SUPERNOVAE: PROGENITOR STARS AND MECHANISMS

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ABSTRACT

Type II supernovae probably arise predominantly in stars of 8-15 $M_\odot$ which leave neutron star remnants but accomplish little in the way of nucleosynthesis. Stars in the mass range $\sim$ 15-70 $M_\odot$ may either explode or collapse. Their evolution and final outcome, including their contribution to nucleosynthesis, may depend strongly on processes of mass loss. Type I supernovae probably involve a deflagrative explosion in a carbon-oxygen core surrounded by a distended helium envelope. The evolutionary origin of such a configuration is obscure.

INTRODUCTION

The purpose of this review is to give an overview of the present theory and basic observations which pertain to the question of which stars explode and why. The following presentations by Nomoto and Mazurek will go into more detail concerning specific models. The developments presented here are given in more detail in reviews by Sugimoto and Nomoto (1980) and by Wheeler (1981).

TYPE II SUPERNOVAE

The rates and kinematics (Tammann 1978; Maza and van den Bergh 1976) light curves (Falk and Arnett 1977; Chevalier 1976; Weaver and Woosley 1980) and spectra (Kirshner et al. 1973) of Type II supernovae (SN II) are all consistently understood in terms of the explosion of a normal massive star. The explosion takes place within an extended red-giant hydrogen envelope. Recent progress has been made toward refining the mass range in which SN II occur and determining the final evolution. Much work is currently being done to understand the explosion mechanism.

One way of setting the lower limit to the mass of stars which become SN II is to determine the mass below which stars leave white

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dwarf remnants, and die a quiet death. This can be done by counting the number of white dwarfs in young open clusters and assigning that number of stars to the main sequence above the cluster turnoff in accordance with the cluster mass function. This exercise has been redone recently by Romanishin and Angel (1980) with the result that all stars below $M \sim 8\ M_\odot$ seem to leave white dwarfs, and to not make supernovae. Koester and Weidemann (1980) study the observed mass distribution of white dwarfs and reach the same conclusion.

Recent theoretical developments strengthen the conviction that $8\ M_\odot$ represents the lower limit to supernovae for normal single star evolution. Although the result depends somewhat on the theory of convection, there has for some time been general agreement that the dividing line between stars which form degenerate carbon/oxygen cores and those which burn carbon in a non-degenerate manner is at $M \sim 8\ M_\odot$ (Sugimoto 1971; Paczyński 1970; Becker and Iben 1979). Work by Barkat and collaborators (Tuchman Sack and Barkat 1979) has given special significance to this dividing line. They find that as the stars with degenerate carbon/oxygen cores evolve and brighten, they become catastrophically pulsationally unstable and eject their envelopes, leaving the cores to cool into white dwarfs.

Thus the pulsational calculations say that all stars which develop carbon/oxygen cores eject their envelopes. Evolutionary calculations say that stars with $M \lesssim 8\ M_\odot$ form such cores and hence should eject their envelopes. These combined theoretical statements are in good accord with the observations that stars with $M \lesssim 8\ M_\odot$ indeed do eject their envelopes and leave white dwarfs. The steep mass function is such that if stars much above $8\ M_\odot$ also failed to explode there would be a difficulty in accounting for the rates of SN II. Stars much above $\sim 15\ M_\odot$ may not make SN II, as discussed below, so the range for the progenitors of most SN II is ~ 8-$15\ M_\odot$.

The evolution of stars in this mass range is very complex, involving semi-dynamical shell flashes and electron capture. Progress in exploring the final evolution in this mass range has recently been made by Nomoto and collaborators (see his contribution) and by Weaver and Woosley (1980; see also Woosley, Weaver, and Taam 1980). Although the details change very rapidly with mass there seems little question that electron captures and/or photodisintegration will cause the cores of these stars to collapse to form neutron stars.

The crucial question is then the mechanism by which the process of neutron star formation causes an explosion. A great deal of work is currently being done on this question. The realization that neutrinos would become degenerate and trapped in the collapsing core (Mazurek 1974; Sato 1975) led to the conclusion that the collapse would be nearly adiabatic and proceed to greater than nuclear densities before the equation of state would stiffen, halting the collapse (Mazurek 1977; Arnett 1977; Lamb et al. 1978; Bethe et al. 1979). In the basic one-dimensional calculations (see Mazurek herein) a cold homologous core of $\sim 0.7\ M_\odot$ forms and collapses to neutron star densities. The bounce of this core and subsequent infall generates an outward moving shock. Early calculations with parametrized equations of state (Van Riper and Arnett 1978; Lichtenstadt, Sack and Bludman 1980) indicated that with a proper choice of core mass near the limiting neutron star mass for a given equation of state the core bounce could give a shock which ejected the envelope with supernova-like energy $\sim 10^{51}$ ergs. Refinements have led to the shock petering out, partly due to the loss of energy in photodisintegrating the infalling material, although numerical problems can not be ruled out.

The outcome may depend on core mass. With their schematic equation of state Van Riper and Arnett found that for very large cores, $M \gtrsim 2.5\ M_\odot$, a hot core bounced and formed an explosion but later collapsed. In principle at least, a star could both explode and leave a black hole although in most cases the result is an explosion with a neutron star remnant, or total collapse with no explosion.

Addition of rotation may cause the core to halt collapse at lower densities (Tohline, Schombert and Bass 1980) and perhaps alter the dynamics appreciably. Convective overturn of the core initiated by rotational deformaties or by alteration of the composition by neutrino losses (Epstein 1979) may enhance the neutrino losses (Livio, Buchler and Colgate 1980) or promote PdV pumping of the core into the envelope (Colgate and Petschek 1980).

The masses and the evolution of the progenitor stars of SN II are being steadily refined. They probably come from 8-15 $M_\odot$ and leave neutron star remnants. There is little material between the collapsing core and the envelope in this mass range so the bulk of SN II can contribute only little to the synthesis of the heavy elements.

VERY MASSIVE STARS

The final stages of evolution of more massive stars $\sim$15-70 $M_\odot$ is more tractable than in somewhat lower masses and has been more thoroughly explored (e.g. Weaver, Woosley, and Zimmerman 1976; Sparks and Endal 1980). These stars form iron cores which collapse to make neutron stars because of photodisintegration of the iron. There are probably too few of these stars to contribute appreciably to the rate of SN II. Even if they explode many of these massive stars may not contribute to the observed rate of optical supernovae. The reason is that these stars are prone to strong mass loss on the main sequence and even late in the core helium burning, Wolf-Rayet, phase. This mass loss probably prevents the formation of an extended envelope. If the envelope has a radius appreciably less than 10^{13} cm the energy deposited by the shock of the explosion will be dissipated in adiabatic expansion before the envelope becomes thin enough to radiate. In such a case there is very little optical display.

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There is indirect evidence that many of these stars explode. Detailed calculations of the evolution, dynamics (assuming an explosion is triggered, e. g. by core bounce) and nucleosynthesis show that a solar distribution of basic elements is created if all stars in this mass range explode (Weaver and Woosley 1979).

This conclusion is important both for supernova theory and for nucleosynthesis so some of the caveats should be presented. Studies of the abundances in old field stars show that the oxygen abundance was high by a factor ~ 3 in the past compared to carbon and iron (Sneden et al. 1980) as if the oxygen were produced more rapidly in the past. This would not happen if the basic nucleosynthetic source of these elements were a fixed ensemble of stars as normally assumed in the theoretical calculations which match the present abundances. One possibility is that the mass distribution of stars is not constant but was weighted more heavily in the past to more massive stars which naturally produce an oxygen excess. Alternatively oxygen, carbon, and iron could have their source in disparate objects, for instance carbon in carbon stars and iron in Type I supernovae as discussed by Tinsley (1979). In this case, the reproduction of the solar distribution by the massive star calculations could be fortuitous.

Another problem is that stellar winds can strongly affect the yield of heavy elements from massive stars. Both main sequence winds (Chiosi and Caimmi 1979) and those during the helium burning Wolf-Rayet phase (Vanbeveren and Olson 1980) can serve to reduce the mass of the core compared to a constant mass star, and hence the ultimate yield. There are many uncertainties concerning the stellar evolution, mass function and birthrates; thus while there are encouraging results the conclusion that all these massive stars do explode in the manner envisaged remains unsure.

Two astronomical objects illustrate the possible divergent fates of massive stars. The supernova remnant Cassiopeia A clearly resulted from an explosion of a massive star which ejected freshly synthesized material, predominantly the products of explosive oxygen burning (Chevalier and Kirshner 1979). There was no optical outburst of the magnitude of a supernova (even the 6th magnitude star reported by Ashworth (1980) is an unsure association) which is consistent with the loss of the envelope to form the nitrogen-enhanced low velocity filaments (Lamb 1978). Thus Cas A could be the result of a typical exploding massive star. No neutron star is observed in Cas A in X-rays (Murray et al. 1980). This may be because the neutron star has cooled rapidly (Glen, and Sutherland 1980; Van Riper and Lamb 1980). Alternatively, the progenitor of Cas A may have been totally disrupted, perhaps by the oxygen deflagration which occurs in very massive stars ($M \gtrsim 70\ M_\odot$).

The second illustrative object is Cygnus X-1. If this X-ray source is a black hole of $M \sim 10\ M_\odot$ it probably represents the core of a star of $\sim 30\ M_\odot$ which lost its envelope in a stellar wind. If

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30 $M_\odot$ stars leave massive black holes, they can not at the same time be the major contributors to the synthesis of heavy elements as indicated by the nucleosynthesis calculations.

Some stars in the mass range 15-70 $M_\odot$ may explode, others may collapse totally depending on the mass and details of the final evolution. These stars may generate a significant portion of the heavy elements but they probably make little if any contribution to classical SN II.

TYPE I SUPERNOVAE

Type I supernovae (SN I) are more difficult to understand than SN II. They are hydrogen deficient and display the famous exponential decay which has defied explanation. The last year has seen a resurgence of interest in the idea that the exponential decay is produced by the radioactive decay sequence $^{56}Ni(6^d_.1,\gamma)\rightarrow{}^{56}Co(77^d,\gamma,e^+)\rightarrow{}^{56}Fe$. The principle impetus has been detailed calculations of the γ-ray and positron energy deposition by Colgate, Petschek, and Kreise (1980) and of the deposition and resulting late-time spectra by Axelrod (1980). These and many related ideas are contained in the proceedings of the Austin SN I Workshop (Wheeler 1980).

Colgate et al. argue that increasing transparency of the expanding envelope to the positrons from Co decay causes the modulation of the intrinsic 77^d half-life into the observed, more rapid decline. Their particular model ejects 1/4 $M_\odot$ of Ni and 1/4 $M_\odot$ of inert material and requires a rise time of $\sim 6^d$. This is less than one-half the observed rise time so more Ni and more total mass is probably required to fit the observations. The synthetic spectra of Axelrod also require more Ni to be ejected $\gtrsim .5\ M_\odot$. In Axelrod's model the positrons are all trapped by a putative magnetic field but a progressively larger fraction of the energy goes into the infrared at the expense of the optical. This picture seems to violate the observations that the IR flux drops more rapidly than the optical (Kirshner et al. 1973).

Another unresolved question concerns the nature of the initial peak. Models in which the peak and the exponential tail come solely from radioactive decay have not yet proven totally self-consistent. The model of Colgate et al. has too short a rise time. A model based on the same deposition theory by Chevalier (1980) ejects 1.4 $M_\odot$ to get the proper rise time and 1 $M_\odot$ of Ni to get the peak (nearly) bright enough but as a result produces too much light in the exponential tail. An alternative is to create most of the peak light with the energy of the initial shock. This requires a large envelope to avoid adiabatic losses and implies the progenitor is not a white dwarf despite the paucity of hydrogen.

The light curves and late-time spectra indicate SN I eject $\sim$ 1/2-1 $M_\odot$ of ^{56}Ni. This is very difficult to do in any model in which a neutron star forms and the Ni is produced by silicon burning in the explosion; only $\sim 0.1\ M_\odot$ of Ni can be produced this way. The only models which have been calculated which produce $\sim 1/2\ M_\odot$ of Ni proceed from a thermonuclear detonation or deflagration and completely disrupt the star leaving no neutron star. Relevant to this conclusion are the observations of historical remnants of SN I by the Einstein X-ray satellite. As for Cas A no neutron stars are observed in the remnants of Tycho's or Kepler's supernovae or SN 1006 (Helfand, Chanan and Novick 1980). Again the neutron stars may have cooled very quickly, but the observations are quite consistent with models which predict no neutron star at all.

The spectra at peak light show no H, Ni or Co (Branch 1980). This implies the existence of a blanketing envelope which is probably mostly He, perhaps enriched in Si, Ca and Fe. Furthermore the absorption lines are observed, even at late times, to have velocity $v > 8000$ km s^{-1}. This feature implies that the progenitor did not have a monotonically decreasing density gradient as would be expected for a white dwarf. If this were the case, the velocity of the material at the photosphere should decrease monotonically in time; there would be no cutoff at 8000 km s^{-1}. Rather this cutoff implies a non-monotonic density gradient as would obtain with a distended envelope which could be ejected as a shell. Whether such an envelope is necessary and whether it is large enough that some shock energy can be contributed to the peak remains to be seen.

The best one can currently say in terms of progenitors is what they are not. They are probably not degenerate He dwarfs because in order to generate enough Ni for the light curve and spectra the resulting velocity would be too high. They are not the result of rapid mass transfer onto a carbon/oxygen white dwarf because a hydrogen rich extended envelope would form. They are not due to moderate mass transfer onto a carbon/oxygen dwarf because despite the fascinating new calculations by Nomoto (1980) and Woosley, Weaver and Taam (1980) that such stars ignite an off-center double detonation wave in the degenerate helium shell, the result is complete burning to Ni with no He blanket remaining. They may result from slow accretion onto a carbon/oxygen dwarf ($\dot{M} \lesssim 4\times10^{-10}\ M_\odot$ yr) because such stars can burn carbon subsonically, and disrupt totally, shoving off an unburned He shell. Unfortunately that shell, once a part of the dwarf structure, will probably not satisfy the kinematic constraint of $v > 8000$ km s^{-1}. In any case the most successful binary dwarf model must be old, triggered as it is by slow mass transfer.

SN I are probably not the explosion of He cores produced by the loss of the envelope from a star of ~ 8-$10\ M_\odot$. These He stars could form distended helium envelopes but, as mentoned in the first section, such stars will develop collapsing cores and probably cannot eject sufficient Ni. In addition such stars may be required to concentrate in spiral arms whereas SN I are not observed to do so (Maza and van den Bergh 1976). In any case this picture for the origin of SN I requires them to be quite young.

An important lesson here is that to construct a model which can be either young or old by the twitch of a parameter is decidely non-trivial. Changing the age of a model, e.g. by changing $\dot{M}$ in the binary picture, qualitatively alters the nature of the model. This is in violation of the observation that SN I are a very homogeneous class particularly in terms of the early spectra which determine the composition and kinematics of the envelope.

To even discuss the age of SN I as a possible parameter is a relatively new proposition. Classically the association of SN I with elliptical galaxies has been interpreted in terms of old progenitor stars. Oemler and Tinsley (1979) have argued strongly, however, that SN I are connected with regions of recent star formation. The question of the age of SN I progenitors is thus an active one, and far from settled.

In a sense the current status of SN I complements that for SN II. For SN II the evolution is beginning to be relatively well understood although the actual explosion mechanism still defies proper explanation. For SN I, there is a growing feeling that the most plausible mechanism is a carbon deflagration in a degenerate core, itself buried in a partially, if not fully, distended helium envelope. The evolutionary origin of such a configuration is still obscure.

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DISCUSSION

Joss: In the old carbon-detonation scenario that you described, the degenerate cores of stars with masses in the range 4-8 $M_{\odot}$ ingnited carbon before the core mass reached the Chandrasekhar limit and before the stellar envelope was ejected. However, according to the new results that you reported, for stellar masses up to 8 $M_{\odot}$ the envelope becomes unstable and is ejected prior to core carbon ignition. Is there a physical reason for the apparent coincidence between the upper mass limits for carbon detonation and prior envelope ejection, or is this merely a conspiracy of nature?

Wheeler: As I understand Barkat the growing core mass sets the growing luminosity, which in turn determines the pulsational properties of the envelope. If his calculations are correct, there is a direct physical connection between the growing carbon core, the double burning shells and the ultimate ejection. Whatever the mass is below which degenerate carbon cores form, that is the mass below which envelope ejection occurs. The formation of a degenerate carbon core automatically forces the envelope ejection in Barkat's picture.

Sugimoto: Evolution of stars in the mass range 4-8 $M_{\odot}$ toward carbon deflagration is considered also to be the origin of carbon stars. If all of such stars lose their envelope by dynamical instability, the number of carbon stars should be significantly decreased. What do you think about this matter? I am asking this question, because the dynamical instability of the envelope should depend sensitively on the assumed value of the ratio of the convective mixing length to the scale height.

Wheeler: I cannot speak in too much detail concerning the calculations of Barkat et al. They are attempting to reproduce the observations of Mira variables with some success. The question of whether they can produce carbon stars depends on whether envelope ejection proceeds or follows any carbon enrichment by dredge-up. I am unsure what their calculations say on this point. They are now actively exploring the sensitivity of their results to the assumed mixing length.

Vanbeveren: I want to make a remark concerning the frequency of stars with masses larger than ~15 $M_{\odot}$ (corresponding to O-types). A set of 200 O-type stars has been extensively studied by P. Conti and collaborators; special attention was given to spectral types and luminosity classes. In a paper that will appear soon in A & A, I have tried to determine the IMF for O-type stars using the former set of 200 stars. Very surprisingly, this IMF goes like M^{-1} which predicts much more massive stars than have been thought in the past (IMF $\sim M^{-2}$ as proposed by Dr. Lequeux in 1979), thus enhancing nucleosynthesis yields from massive stars.

Wheeler: Certainly, the mass function of O-type stars is uncertain. I simply wanted to illustrate that the uncertainties are such that our present understanding does not require that massive iron-core stars carry the burden of galactic nucleosynthesis, despite the plausibility of the picture.

Tayler: In the process which may produce either a neutron star or a black hole, does the maximum mass of a neutron star play any crucial role or do cores, which could in principle become neutron stars, become black holes?

Wheeler: The initial suggestion was that the dividing line between neutron star formation and black hole formation was precisely at a core mass equal to the stability limit. Subsequent studies of the equation of state and dynamics suggest that this interpretation may have been somewhat simplistic.

Lamb: From the calculations of Van Riper and Arnett (1979), I would construct the diagram you have shown somewhat differently. At low values of the mass M_h of the homologous core (that part of the initial configuration that falls inward as one piece), there is a "dud". The rest of the star will then fall in, accrete onto the homologous core, and form a massive black hole. At values of M_h less than but close to M_{max}, the maximum mass of a stable zero temperature neutron star, there is a violent explosion and the formation of a neutron star. But at values of M_h slightly more than M_{max}, there is a violent explosion and the formation of a hot neutron star which is partially supported by thermal pressure. As this neutron star cools, it will become unstable and collapse to form a black hole. Thus one will have a two-stage formation process for the black hole, and its formation will be accompanied by a violent explosion. Finally, if $M_h >> M_{max}$, a black hole is formed without an explosion. I would like to emphasize that the case in which M_h is slightly greater than M_{max} may well be important in explaining the apparent lack of neutron stars in Cas A and other young supernova remnants indicated by the Einstein observations.

Wheeler: I believe the case you make is plausible. I may have oversimplified the behavior near the point of maximum energy. On the other hand, whether the two-stage process you described actually works will depend on the details of the dynamics. If the homologous core is near the mass limit, then the picture may be as you say. If, however, a smaller homologous core forms and the shock depends on the nature of the subsequent accretion, then the outcome does not depend on how near the core is to the mass limit, and your reasoning may not apply. I suppose a black hole and an explosion might have occured in Cas A, but I find that is an implausible explanation for the failure to detect a neutron star in SN 1006, Kepler or Tycho.