PORTIONS OF THIS DOCUMENT ARE ILLEGIBLE

BLANK PAGE

LA-UR-7[illegible]-2030

TITLE: SUPERNOVA MASS EJECTION AND CORE HYDRODYNAMICS

AUTHOR(S): Stirling A. Colgate

MASTER

SUBMITTED TO: Presented at a [illegible] on Supernovae and Supernova [illegible] Erice, Sicily, Italy May 14-23, 19[illegible]

[illegible]

PORTIONS OF THIS REPORT ARE ILLEGIBLE.
[illegible] from the best available
[illegible] the broadest possible avail-

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

SUPERNOVA MASS EJECTION AND CORE HYDRODYNAMICS

by

Stirling A. Colgate

Los Alamos Scientific Laboratory
University of California
P.O. Box 1663
Los Alamos, NM 87545

and

New Mexico Institute of Mining and Technology
Socorro, NM 87801

2

ABSTRACT

We discuss the simplifications that have emerged in the descriptions of stellar unstable collapse to a neutron star. The neutral current weak interaction leads to almost complete neutrino trapping in the collapse and to an electron fraction $Y_e \approx 0.35$ in equilibrium with trapped electron neutrinos and "iron" nuclei. A soft equation of state ($\gamma \approx 1.30$) leads to collapse, and bounce occurs on a hard core, $\gamma \approx 2.5$, at nuclear densities. Neutrino emission is predicted from a photosphere at $r \approx 2 \times 10^7$ cm and $E_\nu \approx 10$ MeV. The ejection of matter by an elastic core bounce and a subsequent escaping shock is marginal at best and indeed may not be predicted for accurate values of the equation of state. Several factors could improve this: Additional neutrino types and, or, neutrino mixing with (transformation to) a noninteracting state are rejected as too speculative. Anisotropy per se - i.e., large critical stress rotation and, or, large magnetic fields (10^{17} Gauss) are rejected on the basis of observations. A new

concept of Rayleigh-Taylor driven core instabilities based upon a suggestion of core convective mixing (R. Epstein, 1978) is invoked to predict an increased mass ejection either (1) due to an increased flux and energy of neutrinos at second bounce time (several milliseconds after first bounce) and, or, (2) the rapid 0.1 to 0.4 second formation of a more energetically bound neutron star. The instability is caused by highly neutronized external matter from which neutrinos have escaped being supported by (accelerated by) lighter (higher pressure) matter of the lepton trapped core. The first case is just an extremum of the second and depends upon the speed of convective overturn of the core. An initial anisotropy of 10^{-2} to 10^{-3} should lead to adequately rapid (several milliseconds) overturn following several (2 to 4) bounces. Finally, subsequent to the overturn with or without a strong ejection shock, a weak ejection shock will allow an accretion shock to form on the "cold" neutron star core due to the reimplosion or rarefaction wave in the weakly ejected matter. The accretion shock forms at low enough mass accumulation rate, $\frac{1}{2} M_{\odot}$ sec^{-1}, such that a black body neutrino flux can escape from the shock front, (kT ~ 10 MeV, $\langle E_{\nu} \rangle \simeq 30$ MeV). This strongly augments the weaker bounce ejection shock by heating the external matter in the mantle by electron neutrino scattering, (~ 10^{52} ergs) causing adequate mass ejection.

SUPERNOVA MASS EJECTION AND CORE HYDRODYNAMICS

The creation of a supernova explosion is still a puzzle. The current consensus is summarized in the cooperative paper by Bruenn, Arnett, and Schramm (1975). Their paper brings together the extensive calculations of Imshennik and Nadyozhin (1973); Wilson (1971, 1973, 1976); Nadyozhin (1976); Sato (1975); and Mazurek (1975, 1977); as well as those of the authors. The conclusion is that regardless of details of neutrino transport and equation of state, neutrinos are trapped in the initial dynamical collapse and a neutrino driven mass ejection is not likely to occur. This conclusion is recently most strongly reinforced in the extensive calculations of Arnett (1977) and Tubbs (1977). In these calculations even with the most optimistic conditions of collapse, roughly ½ the neutrinos are trapped. Furthermore neutrino emission only weakens the bounce-created mass ejection. This conclusion is not the same for Wilson's 1977 recent calculations where mass ejection occurs due to the first bounce of the core and possible assistance is added by the partial neutrino emission at second bounce.

The earliest view of the dynamical collapse to a neutron star maintained that neutrinos were emitted and escaped as fast as they were formed by electron capture (Colgate and White 1966, CW). Hence, once started at high enough density, the electron capture reaction $p + e^- \rightarrow n + \nu_e$ would proceed as fast as it was energetically allowed. This occurred at $\rho > 2 \times 10^{11}$ g cm^{-3} where the electron Fermi level of normal matter equals the n - p mass difference in bound helium nuclei. The completion of the electron capture reaction leads to a neutron star.

What now prevents this from happening is the trapping of the neutrinos by the larger cross section of neutrino neutral current coherent scattering from nuclei (Weinberg 1967; Salam 1968; Weinberg 1974) which increases the transport cross section by an order of magnitude. If the neutrinos are trapped, the pressure in the collapsing matter follows a different history. Since there is no longer any stress or heating from neutrino transport, only sound waves can transport the binding energy of the newly formed core to the mantle and cause mass ejection. Furthermore, the binding energy of the core will be considerably less than what it would be if composed of neutron matter.

Equation of State

One simplistic prior view of the behavior of matter with trapped neutrinos was that the trapped degenerate neutrino Fermi level would inhibit electron capture and one would have essentially the same pressure as without neutrinos, and therefore a relatively weak implosion. The complexities of the equation of state have recently been greatly simplified by Bethe (1978), who points out that the original paper (Baym, Bethe, and Pethick

1971, BBP) as extended by Barkat, Buchler, and Ingber (1972) summarized by Canuto (1975) and further extended by Lattimer and Ravenhall (1978). implies the following simplified equation of state for trapped neutrino matter. When the chemical potentials of the nuclei, electrons, and neutrinos are balanced, then the number fraction Y_e (relative to nucleon number) of electrons reduces to $\simeq 0.35$ from an original preimplosion (White Dwarf) value of $Y_e \simeq 0.48$. The final value of 0.35 is large enough (anything greater than 0.2 will suffice) that the nuclear matter can be approximated by iron nuclei within a very wide range of entropy (finite temperature) because of the nuclear excited state specific heat. Therefore the pressure is determined entirely by the degenerate leptons ($\gamma = 4/3$). The ratio of pressure of normal matter ($\gamma = 4/3$) to that of neutrino trapped matter becomes $(.48)^{4/3}/[(.35)^{4/3} + (.13)^{4/3}] = 1.21$. The pressure defect between compressing normal matter along a 4/3 adiabat (neutral support against gravity) and lepton conserved matter is then roughly 20%. Partial neutrino loss during collapse ($Y_e \simeq 0.25$) might increase this to a maximum of 50%; that is, if a fraction of the core corresponding to a limiting Chandrasekar mass of 1.4 $M_\odot$ collapses along the neutral energy difference, $\gamma = 4/3$ adiabat, then the actual pressure will fall to ~ 4/5 of the pressure support value. This pressure defect adiabat will continue until nuclear density is reached ($\rho \sim 4 \times 10^{14}$ g cm^{-3}) and then, as BBP have pointed out, the pressure will increase as $\gamma \sim 2.5$. This is a very stiff equation of state and the pressure will increase rapidly as a function of density until the core bounces. This occurs at a density only slightly larger, $\simeq 5 \times 10^{14}$ g cm^{-3} where, for bounce, the pressure overshoots the neutral support pressure by the inverse of the pressure defect. The specific binding energy of the trapped lepton core is of the order of the pressure defect, i.e, 20 to 50 MeV/nucleon. If the bounce were entirely elastic, the kinetic energy in the bouncing core would be just this binding energy because there is no other degree of freedom available. The higher binding energy of a neutron star is reached by the release of neutrinos so that only part of the binding energy of the final neutron star will be available to elastic oscillation. In this sense, neutrino emission tends to damp the elastic bounce and a mass ejection which is dependent purely upon bounce may be hindered rather than helped by neutrino emission although the detailed competition between increasing binding energy and neutrino energy loss damping is uncertain.

Mass Ejection by Core Bounce

Ken Van Riper (1977) has made an extensive analysis of various core collapses and the effect of varying γ's on the strength of the reflected shock wave due to bounce. For the typical equation of state parameters $\gamma_{min} \simeq 1.32$, $2 \times 10^{11} \leq \rho \leq 2 \times 10^{13}$ and $\gamma_{max} \sim 1.35$, $2 \times 10^{13} \leq \rho \leq 2.5 \times 10^{14}$, and $\gamma_{nuclear} = 1.75$ $\rho \geq 2.5 \times 10^{14}$ the mass ejected was estimated to be $\simeq 0.01$ $M_\odot$ and the total ejected energy $\sim 5 \times 10^{49}$ ergs. This is too small to describe a supernova. Only when the final γ is significantly less than the stiff nuclear value ($\gamma_{bounce} \lesssim 1.4$ compared to $\gamma_{max} \sim 2.5$) does a reasonable mass ejection ~ 0.05 $M_\odot$ and ejection energy $\sim 10^{51}$ ergs occur, Fig. 1. This softer bounce on a lower value of γ can be created by general relativistic terms with the stiff $\gamma \sim 2.5$, but it is critically mass dependent. The sound wave of an adiabatic bounce turns first into a weak and then later a strong shock wave as it climbs out of the imploding matter. The question of "climb-out" is a subtle one. As Van Riper has shown the shock is swallowed by the imploding matter field if $\gamma \lesssim 1.27$. This result was demonstrated earlier in the initial calculations of CW where the the original supernova explanation of Burbidge, Burbidge, Fowler, and Hoyle (1957) of iron thermal decomposition implosion and core bounce was tested numerically with an artificial hard core ($\gamma = 2$). The shock barely climbed out in the soft ($\gamma \simeq 1.3$) imploding matter field and an inadequate mass ejection $\simeq .01$ $M_\odot$ resulted (Fig. 2). Wilson's (1977) calculations (Fig. 3) and Van Riper's more recently (1977) parameterization of bounce and Arnett and Van Riper's calculations with neutrinos all demonstrate that SN mass ejection is indeed possible due to core bounce, but that its existence is extremely sensitive to details of the equation of state and neutrino transport. Finally general

Fig. 1. Van Riper's calculations for γ_{min} = 1.33 and γ_{max} = 1.38. Note the strong reflected shock.

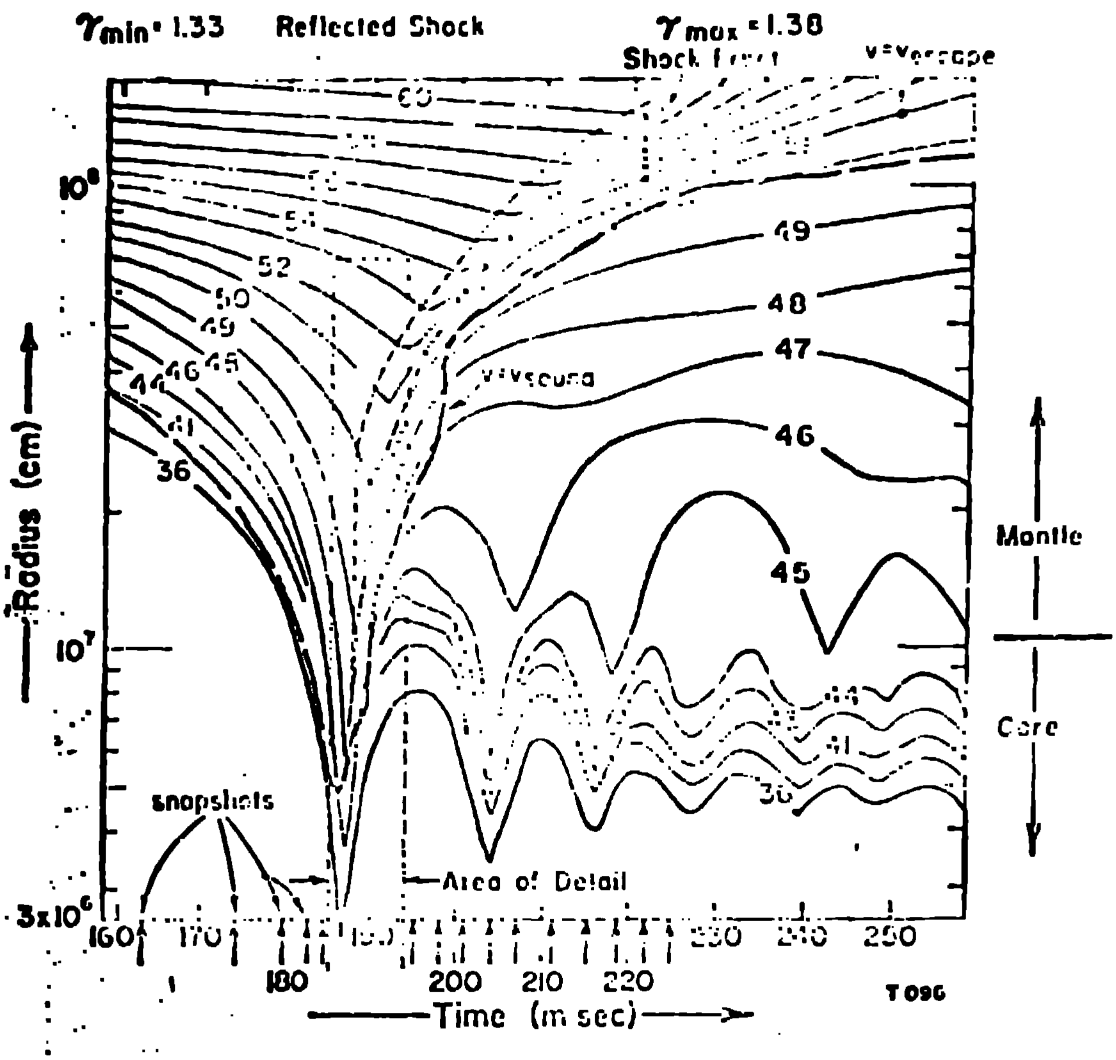

Fig. 1. Van Riper's calculations for γ_{min} = 1.33 and γ_{max} = 1.38. Note the strong reflected shock, but the curvature of the $v = v_{escape}$; Lagrange coordinate is indeterminate on this time scale.

relativity is no longer ignorable in such a delicately balanced process. This is an unsatisfactory state of affairs for such important, dramatic, and ubiquitous phenomena as supernovae.

Possible Cures

The original scenario of CW was that a collapse to a cold neutron star took place immediately. The initial specific binding

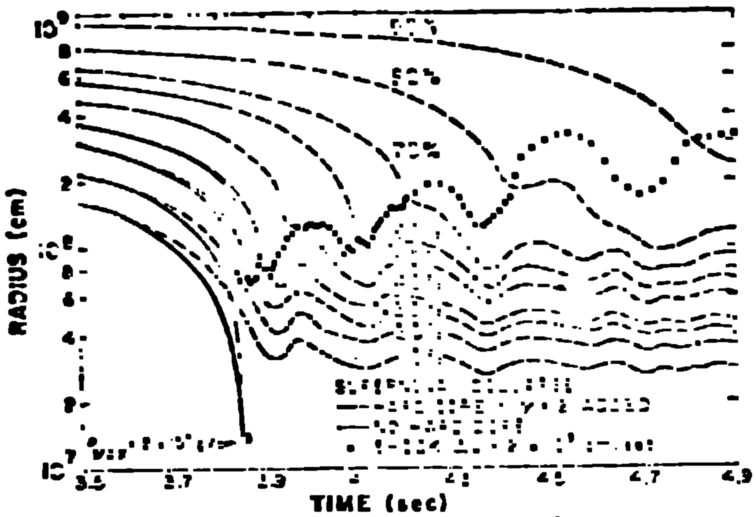

Fig. 2. Colgate and White calculations of a bounce and reflected shock from a fictious $\gamma = 2$ hard core. Since the effective γ of the imploding matter was $\leq 4/3$, $\gamma_{min} \cong 1.30$, the shock barely climbs out of the imploding matter field and does not eject significant matter.

energy of the small mass core was also small and as additional matter imploded onto this core the increasing binding energy of the added mass was released as heat in a (nearly) standing accretion shock on the neutron star surface. The radiation properties of this shock were peculiar - black body neutrino radiation where the lower energy neutrinos had a larger mean free path (different from the usual case with photons), and the shock-heated matter radiated most of its energy through the accreting matter depositing a small fraction in the mantle sufficient to heat it to the point of explosion and mass ejection. (The neutrino momentum stress was not invoked because of the obvious limitation of the Eddington limit.) When neutrinos are trapped, such a heat transport cannot take place. The consequence is that if there is no neutrino transport, only sound waves - or shock waves - can redistribute the binding energy.

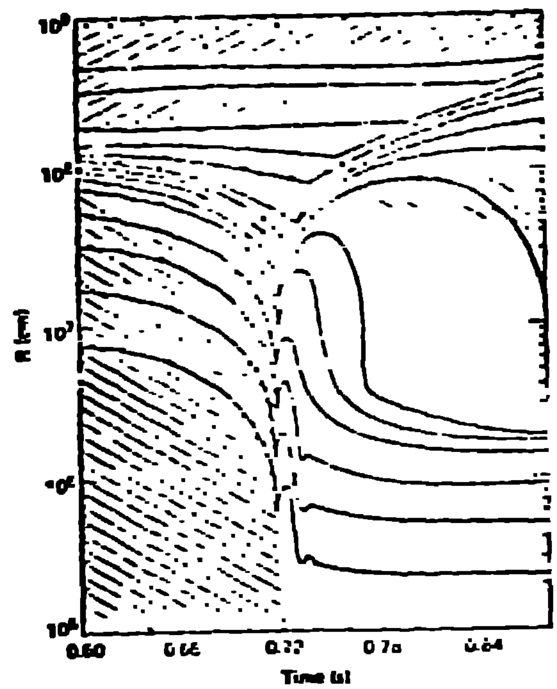

Fig. 3. Wilson's calculation of core collapse and mass ejection by both bounce and the neutrino flux. Note the second bounce transition to a collapsed core - partially neutronized and the one reimplosion trajectory. The cross-hatched region is predominantly Si; the right-slashed region is cargon, left-slashed region is Fe; and the plain area is decomposed Fe. i.e., He, n, and p.

There are several possible ways to recover the original satisfactory concept of thermal transport of the neutron star binding energy to lower gravitational bound mantle matter.

1. Invoke different neutrino properties such as helicity changing or mixing interactions due to finite mass interaction with magnetic or gravitational fields. Presumably if such could happen, a neutrino could spend a fraction of its lifetime in a noninteracting state and then return to a an interacting one. Lifetimes would have to be of the order of r/c $\cong 10^{-3}$ to 10^{-5} sec to prevent trapping.

2. Utilize [illegible] to eject matter [illegible]

3. Utilize [illegible] cooled, [illegible] at a later time a larger [illegible]

4. Utilize [illegible] core at th[illegible] the [illegible]

The first [illegible] without [illegible] Gold[illegible] [illegible] the [illegible] neutrino[illegible] at [illegible]

The [illegible] discus[illegible] duction [illegible] Sterg[illegible] allow[illegible] sible. [illegible] and [illegible] There is [illegible] neutron [illegible] ical rotat[illegible] weak [illegible] quir[illegible] stresses and [illegible] tively long [illegible] Accretion [illegible]

We distance [illegible] between first [illegible] several milliseconds [illegible] and an [illegible] later in order to [illegible] first and/or second [illegible] full mass and energy of a SN, [illegible] sufficient to [illegible] the rate of mass accumulation on the core significantly. If this secondary accretion rate is [illegible] enough, at [illegible] have all [illegible] the [illegible] of the neutrino [illegible] escape so that further [illegible] take place at [illegible] a slower rate yielding [illegible] neutrino [illegible] and less neutrino trapping [illegible] and [illegible] the accretion takes place [illegible]

The [illegible] when the mass [illegible] neutrino trapping [illegible] neutrino trapped core will [illegible] than the [illegible] neutrino [illegible] lead to a greater [illegible]. [illegible] Y_e (trapping [illegible]). Further [illegible] the [illegible] on increasing [illegible] at [illegible] for a [illegible] ~ 0.5 per [illegible] much more [illegible]. [illegible], if we allow a pause between the [illegible] and further accretion, adequate to form [illegible] subsequent accretion, even at a [illegible] rate, can [illegible] a very large neutrino energy flux. [illegible] and [illegible] accreting matter [illegible] the condition of the formation [illegible]

Implo[illegible]

During [illegible], the [illegible] flux is generally governed by a rarefaction [illegible] outwards within the initial core. This [illegible] initially [illegible] constant so that crudely speaking, $\rho \propto r^{-2}$ [illegible] velocity distribution weakly dependent [illegible]. [illegible] a neutrino emitting surface forms when $\rho \kappa_\nu \sim 1$. If we [illegible] that the neutrinos are emitted within a free fall time, we can calculate the necessary conditions at the surface using the [illegible] cross section $(A/24)\,\sigma_0 (E_\nu/m c^2)^2$; A is the nucleon [illegible] number [illegible] and the emission rate is a function of neutrino [illegible] energy E_ν. We find that $E_\nu \sim 10$ MeV at a neutrino [illegible] radius of 2×10^7 cm, a free fall time of $\sim 6 \times 10^{-3}$ sec and a local matter density of $\sim 2 \times 10^{10}$ g cm^{-3}. This is the very [illegible] time, assuming that the neutrino surface is continuously supplied with neutrinos from the inner collapsed core and that furthermore the neutrino energy distribution is fully filled out to the degeneracy level, $E_\nu \sim 10$ MeV. Instead the neutrinos are trapped at high density and thus high energy and greater opacity deep within the core. Neutrino transport and energy redistribution is the subject of complicated calculations (Wilson, 1976; Arnett 1977; Tubbs 1978; Yueh and Buchler 1977a, 1977b) which estimate much longer times, up to several seconds. The particular feature of Tubbs' (1977) Monte Carlo calculations is that neutrinos in the core down scatter fast enough that the approximation of a neutrino photosphere at $E_\nu \simeq 10$ MeV remains valid. How can we then form a neutron star fast enough that the subsequent reimplosion can take place as a luminous accretion shock wave?

Richard Epstein (1978) has pointed out that, when neutrino emission takes place from a neutrino photosphere surface, the matter is then heavier (neutronized) and thus convectively unstable relative to the interior. It is hard to realize that classical convection can take place in the short times between first and second bounces, but let us estimate convection and apply it to the problem of core relaxation. The core will build up in the collapse in such a fashion that the innermost regions have more completely trapped neutrino matter, ($Y_e \simeq .35$) than the exterior layers that fall in later, say ($Y_e \cong .2$) and have had a chance to radiate neutrinos. Thus the first bounce will occur with exterior matter that is heavier - i.e., there is negative gradient of Y_e and there will be unstable Taylor growth. The ratio of pressure defect (relative to $Y_e = 0.48$ and $\gamma = 4/3$) is a measure of the equivalent density ratio [Atwood number $(\rho_1 - \rho_2)/(\rho_1 + \rho_2)$]. The pressure defect is of the order of 3 fold or greater for modest changes in Y_e ($0.35 \rightarrow 0.1$) and so the Atwood correction will reduce the growth rate by $\simeq \frac{1}{2}$. Rayleigh-Taylor instability results in the exponential increase of an initial perturbation across a boundary between ρ_1 and ρ_2. If $\rho_1 >> \rho_2$, then the perturbation amplitude grows as

$$A = A_0 \exp[(ka)^{\frac{1}{2}} t], \qquad (1)$$

where A_o is the initial amplitude, a the acceleration [illegible] the wave number = $2\pi/\lambda$. Then if d [illegible] $at^2/2$ is the distance [illegible] which acceleration takes place and with [illegible] constant acceleration, the number of generations of growth [illegible]

$$\ln(A/A_o) \cdot (4\pi\, d/\lambda)^{\frac{1}{2}}. \qquad (2)$$

In our case of stellar collapse d ~ ½ radius [illegible] the largest unstable wave length [illegible] corresponding to initial rotation, [illegible] $\ln(A/A_o)$ ~ 2 generations of growth per half [illegible] number of ½. (Equal growth takes place [illegible] around of a single [illegible] such as density [illegible] likely to take three or more bounces for the [illegible] reach the nonlinear spike and bubble stage [illegible] A_o [illegible] to 10^{-3}.

Non-linear Growth and Convection

The convective velocities of overturn are determined by the nonlinear limit of growth of the bubbles and spikes. The potential energy difference of the spikes relative to the bubbles leads to velocities of order v_{con} ~ [illegible] where f [illegible] for the bubbles and ~ ½ for the spikes. (The spikes accelerate in free fall leading to a velocity = time x g x Atwood number.) Thus we expect initial turnover velocities of ~ 10^8 cm/sec and turnover of the core in times of r/v_{con} ~ 10^{-2} seconds for r ~ 10^7 cm. This should occur by the end of ~ 3 bounces (30 millisec, Fig. 1, Van Riper) and so ensures a convectively mixed core. Therefore the neutrino composition will be near uniform out to a radius where equilibrium pressure support allows convective overturn. Wilson's (1977) calculations indicate a radius of the trapped neutrino core of ~ 2×10^6 cm. Hence we expect a shorter time to overturn the core by convection but an increase in time to release the neutrinos by emission from 6×10^{-3} sec at a photosphere radius of 2×10^7 cm to 0.6 sec from the convective radius 2×10^6. Since a significantly greater flux (Wilson 1977) exists for 0.1 sec during collapse, a reasonable estimate of the time to produce a cold bound neutron star core is then $t < 0.4$ sec, Fig. 3.

[illegible]

When a mass of matter is shocked to a high enough energy such that [illegible] all the shocked matter results despite a gravitational [illegible] the [illegible] internal and kinetic energy must be [illegible] greater than the gravitational energy. A strong shock in [illegible] matter [illegible] initially equal kinetic and internal energy [illegible] converts the internal energy to kinetic energy [illegible] of internal and kinetic energy relative to gravitational [illegible] to establish a criterion of mass ejection [illegible]. This is necessary but not sufficient. If the interior of the presumed explosion is a mass sink such as a neutron star or black hole, then the shocked matter will expand [illegible] as well as outwards and there is a partial [illegible] only the meant-to-be ejected matter, which turns around [illegible] into the mass sink. This problem was parameterized [illegible] and the fraction of matter reimploded was found to be [illegible] large and surprisingly independent of [illegible] the strength of the initial shock. A stronger shock creates both [illegible] internal as well as kinetic energy so that the [illegible] is larger. The rarefaction wave of reimplosion [illegible] tends to reverse initially outward trajectories. Hence it was found that for the idealized case of a radially uniform [illegible] and energies up to 4 times the gravitational energy, [illegible] of the matter fell back onto the neutron star (Fig. 4). Hydro calculations of SN are usually terminated long before this effect could be evaluated (because of computing time) and hence it would not be calculated. In a typical mass ejection example, Wilson (1977), estimates that several x 10^{50} ergs will eject about 1/10 $M_\odot$ of nuclear synthesized matter as well as the mantle (Fig. 4). This is a marginal result especially if one estimates that in Fig. 4 a significant fraction (up to 50%) of the matter on a radially outward escape trajectory will fall back onto the neutron star and weaken the ejected energy. This fall back or accretion would occur in roughly 0.4 sec by estimating trajectories from Fig. 3. We can calculate this time by observing that it should be roughly 4 times the free fall time from

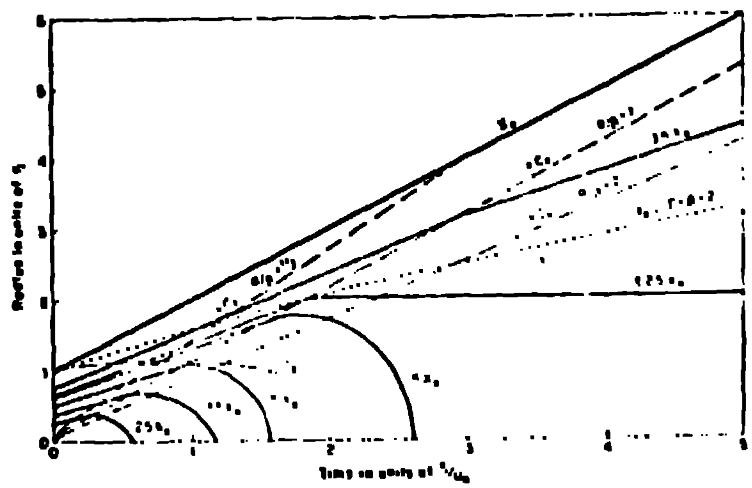

Fig. 4. The parameterized reimplosion trajectory of Lagrange coordinates for an idealized explosion in the presence of a gravitational mass "sink" (Colgate, 1971). The radius versus time of the explosion history is shown in linear coordinates and using the reduced variables $X = r/r_i$ and $\tau = tU_o/r_i$. Heavy lines are the Lagrange coordinates of various mass fractions denoted by the initial radius fraction of the outer boundary X_o. The inner mass fractions reimplode when overtaken by the outgoing rarefaction wave, denoted by $+C_s$. Three such waves (dashed curves) are shown for various ratios of α/β, where α/β is the ratio of internal to kinetic energy. The escape-velocity boundary r_B is shown as a dotted curve for the condition $\Gamma = \beta = 2$. The reimplosion terminates when the rarefaction wave passes the escape-velocity boundary.

$\cong 2 \times 10^8$ cm or $\cong 0.4$ sec. The outward average velocity will be ½ free fall velocity if turn-around takes place and one doubles this time for the return trip. The density of the reimploded matter can be estimated by observing that the mass flux at the neutron star surface must be approximately ½ $M_\odot$ (reimploding) in 0.4 sec at $v \cong c/3$ or $\rho_{surface} \cong 10^{10}$ g/cm^3.

Accretion Shock

The matter accreting onto the surface of the neutron star is now very much lower in density than the initial collapse – so low that neutrino trapping should be negligible ($\rho\sigma_\nu r \sim 10^{-1}$ at $E_\nu = 10$ MeV). Therefore we expect free fall to the neutron star surface and an accretion shock to develop. Recently Bruenn, Buchler, and Yueh (197?) have investigated in detail the neutrino luminosity [illegible], unfortunately not quite in the regime posited [illegible] but in general they substantiate the original suggestion [illegible] that a major fraction of the internal energy will be radiated by electron neutrinos as black body radiation [illegible] (Colgate and Chen 197?). Let us estimate the shock conditions. If the shock were to radiate the energy flux, then the temperature becomes:

$$c/4(7/4)aT^4 \approx \rho_{surface}(v/2)^3 = 10^{40} \text{ ergs cm}^{-2} \text{ sec}^{-1}$$

$$(L_\nu \approx 10^{53} \text{ ergs sec}^{-1}) \qquad (3)$$

for an accretion rate of 1 $M_\odot$ in 0.4 sec at $r = 7 \times 10^6$ cm and $\rho = 10^{10}$ cm^{-3}. Then

$$T \simeq 10 \text{ MeV, and } \langle E_\nu \rangle = 3T = 30 \text{ MeV.}$$

The thickness of the imploding matter is $\rho r \sigma_\nu \simeq 1$ mean free path so that the neutrinos will escape. The thickness of the residual matter $\sim \frac{1}{2} M_\odot$ at $r \sim 10^8$ cm and $\rho \sim 10^8$ g/cm^3 is roughly 0.1 neutrino electron scattering mean free paths at 30 MeV so that 4×10^{51} ergs will be deposited as heat in the outgoing weakly shocked matter. This is enough to ensure a strong mass ejection and a supernova energy release.

Rayleigh Taylor Neutrino Release

Finally the convection (Epstein 1978) that we have postulated driven by the Rayleigh-Taylor growth from a presumed initial small ($\simeq 10^{-3}$) anisotropy may in itself be sufficient to augment the reflected shock at second bounce time to ensure a strong explosion. Wilson's (1977) calculations indicate that the reflected shock forms at the time of the second bounce of the core as well as the major neutrino flux. This flux ~ 10^{52} ergs is still small compared to the total binding energy ultimately available. If immediately following the second bounce, Fig. 4, the neutrino flux were strongly augmented (x 10) by Rayleigh-Taylor driven convective overturn of the core, with the emission of a harder spectrum of neutrinos before complete thermalization, then the reflected shock would be greatly strengthened at the critical point in time and a more energetic explosion would occur. The subsequent re-implosion accretion shock would only strengthen this result Therefore we believe that convective core overturn at second to third bounce time will be driven by Rayleigh-Taylor instability. This may be the critical missing physics that will ensure that we can calculate a SN explosion with confidence.

Conclusion

We have reviewed and confirmed the dilemma of neutrino trapping in the stellar collapse to form a neutron star and a supernova. We believe that core bounce alone is too subtle and marginal to satisfactorily explain SN mass ejection. Instead the recent suggestion of R. Epstein that a partially neutronized core is convectively unstable is critically important. We suggest that it allows Taylor unstable exponential growth of initial asymmetries or perturbations during several bounces. The result is a rapid overturn of the neutrino trapped core. This can have two beneficial results: (1) The augmented released neutrino flux can significantly increase the bounce initiated first and second bounce mass ejection. (2) The convective neutrino release allows the earlier formation of a cold neutron star, ≃ 0.4 seconds, so that a subsequent accretion shock forms with sufficient neutrino luminosity to cause mass ejection.

ACKNOWLEDGEMENT

I am indebted to discussions with R. Buchler, D. Arnett, D. Schramm, J. Wilson, R. Epstein, and A. Petschek.

This work was supported by NSF Astronomy, Los Alamos DoE, and the Aspen Center for Physics.

REFERENCE

Arnett, W. D., 1977, Ap. J., 218, 815.

Baym, G., Bethe, H., and Pethick, C., 1971, Nuc. Phys., A175, 225.

Barkat, Z. Buchler, J. R., and Ingber, L., 1972, Ap. J., 176, 723.

Bethe, H., SN Collapse Conference, Nordita, Copenhagen, May 1978).

Bludman, S. 1978, SN Collapse Conference, Nordita, Copenhagen, May 1978).

Bruenn, S. W., Buchler, J. R., and Yueh, W. R., 1978, Ap. J., 221, L83.

Bruenn, S. W., Arnett, W. D., and Schramm, D. N 1975, Ap. J., 213, 213.

Burbidge, E. M.. Burbidge, G. R., Fowler, W. A., and Hoyle, F., 1957, Rev. Mod. Phys., 29, 547.

Colgate, S. A., 1971, Ap. J. 163, 221.

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

Colgate, S. A., and Chen, Y. H. 1972, Astrophys. and Space Sci., 17, 325.

Epstein, R., 1978, SN Collapse Conference, Nordita, Copenhagen, May 1978.

Imshennik, V. S. and Nadyozhin, D., 1973, Sov. Phys. - JETP 36, 821.

Lattimer, J., and Ravenhall, G., 1978, Ap. J., in press.

LeBlanc, J. and Wilson, J., 1970, Ap. J., 161, 541.

Mazurek, T., 1975, Ap. Space Sci., 35, 117; Mazurek, T, 1977, in preparation.

Nadyozhin, D., 1976, reprint.

Pontecorro, B., 1977, Proc. "Neutrino - 77," Caucausus, USSR., Sov. Acad. of Sci.

Salam, A., 1968, in Elementary Particle Physics, ed by N. Svartholm, Almquist and Wiksells, Stockholm, p. 367.

Sato, K., 1975, Prog. Theor. Phys., 54, 1325.

Schramm, D. N., 1978, SN Collapse Conference, Nordita, Copenhagen, May 1978.

Stevenson, D. H. Goldman, and Gell-Mann, M., 1977, private communication.

Tubbs, D. L. 977, "Direct Simulation Neutrino Transport Aspects of Equilibration," Fermi Lab Preprint and submitted to Ap. J. Supplement.

Van Riper, K. and Arnett, W. D., 1978, submitted to Ap. J. Lett.

Van Riper, K., 1978, Ap. J., 221, 304.

Weinberg, S., 1967, Phys. Rev. Lett., 19, 1264.

Weinberg, S. 1974, Rev. Mod. Phys., 46, 255.

Wilson, J. R., 1971, Ap. J., 163, 209.

Wilson, J. R. 1974, Phys. Rev. Lett., 32, 849.

Wilson, J. R., 1976, Varenna Lectures; also Riviste di Nuovo Cimento, in press.

Wilson J., 1977, preprint UCRL-80167.

Yang, J., Schramm, D. N., Steigman, G., and Rood, R. T., Phys. Letters B submitted.

Yueh, W. R. and Buchler, J. R., 1977a, Ap. J., 211, L121.

Yueh, W. R. and Buchler, J. R., 1977b, Ap. J., 217, 565.