Petschek 1979; Smarr *et al* 1981).

4. TYPE I SUPERNOVAE

There is general consensus that Type I supernovae (SNI) are the explosions of relatively low mass stars, at least compared to Type II's, and that the stars involved are void of substantial hydrogenic envelopes. The former contention is supported by the lack of association of SNI's with the spiral arms of (spiral) galaxies within which they occur (Maza and van den Bergh 1976) and the occurrence of SNI in elliptical galaxies where the rate of massive star formation is very small. The latter is consistent with the absence of hydrogenic lines in the SNI spectrum (unlike SNIi) and the lack of a well defined "plateau" phase in the light curve (Falk and Arnett 1973; Weaver and Woosley 1980a). Most currently favored models are based upon white dwarfs accreting mass in cataclysmic variable systems (Wheeler and Hansen 1971; Whelan and Iben 1973; Mazurek 1973; Nomoto and Sugimoto 1977; Nomoto 1980ab, 1981, 1982ab, this volume; Taam 1980ab; Chevalier 1981; Weaver and Woosley 1980b; Weaver, Axelrod, and Woosley 1980, (WAW); Woosley, Weaver, and Taam 1980; Woosley and Weaver 1981; Woosley, Taam, and Weaver 1983, (WTW); Iben and Tutokov 1983) although a limited range of stellar masses between $8 M_{\odot}$ and $10 M_{\odot}$ may also contribute to the SNI rate (WAW) if such stars lose their hydrogen envelopes and ignite a degenerate thermonuclear runaway.

The fate of the accreting white dwarf as well as the physical mechanism for its explosion is critically dependent upon its mass, accretion rate, and the composition of the accreted matter (see Iben and Tutokov, 1983, for detailed discussion of various evolutionary scenarios expected to lead to SNI). Some combinations lead to common nova outbursts. If the thermonuclear model for novae as commonly formulated is correct (*cf.*, Starrfield, Sparks, and Truran 1974; Starrfield, Truran, and Sparks 1981; Medonald 1983), newly accreted material must mix with the carbon-oxygen substrate during the inter-flash period. Since the nova itself does not appear likely to produce fresh carbon during its outburst, this implies that the white dwarf mass does not grow but may, in fact, shrink. Either way, the critical mass for a SNI is not attained. For some range of accretion rates and dwarf masses, though, the hydrogen shell flashes are expected to be weak (Fujimoto and Taam 1982; WTW; Nomoto this volume) and the mass of the dwarf does grow as a layer of degenerate helium accumulates between the hydrogen burning shell and the carbon-oxygen core (see Nomoto and Sugimoto 1977 for the interesting case of *helium* accretion onto a *helium* white dwarf). Providing that the accretion process is not truncated, the white dwarf has three possible fates: 1) off-center ignition with the accreted helium layer consumed in an outwardly propagating *detonation* wave and (most of) the carbon-oxygen core left behind as a lower mass white dwarf remnant; 2) off-center ignition with *dual-detonation* waves propagating inwards and outwards leading to the complete nuclear incineration and disruption of the star; or 3) a centrally ignited *deflagration*, with runaway occurring just short of the Chandrasekhar mass, that burns only the inner portion of the white dwarf but also leads to its complete disruption. We shall briefly discuss representative models of each variety.

4.1 Detonations and Deflagrations

WTW have recently computed the complete evolution of three accreting white dwarfs, all of which experience "off-center" detonation (cases 1 and 2 above). The results should be representative of a broad range of accretion rates and dwarf masses. Specifically examined were carbon-oxygen white dwarfs of mass 1.2, 0.8, and 0.5 $M_{\odot}$ accreting helium (i.e., assuming hydrogen shell flashes to be weak or the donor star to be pure helium at rates of 10^{-9} , 2×10^{-9} , and 10^{-8} $M_{\odot} \text{ y}^{-1}$ respectively. We shall refer to these calculations as Models 1, 2, and 3. All three models ignited helium burning under conditions that were extremely degenerate and, in all cases, this ignition was achieved prior to the star attaining the Chandrasekhar mass. The total masses of the white dwarfs at helium ignition were 1.43 $M_{\odot}$, 1.34 $M_{\odot}$, and 1.12 $M_{\odot}$ respectively for Models 1, 2, and 3. Model 3 has been discussed previously (Weaver and Woosley 1980b; Woosley, Weaver, and Taam 1980; WAW). The results of Model 2 are summarized in Figure 4.

The temperature and density as helium first begins to run away in Model 2 are 6.1×10^7 K and 7.5×10^7 g cm $^{-3}$ respectively. Owing to the extreme degeneracy, the runaway proceeds

all the way to the iron group, chiefly ^{56}Ni at this relatively low value of neutron excess, before substantial expansion occurs. The nuclear reactions release about 1.5×10^{18} erg g^{-1} and raise the local pressure by about a factor of 5. During the latter stages of the runaway the nuclear time scale becomes extremely short, much shorter than the sound crossing time for the burning region. The short burning time and large overpressure lead to expansion that, in the unburned material, is supersonic. Moving outwards the shock wave experiences a decreasing density gradient as well as a fuel (helium) that has a low ignition temperature. This allows the outward moving shock to propagate as a successful detonation wave, converting all but the outermost portions of the helium shell into iron. The inbound wave meets with less success. It must move up a density gradient and attempt to ignite a fuel (carbon) that has both a higher flash temperature and lower specific energy. As Figure 4 shows, the inward wave does *not* succeed in igniting the carbon-oxygen core (as it does in Model 3; see Woosley, Weaver and Taam 1980), but simply dies out and becomes an acoustic wave which compresses and heats the core only slightly. Consequently, that layer which was helium is converted into iron and ejected with high velocity while most of the carbon-oxygen core is left behind as a bound remnant. Not all of the original white dwarf remains, however, only about $0.54 M_{\odot}$ of the initial $0.8 M_{\odot}$. This is because the total energy (internal minus gravitational) of the new, lower mass white dwarf is less than the total energy of the core of equivalent mass prior to removal of its outer layers and the difference is available for ejecting material. A total of $0.79 M_{\odot}$ is ejected by Model 2 with kinetic energy 1.15×10^{51} erg. This ejected mass includes $0.26 M_{\odot}$ of carbon and oxygen and $\sim 0.50 M_{\odot}$ of ^{56}Ni . Model 1 also leaves behind a white dwarf remnant, $1.16 M_{\odot}$ in this case, and ejects a correspondingly smaller amount of mass, $0.27 M_{\odot}$, which is mostly ^{56}Ni . The total kinetic energy is also much smaller, 3.8×10^{50} erg. Model 3, as mentioned previously, leaves no remnant and generates an explosion of 2.2×10^{51} erg. The light curves, spectra, and nucleosynthesis from these explosions are discussed in subsequent sections.

We have also recently studied a number of models characterized by centrally ignited *deflagration*. Model 4 is the end point of the evolution of a $2 M_{\odot}$ helium core, which might typify a main sequence star of $\sim 9 M_{\odot}$ that has lost its hydrogen envelope prior to the reduction of the helium core mass by convective dredge-up (WAW). This core spends 2.9 million years burning helium in a convective core of $0.73 M_{\odot}$. Typical conditions during this time (evaluated at $1/2$ helium depletion) are central temperature 1.6×10^8 K, central density, 2.7×10^3 g cm^{-3} , radius, 2.3×10^{10} cm, luminosity, 1.2×10^{37} erg s^{-1} , and effective emission temperature, 75,000 K. During the next 300,000 years helium burns in a shell as the carbon-oxygen core grows to $1.1 M_{\odot}$ (60% carbon, 40% oxygen). The envelope of the helium star also expands to $\sim 1.3 \times 10^{12}$ cm and the luminosity rises to $\sim 1.3 \times 10^{38}$ erg s^{-1} . Neutrino losses become quite important during this stage, comparable to the surface luminosity, and a central temperature inversion develops.

Figure 4. A sequence of figures showing the explosive evolution of "off-center" detonation Model 2. The composition at the time of runaway, as defined by that time when the temperature first reaches 5×10^9 K at the base of the accreted layer (d) is shown in a. A small amount of helium has burned to ^{12}C before the runaway ensues. A short time later (41 ms; b, e, and f), a detonation wave has burned 0.4 $M_{\odot}$ of the outlying material to iron group species. As expansion leads to cooling the ^{64}Fe shown in b recombines with protons to produce ^{60}Ni as shown in c. The large overpressure and velocity in the outgoing shock and small overpressure and velocity of the inwardly propagating wave are seen in e and f. The carbon oxygen core never ignites. A portion is left behind as a white dwarf remnant of the supernova explosion.

At this point, i.e., when the CO-core is $1.1 M_{\odot}$, carbon burning ignites non-degenerately, but off-center at $\sim 0.35 M_{\odot}$. Typical conditions in the convective carbon burning shell are 7×10^8 K and 3×10^6 g cm $^{-3}$, while the temperature at the center of the star is only $\sim 4 \times 10^8$ K. Over the next 50,000 years the carbon burning shell moves inwards, eventually reaching the center of the star. During this time the boundary of the CO-core (i.e., the helium burning shell) moves out to $1.22 M_{\odot}$ and, over the next 15,000 years, to $1.3 M_{\odot}$. At this time the inner $1.1 M_{\odot}$ consists of a neon-magnesium core (60% neon, 25% magnesium, and 15% oxygen) with the region 1.1 to $1.3 M_{\odot}$ composed of carbon and oxygen.

Here the helium shell burning became (perhaps unrealistically) violent. We purposefully maintained coarse zoning in the helium layer in order not to spend prohibitive amounts of computer time following thin shell instabilities. As the core grew from $1.3 M_{\odot}$ to the Chandrasekhar value, successive helium shells burned one at a time as they added to the core. Owing to the degenerate conditions, high temperatures, up to 1.5 to 2.0×10^9 K, were attained and these zones experienced carbon, neon, and in some cases, even oxygen burning following their addition. This stage of the evolution is probably not realistic and should be computed with much finer zoning before it is taken seriously. The composition from 1.3 to $1.43 M_{\odot}$ must therefore be regarded, for the time being, as artificial.

Even so, the evolution of the *central core* should be correctly represented and, for purposes of exploring the generic class of deflagrating models, this should be adequate. It is, after all, the central density at runaway, and, to a lesser extent, the composition of the inner solar mass of material, that influences the outcome. The central density determines the mass and binding energy of the (nearly Chandrasekhar) core as well as the rate of electron capture once the explosion gets underway. The composition determines the specific energy released as burning proceeds to the iron group. Of course the exact composition of the outer layers will be important spectroscopically.

The conditions at runaway in Model 4, i.e., when central nuclear energy generation first exceeded neutrino losses, were 2.9×10^8 K and 2.3×10^9 g cm $^{-3}$. As the runaway developed, the central density reached a peak value of 3.7×10^9 g cm $^{-3}$ before burning finally led to expansion. Burning in Model 4 was propagated as a *convective deflagration*, which is to say, ignition proceeded at a subsonic rate with overlying material ignited by the thermal transport of energy by convection from underlying material that was already burning. Numerical simulation of such a phenomenon using mixing length theory is highly uncertain at best, even in one dimension (see Muller and Arnett 1982 for a two-dimensional attempt). The temperature gradients are so extreme (super-adiabatic) that the convective velocity is near sonic. Peak temperature in the burning front is $\sim 7 \times 10^9$ K compared to only a few $\times 10^8$ K a short distance ahead of the front. Furthermore the time scale for nuclear burning is orders of magnitude shorter than the Courant crossing time for any reasonable zoning. Thus it is practically impossible to resolve the

burning front on a numerical grid. This leads to a computational *impasse* which, if great care is not taken, may propagate the burning at an artificial velocity. This occurs, for example, if the luminosity from one zone to the next is allowed to increase at an arbitrary rate set only by the (artificial) temperature gradient which may itself change on a very short time scale. As that gradient becomes large, the "convective luminosity" may become enormous heating the overlying zone rapidly to the flash point in a time short compared to what actual mixing could have achieved, even at the sound speed. After flashing, that zone can ignite the next one in a similar fashion and a chain reaction occurs that can erroneously propagate the burning at a supersonic velocity even though the overpressure is not, in reality, enough to propagate a detonation wave.

We avoided this artificial propagation by restricting the rise in luminosity in a given time step to be no greater than the luminosity at the previous step multiplied by $\exp(\Delta t/\tau_{conv})$ where τ_{conv} is the convective crossing time for the zone (thickness of the zone divided by the convective velocity which was, itself, limited to subsonic values). Obviously, this prescription is somewhat arbitrary and, for that reason, we regard the velocity at which the deflagration propagates as essentially a free parameter (limited, of course, by the speed of sound). Besides the central density at runaway, it is the most important parameter in the deflagrating models since it determines how much material will burn to iron and how quickly the star starts to expand and quenches the burning. For our calculations this critical parameter turned out to be roughly 1/3 the speed of sound (or about 2000 km s^{-1}). We note, in anticipation of subsequent discussions, that models which employ larger propagation velocities will synthesize more iron, develop greater expansion velocities, and experience less electron capture. The final composition and velocity for Model 4 are given in Figures 5 and 6. The total kinetic energy at infinity was $3.5 \times 10^{50} \text{ erg}$.

We also prepared two additional models to simulate deflagration in accreting carbon-oxygen white dwarfs. Models 5 and 6, composed initially of 50% carbon and 50% oxygen throughout their mass, were parametrized by their central densities at the time of runaway. We leave the task of relating these densities to actual evolutionary scenarios and, especially, accretion rates, to others (*cf.* Nomoto 1982ab, Iben 1978ab, 1982; Taam 1980b; Iben and Tutukov 1983). In our calculations ignition was achieved by forming white dwarfs of nearly Chandrasekhar mass having initial central temperature $2 \times 10^8 \text{ K}$ and adding carbon and oxygen to their surfaces until they exploded. The preignition temperature should not be critical except as it partly determines the runaway density. In Model 5 explosion occurred at a peak central density $2.4 \times 10^9 \text{ g cm}^{-3}$ and in Model 6 explosion occurred at a peak density of $7.0 \times 10^9 \text{ g cm}^{-3}$. Final compositions and velocities are shown in Figures 5 and 6. The kinetic energies at infinity were $6.2 \times 10^{50} \text{ erg}$ and $4.8 \times 10^{50} \text{ erg}$ for Models 5 and 6 respectively.

In the final composition of all 3 deflagrating models one sees a tenth of a solar mass or so where burning at intermediate temperatures ($5 \times 10^9 \gtrsim T \gtrsim 2 \times 10^9 \text{ K}$) synthesizes elements from

Figure 5. Final compositions of deflagrating Models 4 and 5. A shell of the products of explosive oxygen burning surrounds the iron core in both cases. This is a result of the expansive quenching of the deflagration. Large quantities of ^{54}Fe are present in the cores of both models. The composition of the outer $0.15 M_{\odot}$ of Model 4 may be artificial.

Figure 6. Final composition of deflagrating Model 6 and terminal velocities for all 3 deflagrating models. Owing to its large central density, Model 6 produces excessive quantities of neutron-rich isotopes. The velocity curves reflect the central densities at runaway (Model 6 more tightly bound than Model 5) and the composition (less specific energy from neon burning in Model 4 than carbon and oxygen burning in Models 5 and 6).

neon to calcium. This burning transpires as the deflagration dies out, quenched by the expansion of the white dwarf. An interesting effect, poorly modeled in the present study, is the mixing that may occur for several seconds following the explosion owing to Raleigh-Taylor instability. The central deflagration naturally produces a density inversion which is maintained by its higher temperature. Partial "overturn" of the region just outside the iron core is a possible consequence.

Another effect, seen in some calculations, but which we regard as "bogus" is classical convection occurring at very late times. The luminosity input by nickel decay is greatly super-Eddington and, while the envelope remains optically thick (several days) and dominated by radiation pressure, it is formally unstable to overturning convection. Allowing this convection to proceed at sonic velocity in the co-moving frame could stir freshly synthesized nuclei throughout most of the exploding star. It is not proper, however, to apply traditional convection theory in a medium which is freely streaming and in which gravity has become a negligible force. The luminosity of a supernova (Type I or II) is *advectively* transported, i.e. carried by expanding matter and released at the optically thin photosphere. The total energy in the radiation is, at times later than a few seconds, an inconsequential fraction of the streaming kinetic energy of the ejecta and, as such, it can have negligible effect on its motion. We turned convection off in our calculations at times later than a few seconds.

4.2 Light Curves

It has long been realized that the light output of a Type I supernovae *cannot* be a consequence simply of the high temperature and kinetic energy created during the explosion. Some late time energy input is required that is not degraded by adiabatic expansion. To see this, one must only realize that the expanding white dwarfs of the previous section will not become optically thin until their radii have increased to roughly 10^{15} cm. This estimate follows from an initial density of $\sim 10^8 - 10^9$ g cm $^{-3}$ and an opacity of a few tenths cm 2 g $^{-1}$ (WAW), typical of the large ensemble of Doppler-broadened lines in the expanding plasma. Since the initial radius was roughly a million times smaller than this, any initial internal energy deposited by the explosion is degraded to a trivial value. In Type II supernovae this problem is circumvented by starting with a configuration that already has a large radius, i.e., the low density envelope of a super-giant star.

The solution to this problem in SNI has also been realized for a long time, namely that the light curve of Type I's is a result of the delayed energy input by the decay of radioactive nuclei produced in the explosion (Borst 1950; Burbidge *et al* 1957), principally the nucleus ^{56}Ni ($\tau_{\frac{1}{2}} = 6.1$ d) and its daughter ^{56}Co ($\tau_{\frac{1}{2}} = 78.5$ d) (Pankey 1962; Colgate and McKee 1967). It is also important to note that the decay of ^{56}Co proceeds 19% of the time though a mode that produces positrons. Thus even at late times when the supernova remnant becomes transparent to γ -radiation the kinetic energy of the positrons still deposits energy ($\sim 4\%$ of the total decay

energy) and can power the late time light curve (Arnett 1979; Axelrod 1980ab). It is also important that the time history of the emission will not be given simply by the decay rate of the radioactive nuclei but will be modulated by both the efficiency of energy deposition by γ -rays, a factor that is density dependent, and by a time dependent fraction of deposited energy that managed to escape without being degraded by adiabatic expansion (WAW). The correct expression for the light output as a function of time is

$$L(t) = M_{60} \dot{S}(t - \tau_l) f_{dep}(t - \tau_l) f_{esc}(t),$$

where M_{60} is the mass of freshly synthesized ^{60}Ni , $\dot{S}$ is the nuclear energy generation rate from radioactive decay, f_{dep} is the fraction of the radioactive decay energy deposited in the remnant (minimum value 4%), f_{esc} is the fraction of previously deposited γ - and positron energy that avoids decompression to escape as optical (or near optical) radiation, and τ_l is the retarding time to approximately reflect the mean lag time between energy deposition and escape (or decompression). Analytic expressions that may be related to any supernova model are given for all of these quantities by WAW. It is interesting that the results are most sensitive to i) the mass of ^{60}Ni synthesized, ii) the expansion velocity (i.e., the kinetic energy of the explosion, and iii) the density structure of the expanding supernova. All these would be quite similar for exploding white dwarfs of nearly Chandrasekhar mass, which might explain why the class of Type I light curves is such a homogeneous sample.

The light curves for Models 1, 2 and 3 are given in Figure 7. A detailed comparison of the light curve for Model 3 and the observational data for supernova 1972e was given by WAW and showed excellent agreement. Model 2, with an appropriate but reasonable adjustment of supernova date and distance to NGC5253, gives almost as good a fit. Light curves for the deflagrating models have not yet been computed, but are expected to closely resemble Models 2 and 3 except that for Model 4, the 2 $M_{\odot}$ helium star, there may be important modifications to its light curve brought about by the presence of $\sim 0.5 M_{\odot}$ of low density helium surrounding the exploding core. Model 1 is too fast and cannot be made to fit the data at all well. The reasons for the dim, rapid display in Model 1 are obvious. Too little ^{60}Ni is synthesized and the ejecta move too fast, hence become thin to γ -radiation too quickly. Models 1 and 2 may, in fact, be even "faster" in their optical light curves than Figure 7 suggests. As we shall see in the next section, the emission from these explosions is dominated by lines of highly ionized iron that may, shortly after peak, emit principally in the ultraviolet. Thus there may be a substantial bolometric correction.

It is also important to recall that Models 1 and 2 leave white dwarf remnants. The calculations of WTW therefore suggest the existence of a class of SNI characterized by i) comparatively fast, dim light curves (hence rendering their detection less likely); ii) ultraviolet emission and "hot"

spectra (see next section); and iii) white dwarf stars present in their remnants, perhaps even still bound in the binary that produced the explosion. No event of this type has been unambiguously identified although the models WTW constructed should correspond to events that occur in nature.

Figure 7. Optical (bolometric) light curves for the 3 "off-center" detonation models as calculated by WTW using the prescription of WAW. The light curves are most sensitive to the mass of ^{60}Ni ejected; the density of the expanding supernova; and the gradient in that density. Model 1 is an extremely "fast", dim Type I explosion because the mass of ^{60}Ni produced is small and the expansion velocity great. The factor of 4 variation in peak luminosity should roughly span the allowable parameter space for Type I models. See WTW for γ -line fluxes corresponding to these light curves.

4.3 Type I Spectra

As was first recognized by Meyerott (1978; 1980ab), the presence of fast particles from radioactive decay in the SNI plasma has important implications for the spectrum produced. In particular, ionization states may result which are far from LTE. Meyerott's work and the observation by Kirshner and Oke (1975) that the late time SNI spectrum bears a close resemblance to that of a pure, Doppler-broadened spectrum of Fe II led Axelrod (1980ab) to undertake a numerical calculation of the spectra resulting from a uniform expanding shell of ^{60}Ni . The numerical model self-consistently determined the temperature and ionization state of the nebula and accounted for a variety of spectral effects due to the rapid expansion of the nebula. Comparison of the results with the observed spectrum of SN1972e showed a close approximation was achieved if the ^{60}Ni

had a mass in the range 0.3 to 1.2 $M_{\odot}$ (depending on an uncertain distance to NGC5253) and an expansion velocity of roughly 7000 km s⁻¹. Of most direct importance for the ⁶⁶Ni hypothesis, the calculated spectrum contained a feature near 6000 Å due to ⁶⁶Co which decayed with time and a corresponding decaying feature was also present in the observations. This formed the first *direct* evidence for the presence of freshly synthesized radioactive ⁶⁶Ni in supernovae.

This picture has been recently clarified by new calculations which account for the fact that the SNI spectrum is strongly influenced by the density profile of the ejecta. This occurs because the ionization balance is very sensitive to density with both the average degree of ionization and the electron temperature decreasing as density increases. The density profile is also reflected in the spectrum through its effect on the transport of far ultraviolet radiation which results from radiative recombination. We have included these effects in calculating the spectra from Models 3 and 5 (Figures 8 and 9). These spectra include only the contribution from those regions of the models which are dominantly ⁶⁶Ni and would be modified by the inclusion of the overlying "atmosphere". During the nebular phase, however, that atmosphere is expected to have only a small effect (Axelrod 1981). The difference between the spectra of Models 3 and 5 is substantial and might therefore, unlike their light curves, be employed to discriminate which model is appropriate for a given explosion. The spectrum calculated for Model 3 is not in agreement with that of SN1972e nor with any other observations we could find in the literature. It is too "hot". That is, the high expansion velocity causes the density to decrease to too low values at too early times thus leading to a preponderance of high ionization states of iron (e.g., Fe V and Fe VI) and excessive Doppler broadening. Spectra for Models 1 and 2 would be even worse (The spectrum of Model 2 has been computed but is not shown. It is dominated by lines of Fe V, VI, and even VII). In fact, an accurate calculation of Models 1 and 2 and the outer regions of Model 3 would require higher temperatures and ionization states than are currently accessible by the code and would probably give an even hotter spectrum. Thus the generic class of detonating (carbon-oxygen) white dwarfs is in difficulty spectroscopically. Such models also pose a problem to the spectrum at early times (Branch 1980ab; 1982; Branch et al 1982) in that the velocities of elements such as Ca and Si, which form p-Cygni absorption lines at early times, tend to be far too high to agree with observations. There may also be inadequate calcium and silicon synthesis to account for the strength of observed absorption features. Possible resolutions to this apparent dilemma involve the two-dimensional geometry of the off-center detonation, currently under study by Fryxell and Woosley, or simply that this class of SNI models is relatively infrequent and our observational data base too small.

On the other hand the computed spectrum for Model 5 is in good agreement with SN1972e, in fact, given uncertainties in the atomic data, the agreement is *excellent*. Many details of the spectrum are congruent in both theory and observation lending credence to the modeling process

Figure 8. Optical spectrum of detonating Model 3 as compared to that observed (Kirshner *et al* 1973) from supernova 1972e 264 days after its explosion and the calculated ionization distribution of iron group species as a function of interior mass. Rapid expansion of the model results in a diminished abundance of free electrons and less efficient cooling. Thus highly ionized states of iron are abundant in the model that are not seen in the supernova. Line widths in the model are also typically broader than observed. This is *not* a good fit (see also WAW and WTW).

Figure 9. Optical spectrum of deflagrating Model 5 compared to supernova 1972e. The slower expansion gives rise to narrower lines and less highly ionized states of iron and cobalt. This is a much better fit than Figure 8. An absorption feature due to calcium is apparent in the observations at $\log \nu \approx 14.90$ which was not included in the model calculation.

in general. The spectrum for Model 4 (not shown) has also been computed (without including the overlying atmosphere) and is similar to that for Model 5, although a slightly "cooler". Model 6 is expected to be similar. Moreover, the deflagrating models offer a natural site for the synthesis of silicon and calcium seen as absorption features in the observed spectrum (but not included in the present spectral synthesis calculations). Model 5 makes $\sim 0.02 M_{\odot}$ each of ^{28}Si and ^{32}S and $\sim 0.003 M_{\odot}$ each of ^{36}Ar and ^{40}Ca . Model 4 makes $\sim 0.08 M_{\odot}$ of ^{28}Si , $\sim 0.02 M_{\odot}$ of ^{32}S , $\sim 0.003 M_{\odot}$ of ^{36}Ar , and $\sim 0.004 M_{\odot}$ of ^{40}Ca . Unfortunately, the calcium in Model 5 is moving at a maximum velocity of $8,000 \text{ km s}^{-1}$, which is too slow according to Branch (1980ab, 1982). Indeed, all things considered, it would be better if the deflagrating models had acquired greater kinetic energy and a more rapid expansion (see especially the next section on nucleosynthesis). This might occur if the deflagration wave has greater velocity, and as we argued that that velocity is essentially a free parameter, such may well be the case. The deflagration of a *helium* dwarf would also give a greater expansion velocity because of the greater specific energy available from burning helium to iron. There will, of course, always be *some* calcium, as well as traces of other heavy elements, present primordially in the outermost layers which are ejected with the greatest velocity (roughly $11,000 \text{ km s}^{-1}$ in Model 5). Thus it is important to know *quantitatively* just what fraction of the calcium abundance is observed at what velocity. So far that deconvolution of the observations has not been carried out, but the (simple one-dimensional) deflagrating models may be in some, hopefully slight, trouble here.

4.4 Nucleosynthesis

The chief nucleosynthetic product of these explosions is iron, principally the nucleus ^{56}Fe synthesized, in part, although not exclusively in the deflagrating models, as its radioactive progenitor ^{56}Ni . Owing to their rapid expansion and comparatively low ignition density, electron capture during the explosion of the *detonating* models is of no great consequence except for determining the abundances of trace elements such as ^{57}Fe , ^{59}Co , and $^{58,61,62}\text{Ni}$. Important synthesis of ^{44}Ca , ^{60}Ni , and ^{64}Zn also occurs but these species are produced as radioactive progenitors (^{44}Ti , ^{60}Zn , and ^{64}Ge) in amounts that are relatively insensitive to the neutron excess. Models 1, 2, and 3 eject 0.24 , 0.50 , and $1.06 M_{\odot}$ of iron group products respectively. Normalizing to ^{56}Fe , the isotopes ^{57}Fe , ^{59}Co , $^{60,61}\text{Ni}$, and ^{64}Zn are produced in all three models within a factor of 30% of their solar abundances. The species ^{44}Ca is underproduced by a factor ranging from 3 (Model 3) to 16 (Model 1), ^{58}Ni is underproduced by a factor of 2 to 6, and ^{62}Ni , by a factor of 3 to 20. It is especially interesting that these models synthesize so little ^{54}Fe ($< 1\%$ solar). This is partly a consequence of the α -rich freeze out (Arnett, Truran, and Woosley 1971; Woosley, Arnett, and Clayton 1973) in which all ^{54}Fe is converted into nickel isotopes, and partly a result of the small neutron excess of these models. It is particularly interesting because no other models we have ever studied, including Type II supernova models, appear capable of making ^{56}Fe without ^{54}Fe .

A nucleosynthetic component of this sort may be required in order to dilute the ^{54}Fe -rich ejecta of other types of supernovae, especially the deflagrations we shall now discuss.

The nucleosynthesis from (deflagrating) Models 4, 5, and 6 was given in Figures 5 and 6. The final electron mole number (Y_e), is given for the inner core of all three models in Figure 10. The quantity Y_e is related to the electron number density, n_e , by $n_e = \rho N_A Y_e$ and the neutron excess, η , by $Y_e = 1 - 2\eta$. For nuclei having equal numbers of neutrons and protons, $Y_e = 1/2$. Owing to the high ignition density and comparatively slow expansion rate of these models, substantial electron capture occurs during the explosion leading to a decrease in Y_e in the central core, so much so in fact that the dominant iron group nucleus at the center of the star shifts from first ^{56}Ni to ^{54}Fe to ^{56}Fe and, in the extreme case of Model 6, to ^{58}Fe . Electron capture was calculated here using the older version of KEPLER that employs weak interaction rates from Mazurek (1973) and Hansen (1966) and the quasi-equilibrium network described by Weaver, Zimmerman, and Woosley (1978). If anything, these weak rates should *underestimate* the actual electron capture flows. Compared to more realistic rates by Fuller, Fowler, and Newman (1982ab), key reactions, eg., $^{56}\text{Ni}(e^-, \nu)^{56}\text{Co}$, are generally slower by a factor of order 5. Thus in reality one might expect the curves of Figure 10 to be shifted to slightly *lower* values of Y_e . (There is some compensation since the formation of a more neutron-rich daughter leads to a substantial reduction in the rate of neutronization. Also capture on free protons, a process that was accurately modeled, is a major contributor to the decrease in Y_e , especially for values near 0.5).

The principal nucleosynthetic creation of the deflagrating models is still iron group species but, owing to the neutronization, there is considerable variation of the isotopic composition and none of it is very good news. Model 4 ejects $0.53 M_\odot$ of ^4He , $0.12 M_\odot$ of ^{16}O , $0.30 M_\odot$ of ^{20}Ne , $0.16 M_\odot$ of ^{24}Mg , $0.08 M_\odot$ of ^{28}Si , $0.017 M_\odot$ of ^{32}S , $0.0032 M_\odot$ of ^{36}Ar , $0.0039 M_\odot$ of ^{40}Ca , $0.16 M_\odot$ of ^{54}Fe , and $0.61 M_\odot$ of ^{56}Ni which decays to ^{56}Fe . The ^{54}Fe to ^{56}Fe ratio is an obvious problem. In the sun this ratio is 0.061. In Model 4 it is 0.26 which means that supernovae like Model 4 could have been responsible for synthesizing no more than $\sim 25\%$ of the iron in our Galaxy. Even so, the remainder of iron would have to be synthesized in objects that make no ^{54}Fe themselves, eg., the detonating models. Nor do Models 5 and 6 fare any better. Model 5 ejects 0.34 and $0.36 M_\odot$ of unburned ^{12}C and ^{16}O (the near equality given by initial assumptions), $0.0037 M_\odot$ of ^{20}Ne , $0.0052 M_\odot$ of ^{24}Mg , $0.027 M_\odot$ of ^{28}Si , $0.017 M_\odot$ of ^{32}S , $0.0035 M_\odot$ of ^{36}Ar , $0.0033 M_\odot$ of ^{40}Ca , $0.17 M_\odot$ of ^{54}Fe , and $0.49 M_\odot$ of ^{56}Ni . This gives roughly the same ^{54}Fe constraint as Model 4. Model 6, because of its larger ignition density, faces even graver difficulties. Amounts of elements lighter than iron are ejected that are comparable to Model 5 but, within the iron group, $0.15 M_\odot$ of ^{54}Fe , $0.44 M_\odot$ of ^{56}Fe (with $0.31 M_\odot$ made as ^{56}Ni and $0.13 M_\odot$ made as ^{56}Fe itself), and $\sim 0.07 M_\odot$ of ^{58}Fe are produced. This gives a $^{54}\text{Fe}/^{56}\text{Fe}$ ratio roughly 5 times that of the sun and a $^{58}\text{Fe}/^{56}\text{Fe}$

Figure 10. Distribution of the final electron mole number with interior mass in the 3 deflagrating models. The quantity Y_e is initially 0.5 throughout the star (initial composition is of nuclei having $Z = N$) but is decreased by electron capture during the explosion. The dominant iron group isotope in nuclear statistical equilibrium at a given Y_e is indicated by bands. Large overproductions of ^{54}Fe and ^{58}Fe are a troubling aspect of deflagrating models.

ratio roughly 40 times that of the sun! We conclude that deflagrating white dwarfs igniting at central densities $\gtrsim 2.5 \times 10^9 \text{ g cm}^{-3}$, i.e., the central density of Model 5, must have been very rare in nature.

4.5 Type I Summary

We seem to have painted ourselves into a bit of a corner! All models studied here, with the possible exception of Model 1, apparently give reasonable light curves but the class of off-center detonations on carbon-oxygen cores produces unacceptable spectra (although quite reasonable nucleosynthesis) while the carbon-oxygen and neon deflagrations give unacceptable nucleosynthesis (although quite reasonable spectra). Something must be wrong. At this point we do not know the resolution of this dilemma. Obvious, but to us, presently unacceptable, solutions could be i) SNI are not a major source of iron in nature; ii) our nuclear reaction rates and/or atomic data are in much greater error than we believe, or iii) the spectrum of SN1972e is not that of a typical SNI. More likely hypotheses we would suggest are i) the existence of another class of SNI models (helium dwarf deflagrations?) having faster expansion rates and lower central ignition densities than our Models 4-6 but slower velocities than Models 1-3; ii) a low density "atmosphere" surrounding a detonating model which would "tamp" the high expansion velocities of the outer layers; iii) important 2 and 3 dimensional modifications to our current models, especially those involving off-center ignition, and/or iv) a preponderance of deflagrating models with central densities close to that of Model 5 but with more rapid velocities for the deflagration wave than we employed. Obviously the search for the "correct" SNI model is still on.

One of the authors (SEW) gratefully acknowledges the hospitality and stimulating environment of the Erice conference on nucleosynthesis, especially conversations with D. Bond, D. Branch, C. Chiosi, J. Gallagher, and I. Iben. He also is grateful to the Lawrence Livermore National Laboratory for support and computer time over the last 14 months while the work described here was carried out. This work has been supported by the National Science Foundation (AST-81-08509) and under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

DISCUSSION

Edmunds: Can you predict what will happen to nucleosynthesis in the new $25 M_{\odot}$ star?

Woosley: Qualitatively the results should resemble what was calculated for the old $25 M_{\odot}$ star. In detail, the new model may give better production of the silicon to calcium group because the core of the new star is surrounded by material with a shallower density gradient. It is our hope that material which once was a part of the old iron core will now experience explosive oxygen burning with an enhanced production of intermediate mass elements. This remains to be seen. Also you may note (Fig. 2) that the helium core is a little smaller (by about $1 M_{\odot}$) and carbon abundance somewhat larger (by about a factor of 2) than reported by Woosley and Weaver 1982b.

Thielemann: The peak in the abundance curve you and Weaver published (Woosley and Weaver 1982b) contains carbon burning products while the minimum contains oxygen burning products. The new $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate (Kettner *et al* 1982), which is enhanced by a factor of 3 to 5, will leave less carbon and more oxygen after helium burning. Since this changes the fuels for subsequent burning stages will your yield curve be flattened (i.e., improved) by using the new rate?

Woosley: As Willy Fowler has long reminded us, we must get the reaction rates right before we can trust the nucleosynthesis calculations. However, I do not expect the yields of *intermediate* mass nuclei to be grossly affected (I differ with you and Arnett here). These nuclei are produced by *explosive* oxygen burning and, as Arnett, Clayton and I discussed many years ago (1973), it is the peak *temperature* in the explosion which most sensitively determines its yield. That is, a carbon composition exposed to the same peak temperature (above $T_p \approx 3$) as an oxygen composition will give the same nucleosynthesis. Memory of the initial composition is lost. The explosion temperature is set by the pre-explosive density gradient and by the explosion energy of the supernova, both of which are relatively insensitive to the rate for $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$. The ratio of carbon to oxygen in the ejecta may, of course, change greatly.

Trautvetter: Since you mentioned ^{26}Al as an important candidate for γ -line astronomy, I would like to comment that our group has recently measured the cross section for $^{26}\text{Al}(p, \gamma)^{27}\text{Si}$ which could eventually destroy freshly produced ^{26}Al . We found, in the energy range $0.27 \leq E_p \leq 1.8$ MeV, five resonances which are all very weak indicating that ^{26}Al can survive H-burning.

Woosley: That is very interesting, especially for ^{26}Al production in novae. Having done the difficult task of preparing an ^{26}Al target you should now measure the (n,p) cross section

since that is the principal destruction mechanism in explosive neon burning which dominates ^{26}Al production in supernovae (Woosley and Weaver 1980).

Renzi: I have 3 short questions: 1) What was the *surface* N/O ratio in the $25 M_{\odot}$ star at the time of its explosion? 2) Where is the ^{17}O produced? and 3) Has neon production in the *new model changed substantially?* The neon production you obtained in earlier models was quite different from Arnett (1978).

Woosley: The surface N/O ratio is close to unity (actually 4:5; see Fig. 2). The species ^{17}O is produced by hydrogen shell burning by the CNO tri-cycle. Neon production has not changed substantially. It is still large.

Renzi: Iben and Truran (1978) have shown that massive AGB stars (if they exist) may make large amounts of ^{22}Ne which, in this case, is mostly primary. Anomalies of ^{22}Ne could then be incorporated into grains forming around such AGB stars.

Woosley: Perhaps, but it might be difficult to incorporate ^{22}Ne , a noble gas, into stellar grains. There exist in the solar system components of neon in meteorites (Ne E) that are almost pure ^{22}Ne . A ^{22}Na carrier which decays after chemical incorporation seems more likely.

Bond: Could you comment on your work with Bodenheimer concerning rotation and oxygen burning driven ejection in massive stars? This is related to the question of how to get Cygnus X-1 black holes with explosions.

Woosley: That work is now published (Bodenheimer and Woosley 1983). The major uncertainty is our treatment of the inner boundary condition which must act, at least partly, to inhibit the accretion flow. We are encouraged that supernova remnants have been observed that do exhibit toroidal symmetry.

Nomoto: What is the propagation velocity of the deflagration wave in your Type I models?

Woosley: It varies, but typically $\sim 2000 \text{ km s}^{-1}$, or about 1/3 the speed of sound.

Nomoto: I have also calculated the model of a single detonation leaving a white dwarf remnant behind. Such events occur in a relatively small region of parameter space (i.e., accretion rate vs white dwarf mass) and might therefore be expected to be relatively rare.

Woosley: Your calculations may have underestimated the probability of leaving a white dwarf behind because they do not account for the transfer, by hydrodynamical means, of energy in the central portions of the white dwarf to the kinetic energy of ejecta. The total energy of the white dwarf core stripped of its helium (now iron) envelope may be zero, or even positive, and still leave a remnant because excess energy goes into accelerating a portion of the outer layers to high velocity. This happened, in fact, in Model 2 which I believe according to your phase diagram would not have been expected to leave a remnant. Still the parameter space may be restricted. I agree.

Braun: If it is indeed the case that the SNI light curve shape is relatively insensitive to the details of the model, we may have to wait for a more complete sample of SNI spectra before demanding that there be a unique class of progenitors.

Woosley: I certainly agree we need more spectral data, particularly at late times, but Dave Branch tells me that many spectra have been taken near peak light and they all fit one another like gloves. Perhaps it is only the late time spectrum (which is all that Axelrod is presently capable of modeling) that is so discriminatory.

Rayet: What would be the physical reason why Nomoto and Hillebrandt claim the possibility of an r-process site in their $9.6 M_{\odot}$ explosion while you do not mention it for your $10 M_{\odot}$ model? Is it related to the steep entropy increase during explosion quoted by Nomoto?

Woosley: Evolutionary endpoints vary rapidly in the mass range 9 to $10 M_{\odot}$. Our $10 M_{\odot}$ star underwent an ordinary core collapse following silicon core depletion. Nomoto's $9.6 M_{\odot}$ model, if my memory serves me correctly, collapsed on electron capture prior to oxygen depletion. The smaller core mass and energy input from nuclear burning during the collapse combined to produce an energetic explosion. I am not surprised that they get production of large amounts of neutron-rich isotopes in such a powerful explosion. In fact, they may find it far too much of a good thing. That is, *overproduction* of neutron-rich isotopes may be a problem.

LIST OF REFERENCES

- Arnett, W. D. 1979, *Ap. J. Lettr.*, **230**, L37.
- . 1980, *Ann. N. Y. Acad. Sci.*, **336**, 366.
- Arnett, W. D., Truran, J. W., and Woosley, S. E. 1971, *Ap. J.*, **165**, 87.
- Appenzeller, I., and Fricke, K. J. 1972, *Astron. and Ap.*, **21**, 285.
- Appenzeller, I., and Tscharnuter, W. 1973, *Astron. and Ap.*, **25**, 125.
- Axelrod, T. S. 1980a, PhD thesis, Univ. California at Santa Cruz and Lawrence Livermore Laboratory Report UCRL-52994.
- . 1980b, in *Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p. 80.
- . 1981, Lawrence Livermore Laboratory Report UCRL-86350 and in preparation for *Ap. J.*.
- Barkat, Z., Rakavy, G., and Sack, N. 1967, *Phys. Rev. Lettr.*, **18**, 379.
- Bessel, M. S., and Norris, J. 1981, *IAU Colloq. No. 86: Astrophysical Parameters for Globular Clusters*, ed. A. G. D. Philip and D. S. Hayes, (L. Davis Press: Schenectady), 137.
- Bodenheimer, P. B., and Woosley, S. E. 1983, *Ap. J.*, **269**, 281.
- Borst, L. B. 1950, *Phys. Rev.*, **78**, 807.
- Bond, H. E. 1981 *Ap. J.*, **248**, 606.
- Bond, J. R., Arnett, W. D., and Carr, B. J. 1982, in *Supernovae: A Survey of Current Research*, ed. M. J. Rees and R. J. Stoneham, (D. Reidel: Dordrecht).
- . 1983, *Ap. J.*, in press.
- Bowers, R. L., and Wilson, J. R. 1982a, *Ap. J. Suppl.*, **50**, 115.
- . 1982b, *Ap. J.*, **263**, 366.
- Branch, D. 1980a, in *Supernovae Spectra*, ed. R. Meyerott and G. H. Gillespie, (Am. Inst. Phys.: New York), Proc. No. 63, p. 39.
- . 1980b, in *Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p. 66.
- . 1982, *Proc. XI Texas Symp. on Relativistic Ap.*, to be published by *Ann. N. Y. Acad. Sci.*
- Branch, D., Buta, R., Falk, S. W., McCall, M. L., Sutherland, P. G., Uomoto, A., Wheeler, J. C., and Wills, B. J. 1982, *Ap. J. Lettr.*, **252**, L61.
- Brown, G. E., Bethe, H. A., and Baym, G. 1982, *Nuclear Physics*, **A375**, 481.
- Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F. 1957, *Rev. Mod. Phys.*, **29**, 547.
- Butler, D., Dickens, R. J., and Epps, E. 1978, *Ap. J.*, **225**, 148.
- Cameron, A. G. W. 1973, *Spac. Sci. Rev.*, **15**, 121.
- Chevalier, R. A. 1981, *Ap. J.*, **246**, 267.
- Colgate, S. A., and McKee, C. 1969, *Ap. J.*, **157**, 623.
- Colgate, S. A., and Petschek, A. 1979, *Ap. J. Lettr.*, **236**, L115.
- Colgate, S. A., Petschek, A. G., and Kriese, J. T. 1980, *Ap. J. Lettr.*, **237**, L61.
- Cox, A. N., and Stewart, J. N. 1970a, *Ap. J. Suppl.*, **19**, 243.

- . 1970b, *Ap. J. Suppl.*, **10**, 261.
- Dicke, R. H., and Peebles, P. J. E. 1968, *Ap. J.*, **154**, 891.
- Epstein, R. 1979, *MNRAS*, **188**, 305.
- Ezer, D., and Cameron, A. G. W. 1971, *Ap. and Spac. Sci.*, **14**, 399.
- Falk, S. W., and Arnett, W. D. 1973, *Ap. J. Lettr.*, **180**, L65.
- Fowler, W. A. 1966, in *High Energy Astrophysics*, ed. L. Gratton, (Academic Press: New York), 313.
- Fricke, K. J. 1973, *Ap. J.*, **183**, 941.
- . 1974, *Ap. J.*, **189**, 535.
- Fujimoto, M. Y., and Taam, R. E. 1982, *Ap. J.*, **260**, 249.
- Fuller, G. M., Fowler, W. A., and Newman, M. J. 1982a, *Ap. J. Suppl.*, **48**, 279.
- . 1982b, *Ap. J.*, **252**, 715.
- Fuller, G. M., Woosley, S. E., and Weaver, T. A. 1982, *Bull. Am. Astron. Soc.*, **14**, 957.
- . 1983, in preparation for *Ap. J.*
- Hansen, C. J. 1966, PhD Thesis, Yale University.
- Hillebrandt, W. 1982a, *Astron. and Ap.*, **110**, L3.
- . 1982b, in *Supernovae: A Survey of Current Research*, ed. M. J. Ress and R. J. Stoneham, (D. Reidel: Dordrecht).
- . 1983, as presented at XI Texas Symposium on Relativistic Astrophysics, to be published by *Ann. N. Y. Acad. Sci.* preprint.
- Iben, I. 1963, *Ap. J.*, **138**, 1090.
- . 1978a, *Ap. J.*, **219**, 213.
- . 1978b, *Ap. J.*, **226**, 996.
- . 1982, *Ap. J.*, **253**, 248.
- Iben, I., and Tutukov, S. 1983, preprint. Univ. of Illinois.
- Kirshner, R. P., and Oke, J. B. 1975, *Ap. J.*, **200**, 574.
- Kirshner, R. P., Oke, J. B., Penston, M. V., and Searle, L. 1973, *Ap. J.*, **185**, 303.
- Maza, J., and van den Bergh, S. 1976, *Ap. J.*, **204**, 519.
- Mazurek, T. J. 1973, *Ap. and Spac. Sci.*, **23**, 365.
- McDonald, J. 1983, *Ap. J.*, **267**, 732.
- Meyerott, R. E. 1978, *Ap. J.*, **221**, 975.
- . 1980a, in *Supernovae Spectra*, ed. R. Meyerott and G. H. Gillespie, (Am. Inst. Phys.: New York), Proc. No. 63, p. 49.
- . 1980b, in *Type I Supernovae*, ed. J. C. Wheeler, (University of Texas), p. 72.
- Miyaji, S., Nomoto, K., Yokoi, K., and Sugimoto, D. 1980, *Pub. Astron. Soc. Japan*, **32**, 303.
- Muller E., and Arnett, W. D. 1982, *Ap. J. Lettr.*, **261**, L109.
- Nomoto, K. 1980a, in *Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p. 164.
- . 1980b, *Spac. Sci. Rev.*, **27**, 563.

- . 1981, in *IAU Symposium 93, Fundamental Problems in the Theory of Stellar Evolution*, ed. D. Sugimoto, D. Q. Lamb, and D. N. Schramm (Dordrecht: Reidel), p. 295.
- . 1982a, *Ap. J.*, **253**, 798.
- . 1982b, *Ap. J.*, **257**, 780.
- . 1983, *Max-Planck Inst. für Physik und Astrophysik Preprint MPA72*.
- Nomoto, K., and Sugimoto, D. 1977, *Publ. Astron. Soc. Japan*, **29**, 765.
- Norgaard, H., and Fricke, K. J. 1976, *Astron. and Ap.*, **49**, 337.
- Ober, W. 1981, Ph D Thesis, Universität zu Göttingen.
- Ober, W., El Eid, W., and Fricke, K. J. 1983, *Astron. and Ap.*, **119**, 61.
- Palla, F., Salpeter, E. E., and Stahler, S. W. 1983, *Ap. J.*, **271**, 632.
- Pankey, T. 1982, PhD Thesis, Howard University. *Diss. Abstr.*, **23**, 4.
- Papaloizou, J. C. B. 1973, *Mon. Not. R.A.S.*, **162**, 169.
- Sanders, R. H. 1970, *Ap. J.*, **162**, 791.
- Silk, J. 1977, *Ap. J.*, **211**, 638.
- Smarr, L., Wilson, J. R., Barton, R., and Bowers, R. 1981, *Ap. J.*, **246**, 515.
- Snedden, C., Lambert, D. L., and Whitaker, R. W. 1979, *Ap. J.*, **234**, 964.
- Starrfield, S. G., Sparks, W. M., and Truran, J. W. 1974, *Ap. J. Suppl.*, **28**, 247.
- Starrfield S. G., Truran, J. W., and Sparks W. M. 1981, *Ap. J. Lett.*, **243**, L27.
- Stothers, R., and Simon, 1970, *Ap. J.*, **160**, 1019.
- Sugimoto, D., and Nomoto, K. 1980, *Spac. Sci. Rev.*, **25**, 155.
- Taam, R. E. 1980a, *Ap. J.*, **237**, 142.
- . 1980b, *Ap. J.*, **242**, 749.
- Talbot, R. J. 1971, *Ap. J.*, **165**, 121.
- Trimble, V. 1982, *Rev. Mod. Phys.*, **54**, 1183.
- Wallace, R. K., and Woosley, S. E. 1981, *Ap. J. Suppl.*, **45**, 389.
- Wallace, R. K., Woosley, S. E., and Weaver, T. A. 1982, *Ap. J.*, **258**, 696.
- Weaver, T. A., Zimmerman, G. B., and Woosley, S. E. 1978, *Ap. J.*, **225**, 1921.
- Weaver, T. A., and Woosley, S. E. 1979, *Bull. Am. Astron. Soc.*, **11**, 727.
- . 1980a, *Ann. N. Y. Acad. Sci.*, **336**, 335.
- . 1980b, in *Supernovae Spectra*, ed. R. Meyerott and G. H. Cillespie, (Amer. Inst. Phys.: New York), Proceedings No. 63, p. 15.
- Weaver, T. A., Axelrod, T. S., and Woosley, S. E. 1980, in *Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p 113 (WAW).
- Weaver, T. A., Woosley, S. E., and Fuller, G. M. 1982, *Bull. Am. Astron. Soc.*, **14**, 957.
- . 1983, in *Numerical Astrophysics: In Honor of J. R. Wilson*, ed. R. Bowers et al, (Science Books Intern'l: Portola CA), in press (WWF).
- Wheeler, J. C. 1981, *Rept. Prog. Phys.*, **44**, 85.
- Wheeler, J. C., and Hansen, C. 1971, *Ap. and Spac. Sci.*, **11**, 373.
- Whelan, J., and Iben, I. 1973, *Ap. J.*, **186**, 1007.

- Wilson, J. R. 1983, in *Numerical Astrophysics: In Honor of J. R. Wilson*, ed. R. Bowers *et al*, (Science Books Intern'l: Portola CA), in press.
- Woosley, S. E. and Weaver, T. A. 1980, *Ap. J.*, **238**, 1017. ———. 1981, *Ann. N. Y. Acad. Sci.*, **375**, 357.
- . 1982a, in *Supernovae: A Survey of Current Research*, ed. M. J. Rees and R. J. Stoneham, (D. Reidel: Dordrecht), p. 79.
- . 1982b, in *Essays on Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm, (Cambridge Univ. Press), p. 377.
- Woosley, S. E., Weaver, T. A., and Taam, R. E. 1980, in *Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p. 96.
- Woosley, S. E., Arnett, W. D., and Clayton, D. D. 1973, *Ap. J. Suppl.*, **231**, 26.
- Woosley, S. E., Taam, R. E., and Weaver, T. A. 1983, in preparation for *Ap. J.* (WTW).

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government thereof, and shall not be used for advertising or product endorsement purposes.