UCRL-12191

University of California
Ernest O. Lawrence
Radiation Laboratory

PATENT CLEARANCE OBTAINED. RELEASE TO
THE PUBLIC IS APPROVED. PROCEDURES
ARE ON FILE IN THE RECEIVING SECTION.

MECHANISM OF TYPE II SUPERNOVA EXPLOSIONS

Livermore, California

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Livermore, California

Contract No. W-7405-eng-48

MECHANISM OF TYPE II SUPERNOVA EXPLOSIONS

Stirling A. Colgate

Richard H. White

December 16, 1964

MECHANISM OF TYPE II SUPERNOVA EXPLOSIONS

Stirling A. Colgate and Richard H. White

Lawrence Radiation Laboratory, University of California
Livermore, California

December 16, 1964

The original theory of the origin of supernovae has been proposed by Burbidge, Burbidge, Fowler and Hoyle.¹ It is thought that as a massive star continues to contract after the end of nuclear burning it will ultimately reach a sufficiently high temperature to cause the endothermic conversion of iron back into helium. This thermal decomposition absorbs so much energy that the resulting decrease in pressure triggers the collapse of the star. Supposedly, the collapsing material eventually becomes so dense that it bounces and generates a shock wave which blows off some of the outer stellar material. It is actually very difficult to propagate a shock "up" the imploding velocity gradient and out of a star, and so another mechanism is needed to transfer the energy of the collapsing core to the outer layers to blow them off. Such a mechanism is found in the very-high-energy thermal neutrinos which are emitted from the high-temperature-core shock wave. These neutrinos have a mean free path less than the stellar radius.

The calculation of most stellar models starts out with the assumption of equilibrium, but supernova explosions are, however, dynamic events and explicit hydrodynamics must be used. A Lagrangian hydrodynamic calculation with gravitation represents the instability of a presupernova star [(10 $M_{\odot}$) and polytropic index 3] when the star is evolved quasistatically from an equilibrium situation to instability by the "slow" removal of energy from the inner zones ($\sim 2\frac{1}{2}\%$ in 40 seconds), Figs. 1, 2, and 3. The small oscillations of the zones is an indication of equilibrium and quasistatic evolution.

The equation of state of the stellar material² (Fig. 4) included electron, nucleon, and radiation pressure as well as the respective heats of thermal dissociation of $\text{Fe} \rightarrow \text{He}$ and $\text{He} \rightarrow \text{n} + \text{p}$. It is this latent heat that causes sudden gravitational collapse. The thermal dissociation equilibrium time (radiative) is short ($< 10^{-16}$ sec) compared to dynamic times (~ 0.1 sec).

Since the initial star was chosen with a polytropic index 3, i. e., $T \propto (\rho)^{1/3}$, all zones of the star, even during collapse, evolve very closely along this same adiabat, $\gamma = (4/3 - \epsilon)$, $\epsilon \ll 1$. One additional star has been evolved with three solar masses and reproduced the same instability.

A rezoned star (10 $M_{\odot}$, Fig. 5) started at the condition of instability and collapsed inward with no indication of bouncing at a central density of $\rho_{\max} = 3 \times 10^{11}$ g/cc. Further calculation with the initial equation of state becomes invalid because the rate of inverse β decay of protons to neutrons becomes comparable to the dynamic collapse time so that a neutron star equation of state must be used.

The free fall at high density and lack of reflected energy (bounce) (Fig. 5) is to be expected from the equation of state, and so to confirm our understanding of the requirement for a new equilibrium, or "bounce," the equation of state was modified to include a small fraction of initial pressure (10^{-3}) of a hypothetical gas of $\gamma = 2$. The dashed curves show the resulting bounce at the expected 10^3 - fold compression and the heavy dots the reflected shock wave. This shock wave is probably strong enough to eject 10% of the mass of the star, although a detailed calculation was not completed. The artifice of introducing a component of $\gamma = 2$ gas was thought to possibly represent a small component of angular momentum or dipole magnetic field. The first possibility is rejected on the basis of wheel rotation of the star as a whole and the concomitant small angular momentum of the collapsing core. The second possibility must be rejected because for a spherical contraction of a dipole magnetic field, the equivalent γ becomes $4/3$ (pressure $\sim B^2 \sim r^{-4}$, volume $\sim r^3 \sim pV^{4/3} = \text{constant}$). Therefore, a further dynamical collapse of the star is expected until a change occurs in the equation of state due to the formation of a neutron star.

An equation of state was synthesized from the cold matter approximation of Salpeter³ shown in Fig. 6. The pressure defect (below the $\gamma = 4/3$ extrapolation of equilibrium) is much larger in this than in the Wheeler⁴ equation of state, but the difference to the hydrodynamics is negligible because the matter is close to free fall in either case following the Fe-He conversion.

For the pressure we have

$$p = 10^{16} \times \left[0.032 \rho T + 0.004567 T^4 + \begin{cases} 0.04 \rho^{4/3} & \rho < 2 \times 10^{11} \\ 4.67 \times 10^{13} & 2 \times 10^{11} < \rho < 2 \times 10^{12} \\ 23 + 121.9 \times 10^{-22} \rho^{2.6} & \rho > 2 \times 10^{12} \end{cases} \right] \text{ dynes/cm}^2, \quad (51)$$

where ρ is in g/cm^3 and T in keV. And for the internal energy we have

$$\epsilon = 10^{16} \times \left[\epsilon_0 + \frac{0.0137 T^4}{\rho} + \begin{cases} 0.12 \rho^{1/3} & \rho < 2 \times 10^{11} \\ 933.5 - 4.67 \times 10^{13} \rho^{-1} & 2 \times 10^{11} < \rho < 2 \times 10^{12} \\ 23 \ln \rho + 0.76 \times 10^{-20} \rho^{1.6} & \rho > 2 \times 10^{12} \end{cases} \right] \text{ erg/g}, \quad (52)$$

$$\text{where } \epsilon_0 = \begin{cases} 0.096 T & T < 509 \text{ keV} \\ 0.267 T - 87 & T > 509 \text{ keV} \end{cases}$$

For T less than 509 keV, the coefficient ϵ_0 represents an equivalent specific heat ratio $\gamma = 4/3$; and above 509 keV, $\gamma = 1.12$, corresponding to the thermal decomposition of iron and then helium as determined earlier in more exact calculations (Fig. 4). The remaining terms correspond to radiation energy and cold neutron matter. (The electron positron pair energy is strongly suppressed due to the high matter density.) Normal matter is converted to neutron matter by inverse beta decay, and so a time-dependent energy loss term was included with assumed KT emitted per neutrino from the reaction $p + e \rightarrow n + \nu$. The (Reines, Cowan⁵) cross section and the fractional He thermal decomposition to free protons leads to an energy loss rate

$$\frac{d\epsilon_\nu}{dt} = - 0.1 \rho^{5/3} T \text{ erg/g sec} \quad (53)$$

where ρ is in g/cm^3 , T in keV.

Figure 7 shows the equilibrium and unstable collapse of the 10 M $\odot$ star as before, except in this case the calculation was continued until a core was formed. Matter continues to fall in on the core, but no shock wave is reflected outwards because the rapid neutrino energy loss completely dissipates any thermal energy generated. As more matter accumulates on the core ($>2M\odot$) the general and special relativistic effects become large enough to represent a major error in the calculation. As a measure of the size of this correction, the equilibrium condition for the static solution becomes (Oppenheimer and Volkoff⁶)

$$\frac{dp(r)}{dr} = - \frac{[\rho(r) + c^{-2}p] G [M(r) + 4\pi c^{-2}p(r)r^3]}{[r - 2c^{-2}GM(r)]} \quad (54)$$

The factor enhancing the nonrelativistic pressure gradient is shown in Fig. 7 as a function of various stages of core collapse and suggests the impossibility of any sizable reflected energy. However, aside from the extreme dubiousness of extrapolating general relativistic static solutions to the dynamic case, a more detailed account of the neutrino energy flux offers the possibility of "exploding" the star before general relativistic effects become of overwhelming importance.

Figure 6 also shows the result of the same calculation except $d\epsilon_\nu/dt = 0$. The core temperature of 80 MeV is artificially high due to the neglect of electron positron and neutrino-antineutrino pairs in the equation of state. However, the core shock wave is demonstrated and the high temperature focuses attention upon the approximation of stellar neutrino transparency. The core shock wave is formed by matter falling onto a pressure-equilibrium neutron core. The gravitational potential is approximately 100 MeV per nucleon so that following free fall a shock temperature some fraction of this is expected. Using a density of 10^{13} g/cc behind the shock from the hydrodynamic calculation results in a temperature of ≈ 55 MeV depending on the number of leptonic degrees of freedom that reach equilibrium. Neutrinos emitted at this energy have a mean free path for inverse beta decay absorption in the imploding matter of $\rho = 2 \times 10^{12}$ g/cm³ of

$$\lambda_\nu = \frac{1}{n\sigma} = 10^4 \text{ cm}, \quad \left(\sigma = \sigma_0 (E/mc^2)^2 = 1.7 \times 10^{-40} \text{ cm}^2 \right)$$

which is small compared to the radius of the star, $r \sim 5 \times 10^6$ cm. Therefore, we expect a diffusion wave of neutrinos to conduct the core shock wave heat out

through the remainder of the star. Since the mean free path for neutrino scattering is increasing as the neutrino energy decreases, we expect that the neutrino surface will emit such that $1/2$ of the neutrino heat flux will be deposited in the external matter of the star.

Figure 8 also shows the calculation of a $10 M_{\odot}$ star in which 10% of the energy behind the core shock is deposited throughout the external matter of the star. The resulting explosion removes approximately 80% of the original mass leaving a core of $2 M_{\odot}$. When no neutrino energy was emitted at any stage of collapse, a core of $5 M_{\odot}$ was formed and a weak reflected shock removed the outer $5 M_{\odot}$ of $\gamma = 5/3$ matter. Such a stiff γ is unrealistic even for hydrogen because the electrons are relativistic. The lack of neutrino emission is also unrealistic since the process of inverse beta decay has been observed (Reines-Cowan⁵).

Calculations of the effect of a thermonuclear explosion have also been performed. An equilibrium stellar model was used with an envelope of $3 M_{\odot}$ with $\gamma = 5/3$ and a core of $7 M_{\odot}$ with the iron equation of state. This model was evolved quasi-statically for 74 seconds, and then 5×10^{17} ergs/g were injected into the $3 M_{\odot}$ envelope, simulating a thermonuclear explosion corresponding to the synthesis of carbon to iron. It is assumed that there are no neutrino losses, so the star has the maximum possibility of exploding. Immediately following the simulated thermonuclear explosion the equation of state of the thermonuclear material was shifted from approximately $\gamma = 5/3$ to the equation of state of iron, including the potential Fe-He decomposition energy. The injection of this energy and the resulting shift in temperature is shown in Fig. 9. The outer few zones that were heated by thermonuclear energy remain essentially static while the inner zones continue to fall in, as shown in Fig. 10. The actual velocities of these zones Fig. 11 show that they initially expanded outward but then fell back because their pressure support has been reduced from the collapse of the core. Therefore, in order to blow off the zones, they must acquire a kinetic energy comparable to their gravitational potential energy, but their kinetic energy obtained from the thermonuclear explosion is found to be only $1/40$ of their gravitational potential. Therefore, when the inner zones undergo the iron-helium transformation they fall away from the outer zones so that regardless of the thermonuclear reaction, the outer zones become unstable and collapse.

Thus the possibility of blowing off the outer layers of a star by a thermonuclear explosion triggered from the dynamic collapse of the core is exceedingly unlikely.

On the other hand the emission of very-high-energy neutrinos from the collapsing core does provide a mechanism for distributing the dynamic energy of the collapsing core throughout the rest of the mass of the star and this process, even though inefficient, is still sufficient to blow off most of the outer regions of the star.

DISCUSSION

Schatzman: Povedo has recently discussed the question of the mass ejected from Type II supernova. He considers that at maximum light, if the optical thickness is about 1 (which corresponds to the idea that when the light decays it is because the shell becomes transparent), and assuming a mass per square centimeter of the shell of the order of 1 g (it may be a little but not much larger), then the development of ejection velocities of about 7000 km/sec gives a mass of the order of 0.2 $M_{\odot}$, which is much below what is usually assumed for a Type II supernova. He has other evidence concerning this mass based on interpretation of radio sources. It seems that the whole picture makes sense with ejected mass which may not be larger than 1/10 of a solar mass.

Colgate: It is certainly crucial whether a supernova has the possibility of ejecting essentially all of its mass, so that it is left with a stable core which is below the Chandrasekhar limit, or whether there is no general mechanism for getting rid of the mass. Unfortunately, optical observations do not have a simple and obvious interpretation and so that even though a small ejected mass at a given velocity may be observed, it does not exclude the possibility of the existence of a larger mass at a different velocity. The difficulty is that the adiabatic expansion of the ejected matter following even the extreme shock heating to 5×10^9 degrees causes the ejected matter to cool too rapidly to give rise to the observed (optical) luminosity. An additional mechanism must be sought for heating the matter late in time (weeks) when it has become transparent. I believe this late heating is due to beta decay of the radioactive debris, but this mass fraction will correspond to the innermost ejected matter which expands the slowest.

Fowler: The history of the desire to explode a massive star entirely is a rather interesting one, in view of recent developments. We were all motivated in the early days by the feeling that a massive star had to get rid of all of its mass in order to get below the Chandrasekhar limit and become a white dwarf. Clearly, from the recent developments in the application of general relativity to this problem, there are no static solutions in general relativity but rather dynamic ones which last for an infinite time, and it is not necessary, apparently, for a star to relieve itself of the excess mass over the Chandrasekhar limit.

As pointed out, the question of whether the thermonuclear reactions are sufficient to explode a star is a very delicate one. Even with a competent nuclear reaction such as the burning of helium on outward, and carbon on out, the envelope needs something to push against in order to throw itself off. Here the core has fallen away but this is for nonrotating cases. Large massive stars have rotation, and rotation acts in just such a way as to give a stiffening of the core. For this reason, we have some hope that one can still eject a fairly substantial fraction which will now depend in some measure on how much rotation the star has at this stage.

Colgate: The $\gamma = 2$ fictitious adiabat was a mistaken effort to simulate rotation or magnetic fields. Magnetic fields have a γ of $4/3$ regardless of multipole, and the rotation has an effective γ of $5/3$ in these equations. It would take a fractional energy content of the order of 10^{-2} to 10^{-3} in rotation to seriously perturb these calculations. And there would have to be that fractional energy content within the core. Further, there cannot be rigid-body rotation of the star immediately prior to the implosion because a rigid-body rotation puts the mantle beyond the stability limit at the time of implosion.

REFERENCES

- ¹E. M. Burbidge, G. R. Burbidge, W. A. Fowler and F. Hoyle, 1957, Rev. Mod. Phys. 29, 547.
- ²Wm. H. Grasberger, UCRL-6196 (1961); and Wm. H. Grasberger, J. N. Yeaton, UCRL-6465 (1961).
- ³E. E. Salpeter, Ann. Phys. 9 (1960) 11.
- ⁴J. A. Wheeler, Meeting on "Neutron Stars and Celestial X-Ray Sources" held at the NASA Inst. for Space Studies, New York, March 20, 1964, to be published.
Also, Chapter 10, by Wheeler, "Gravitation and Relativity" Ed. H. Chin and W. F. Hoffman, W. A. Benjamin Inc., New York, 1964.
- ⁵F. Reines and C. L. Cowan, Jr., Phys. Rev. Vol. 113, 273, 1959.
- ⁶J. R. Oppenheimer and G. M. Volkoff, Phys. Rev. 55, (1939) 374.

Fig. 1. The velocity versus time oscillations of the zone boundaries represent sonic disturbance around the equilibrium condition. The kinetic energy of these oscillations is about 10^{-4} of the internal energy.

Fig. 2. The circles and crosses represent the many maxima and minima of the oscillations of an inner zone before and after the introduction of a slow artificial heat sink 6×10^{-2} percent per second on initial internal energy and 2-1/2% at time of unstable collapse.

Fig. 3. Velocity history of zones at start of collapse. The ordering of the zones in radius is consecutive, but is partially random in velocity space.

Fig. 4. The equation of state of stellar material for a supernova of $10 M_{\odot}$. All zones of the initial star and subsequently during implosion fall along the same adiabat.

Fig. 5. Mass zone interface radial time history during instability collapse of a supernova star. The solid curves describe the case with no hard core while the dashed curves show the effect of introducing an initial gas of $\gamma = 2$ and fractional energy of 2×10^{-3} . The generation of a shock wave is indicated by the circles showing the emergence of the shock into the outer stellar zones.

Fig. 6. The pressure versus density of stellar matter during a supernova gravitational collapse. When the inverse beta decay energy sink is used with no neutrino deposition, the stellar material follows the "cold" neutron star equation of state from the terminal point of the iron equation of state.

Fig. 7. Collapse of a 10 M_⊙ star including both a neutron star equation of state and an inverse beta decay energy sink with the assumption of infinite neutrino mean free path, i. e., no deposition. The shock formed at the surface of the core (2 M_⊙) does not progress outward faster than the implosion velocity and so negligible energy is reflected. The combined general and special relativistic correction is large enough by 4 M_⊙ core to cause a major change in the phenomena, presumably in the direction of further implosion.

Fig. 8. When 10% of the neutrino energy from the collapse of the core and/or from the reflected shock wave is deposited in the envelope 5 M $\odot$, ($\approx 5 \times 10^{19}$ ergs/g) the resulting explosion removes 70 to 80% of the mass of the star at an initial shock velocity of 4×10^9 cm/sec. When this envelope of 5 M $\odot$ is given a "stiff" $\gamma = 5/3$ and molecular weight of hydrogen and no deposited neutrino energy, a weak shock is reflected that removes only a few percent of the star.

Fig. 9. Log temperature versus time for the 10 M $\odot$ simulated thermo-nuclear detonation. The slow initial rise in temperature corresponds to the initial instability. The sudden increase in temperature for the 3 M $\odot$ in the envelope corresponds to the mock detonation with the deposition of 5×10^{17} ergs/gm. The subsequent implosion proceeds unaffected by the detonation.

Fig. 10. Velocity versus time for the outer zones of the 10 M $\odot$ thermonuclear detonation. The reversal in velocity from negative to positive and returning to negative corresponds to (1) initial radial implosion, (2) detonation outward shock, and then (3) reimplosion from the core rarefaction. The kinetic energy of these zones is shown to be 1/40 of their gravitational potential.

Fig. 11. Log temperature versus log density for the 1.5 M $\odot$ thermonuclear detonation. The detonation was exaggerated by depositing 5×10^{17} ergs/g throughout the entire star at the time when the central density was 2×10^{11} g/cm 3 . The neutrino loss rate was reduced to 1/10 the previous value and the subsequent explosion by neutrino deposition behaved similarly to the nonthermonuclear case with the exception that the remaining core mass was 0.68 M $\odot$ versus 0.87 M $\odot$ nonthermonuclear.

— LEGAL NOTICE —

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission " includes any employee or contractor of the commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.