CORE COLLAPSE, BOUNCE AND SHOCK PROPAGATION

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Abstract. Recent developments in the physics input for iron core collapse models of type II supernovae are reviewed. The effect of these developments on collapse calculations is also discussed. The inner core collapses homologously, with little change in specific entropy, bounces in the neighborhood of nuclear density, and sets up an outward moving shock. In adiabatic models an explosion may result. The inclusion of neutrino effects may produce substantial shock damping. Current results indicate that core collapse, bounce and shock propagation does not produce an explosion when neutrino effects are included.

1. Introduction

Substantial improvements have been made during the past several years in our understanding of the physics input for iron core collapse models of type II supernovae. The most important of these involve neutrino processes and the nuclear equation of state, which we review, emphasizing their role during the subsequent shock propagation. Core collapse (involving typically the inner 1-2 $M_\odot$) occurs on a timescale small relative to that characteristic of the stellar mantle and envelope, and these outer regions may be omitted from consideration. Recent work on type I and II light curves, which do involve the mantle and envelope, are discussed in the review by Falk. Type I supernovae have recently been discussed by Sugimoto and Nomoto (1980) and in the paper by Nomoto (1980), and Canal (1980). Recent pre-core collapse configurations, which we use for our initial models, and the nucleosynthetic yield of a 15 $M_\odot$ and 25 $M_\odot$ model have been discussed by Weaver and Woosley (1980.

2. Neutrino Processes (Pre-Bounce)

The electron neutrinos ν_e, are currently believed to dominate during core collapse. Initially ν_e emission from electron capture is the most important. The electron capture processes are

$$e^- + A(N,Z) \rightarrow A^*(N+1,\ Z-1) + \nu_e \qquad (1a)$$

$$e^- + p \rightarrow n + \nu_e; \qquad (1b)$$

A* represents a nuclear excited state. The excitation energy (3-6 MeV

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per excited nucleus) is redistributed as internal energy of the stellar matter. For $\rho \lesssim 10^{10}$g/cm^3, (1a) dominates (1b) due to the small free proton abundance, but at higher densities (1b) becomes important. Recently Fuller (1980) has suggested that capture on heavy nuclei effectively turns off for $N \lesssim 40$ and $Z \lesssim 40$. The effect on collapse of a decreased capture rate is to increase the ratio of lepton to baryon number Y_L and the size of the homologous core (see below).

Pre-bounce entropy generation results primarily from nuclear de-excitation following electron capture (1a), neutrino bulk viscosity and direct neutrino losses (Bethe, Brown, Applegate and Lattimer 1979; Wilson 1980a, Arnett 1980). The first two processes increase the specific entropy s, but neutrino losses reduce it; the net change prior to bounce $\Delta S/k \lesssim 0.5$, where k is Boltzmann's constant.

For $\rho \lesssim 10^{12}$g/cm^3 ν_e coherent scattering on heavy nuclei

$$\nu_e + A \rightarrow \nu_e + A \qquad (2)$$

produces a ν_e mean free path λ which is smaller than the core radius r_c. This confines the neutrinos within the inner core, establishing a diffusion regime (Arnett 1980; Wilson 1980a). The outermost portion of this regime, where $\tau \quad \int_\infty^r \lambda^{-1}\, dr' \approx 2/3$ defines the neutrinosphere. Within the neutrinosphere electron scattering

$$e^- + \nu_e \rightarrow \nu_e + e^- \qquad (3)$$

and the emission and absorption on free nucleons thermalizes the neutrinos. For $\rho \gtrsim 10^{13}$g/cm^3 the neutrinos are best described by a chemical potential and a Fermi-Dirac distribution with the local electron temperature (Tubbs 1978, Arnett 1977).

As a result of the processes described above, the specific entropy of the core material increases by

$$\Delta S = \Delta S_{el.cap.} + \Delta S_{loss}. \qquad (4)$$

The first term on the right is the increase in S due to thermalization of nuclear excitation energy (1a) and neutrino bulk viscosity. The second term (which is negative) results from neutrino losses. The net change $\Delta S/k \sim 0.5$.

As the core collapses an homologous inner is formed whose mass is given roughly by the Chandrasekar mass formula

$$M_{HC} \lesssim 1.45\ (Y_e/.5)^2\ M_\odot. \qquad (5)$$

The mass of the homologous core is very sensitive to Y_e. For our standard model $M_{HC} \simeq .5\ M_\odot$. If we allow electron neutrinos to turn into mu and tau neutrinos then the additional phase space for leptons allows Y_e to drop from about .3 $M_\odot$ to .23 $M_\odot$ and M_{HC} falls to about .3 $M_\odot$. Recently Fuller has argued that in the density range 10^{10} to 10^{11}gm/cc electron capture on heavy nuclei is strongly inhibited since nuclei in this range probably have filled shells. This decreases the capture rate enough to raise the homologous core mass to about .6 $M_\odot$. The older calculations of Wilson (1980a) had both a lower capture rate and a nuclear model that had a greater difference (25%) of neutron and proton chemical potentials. This model gave an homologous core mass of .75 $M_\odot$. The size of the homologous core can be important for two reasons. First

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if the core bounces it is advantageous for the mass to be large since it pushes back on the infalling material and strengthens the outward bound shock wave. Secondly, for late time instabilities as discussed by Livio et.al. and Smarr et.al. (Livio, Buchler, Colgate 1979; Smarr, Wilson, Barton and Bowers 1980) the mass of the inner cold core is probably crucial.

3. Nuclear Equations of State

Collapse models published prior to 1980 incorporated a wide range of equations of state for the baryons (nuclei and nucleons) due to uncertainties in the underlying nuclear physics input. This resulted in models which bounced at densities from 10^{13}g/cm^3 to 10^{15}g/cm^3. Recent refinements in the nuclear physics input have reduced the uncertainties.

Nuclei possess extensive internal degrees of freedom which correspond thermodynamically to a large nuclear heat capacity (Bethe, Brown, Applegate and Lattimer 1979). Consequently for $T \lesssim 8$ MeV thermal energy goes primarily into nuclear internal excitation rather than dissociation. The baryons in the core remain essentially inside nuclei up to $\rho_T \approx (1/3)\rho_n$ 2.5×10^{14}g/cm when they undergo a phase transition to uniform nuclear matter. For $\rho < \rho_T$ the pressure is due primarily to relativistic electrons and the adiabatic index $\gamma \approx 4/3$. Nuclear dissociation reduces γ below $4/3$ until it is complete, at which point the pressure is due to free (non-relativistic) nucleons and γ rises rapidly. Collapse continues through the region of the phase transition, and bounce occurs on the nuclear matter portion of the equation of state at $\rho_b \approx 2\rho_n$ (Van Riper 1980; Wilson 1980a).

Figure 1 shows schematically how the baryonic composition varies in the ρ,T plane. Figure 2 shows the schematic dependence of p and γ on the density. Recent equations of state indicate that ρ_T is in the range 7×10^{13}g/cm^3 to 1×10^{14}g/cm^3, and that the width of the phase transition $\Delta\rho \approx 3 \times 10^{13}$g/cm^3. The critical temperature ($\Delta\rho=0$) is about 10 MeV (Lamb, Lattimer, Pethick and Ravenhall 1978; 1980; Wilson 1980b).

The value of P for $\rho > \rho_T + \Delta\rho$ is, even at T=0, still uncertain by as much as a factor of four. (See for example Arnett and Bowers 1977).

Because ρ_b is just above nuclear density the nuclear and nucleon equation of state may have a significant effect on the outcome of iron core collapse. The qualitative features of the baryonic equation of state appear to be reasonably well established, but the quantitative details are still uncertain. The latter are probably important primarily for models which are on the verge of exploding.

4. Recent Collapse Models

Iron core collapse appears to continue up to densities of one to two times of ρ_n. The formation of an homologous core prior to bounce is well established. At bounce, an overpressure forms outside the homologous core and steepens into a shock as it propagates outward. The homologous core remains unshocked, and its final specific entropy

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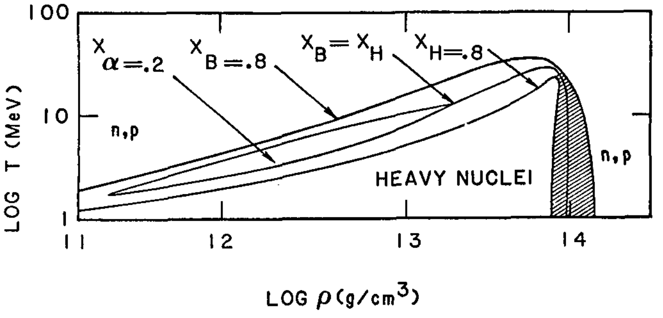

Figure 1. Composition in ρ,T plane (schematic). The striped region is the density interval in which the phase transition from heavy nuclei (A) to nucleons (n,p) occurs. Also shown are lines along which the mass fraction of heavy nuclei $X_H = .8$, and free baryons $X_B = .8$, and helium $X_A + .15$. Nuclear photodissociation occurs across these lines. The arrow on the ρ axis locates ρ_b.

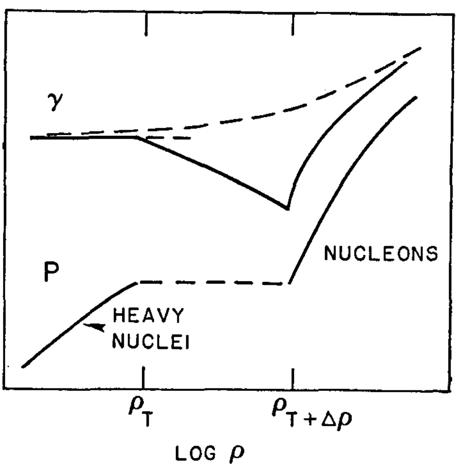

Figure 2. Pressure and $\gamma \equiv 1 + p/\rho\varepsilon$ vs. density (schematic) for low temperatures. The dashed curve for γ represents the EOS used by Wilson (1980b).

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is comparable to the pre-collapse value (section 2). At bounce the core overshoots its quasi-equilibrium configuration (a hot neutron star), rebounds and then settles down to a quasi-static state. The nuclear EOS used by Wilson (1980a) resulted in substantial core overshoot and rebound (a factor of two in r, and eight in density). Table 1 summarizes our recent collapse results. In the last three models, there is very little core overshoot or rebound. SM(1980) is our current standard calculation.

Table 1

Model	$M_{HC}/M_{\odot}$	Explosion
Wilson (1980a)	0.75	Marginal
SB (1980)	0.5	None
Suppressed E.C.	0.6	None
ν Oscillations	0.3	None

The "suppressed E.C." model has electron capture (1a), via heavy nuclei, turned off for $\rho > 3\text{x}10^{10}$g/cm^3 as suggested by Fuller (Section 2).

Idealized equations of state have been used within the framework of adiabatic (no neutrino) models to show that if the shocked region outside the homologous core is sufficiently stiff, then an explosion can result even when the bounce of the homologous core is weak (Sack and Lichtenstadt 1979; Lichtenstadt, Sack and Bludman 1980). Van Riper has also done hydrodynamic calculations with a tabular fit to the Lamb et.al. 1978 equation of state and found mass ejection with only a small amplitude bounce of the homologous core.

We will now discuss in a little more detail the shock wave formed after core bounce.

5. Shock Propagation

The strength of a shock is conventionally expressed in terms of the Mach number. In our most recent collapse models there is little core rebound, and the Mach number 1 ms after bounce is 2.7. This, however, is not necessarily sufficient to lead to mass ejection. The shock must propagate through about 0.5 $M_{\odot}$ of heavy nuclei and break through the neutrinosphere with enough energy to eject the overlying mantle. Just after bounce we find shock velocities (relative to the infalling matter) of order $5\text{x}10^9$ (similar results have been obtained by Wilson 1980); and Van Riper 1980). The matter ahead of the shock is at temperatures T $\lesssim$ MeV, while the shocked matter is heated to values in excess of 10 MeV near the core. Heavy nuclei dissociate for T $\lesssim$ 8 MeV, which correspondsto a loss of about $3\text{x}10^9$cm/s in shock velocity. In reaching the neutrinosphere the shock has dissociated the nuclei interior to it, and has slowed to about $3x10^9$cm/s in shock velocity (the corresponding Mach number is still about 3).

Interior to the shock, the temperature is high enough for ν_e, ν_μ and ν_τ pair production to occur as well as ν_e emission and absorption on free nucleons. The energy release rate due to pairs goes as T^9 (Dicus 1972; Bethe, Applegate and Brown 1980) for matter which is not too degenerate. Thus, if the shock velocity is large there will be significant heating and the muon and tau neutrino losses become large. The ν_e processes are strongly inhibited due to neutrino degeneracy (see section 2), and once ν_μ and ν_τ build up they also become degenerate. However, when the shock reaches the neutrinosphere, the material becomes neutrino transparent and significant damping of the shock occurs. For example, the shock luminosity, defined as the kinetic energy flux carried by the shock

$$L_s \approx 1/2\rho_s v_s^3 \, 4\pi r_s^2, \qquad (4)$$

where v_s is the shock velocity, r_s its location and ρ_s the density just behind the shock, is of order $8x10^{53}$ergs/s at 1.1 ms after bounce in our recent models. The change in neutrino luminosity $\Delta L_\nu \approx$ across the shock is of order $7x10^{53}$erg/s. Roughly 10 ms later, the shock has become an accretion shock within a distance $r \approx \lambda$ outside the neutrinosphere. At this time $L_s \approx 8x10^{52}$erg/s and $\Delta L_\nu \approx 7x10^{52}$erg/s. Although the initial shock is quite strong, neutrino damping appears to weaken it near the neutrinosphere to such an extent that no explosion occurs. We note that Van Riper, using the tabular EOS of Lamb, Lattimer, Pethick and Ravenhall, obtains an explosion from adiabatic collapse, but does not when ν_e emission and absorption are included (Van Riper 1980).

6. Conclusions

Assuming that current nuclear equations of state are sufficiently accurate for hydrodynamic purposes, and that the remaining input physics has been modeled with reasonable accuracy, we find that core collapse and bounce near nuclear density is unlikely to produce a supernova explosion. Some stars do explode; whether or not some as yet unidentified physics input can turn one dimensional collapse into explosions, or whether some mechanism other than the one reviewed above occurs, is not known.

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DISCUSSION

KLEIN: I take it that you have done a fully time-dependent treatment of neutrino transport. Are you including all orders of v/c?

BOWERS: We do not include v^2/c^2 effects, mainly because I think they are very small. We do not include v/c terms consistently. If you worry about v^2/c^2 terms, there are kinematic terms, special relativistic terms, and also gravitational redshift terms that are comparable, which come about because you have a stationary core emitting photons onto something moving towards you with a difference of gravitational potential.

KLEIN: If you are doing fully time-dependent transport and you leave out v/c terms, there is some internal inconsistency in the equations. You have to be very careful in what you exclude and what you include in v/c.

BOWERS: The answer is that some of the v/c terms are in there. I couldn't respond fully in the time available.

KLEIN: Do you use a Wilson standard flux limiter form, and have you tried experimenting with this?

BOWERS: We have tried a number of different flux limiters. So far, we have not found any real sensitivity to the exact form of the flux limiter.

YOUNG: What is the time scale for all of these events?

BOWERS: I should emphasize that the entire time scale for collapse to bounce is about 0.2 second. The time for the shock to reach the mantle is perhaps 0.3-0.4 second. The outermost ten percent of the mass is not going anywhere. It is just sitting there as the core does its thing.

YOUNG: Do you have some feeling for what the fraction of momentum transport of neutrinos relative to photons is?

BOWERS: The photons are not really followed in the detail that the neutrinos are. The energy of the photons is many orders of magnitude below that of the neutrinos.

WINKLER: How much energy is carried by the neutrinos? Is that the important point?

BOWERS: I can summarize the important point in a very simple, qualitative way. In all of the work that we have done, we seem to find that a strong shock is what you want in order to get an explosion. You might say that the stronger the shock, the better off you are, but the shock heats the material; hot material produces neutrinos, electron captures, emission and absorption of free nucleons, and pair processes. Pair process energy release rates go like the ninth power of the temperature. The neutrinos dissipate the shock, and it just does not get much beyond the neutrinosphere.

A. COX: I would like to ask you about your initial condition. I gather that you got yourself in a situation when it is unstable. What is the mechanism for this?

BOWERS: Tom Weaver and Stan Woosley have what I believe is the state of the art stellar evolution code. They start at the main sequence and follow the star in its evolution. The inner core structure at the point where it is becoming dynamically unstable is used as our starting model.

A. COX: What is the first instability mechanism?

BOWERS: As I understand it, it is electron captures.

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