LA-UR -81-2575

CONF-810876-1

MASTER

TITLE SUPERNOVA HYDRODYNAMICS

AUTHOR(S) Stirling A. Colgate, T-6

SUBMITTED TO To be presented at the Italian Summer School at Varenna, Italy "Plasma Astrophysics Course & Workshop," August 27-September 7, 1981. To be published in the proceedings of the meeting.

August 21, 1981

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

SUPERNOVA HYDRODYNAMICS

Stirling A. Colgate
August 17, 1981

University of California
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, New Mexico 87545 USA
and
New Mexico Institute of Mining and Technology
Socorro, New Mexico 87801 USA

ABSTRACT

The explosion of a star supernova occurs at the end of its evolution when the nuclear fuel in its core is almost, or completely, consumed. The star may explode due to a small residual thermonuclear detonation, type I SN or it may collapse, type I and type II SN leaving a neutron star remnant. The type I progenitor should be thought to be an old accreting white dwarf, 1.4 $M_\odot$, with a close companion star. A type II SN is thought to be a massive young star 6-10 $M_\odot$. The mechanism of explosion is still a challenge to our ability to model the most extreme conditions of matter and hydrodynamics that occur presently and excessively in the universe.

1. INTRODUCTION

A position in the sky associated with a distant galaxy brightens up for a period of a month with a luminosity comparable to the galaxy as a whole. This phenomenon, known as a supernova, is associated with the explosion of a star because the mass required to admit this luminosity at the inferred temperature is of the order of a stellar mass. The simplest explanation for the observed luminosity requires the diffusion of radiation from an internal energy source and the further assumption that the star has expanded to a dimension sufficient to give the necessary radiating area as well as to allow the diffusion of radiation from its interior. The time to maximum luminosity and the width of the peak luminosity are comparable and so the inferred expansion rate is of the order of 10^9 cm s^{-1}. This velocity is substantiated by the Doppler shifts of the lines observed in the early stages (Branch 1980). This general description of the dynamical expansion of a star is the reason for interpreting the phenomenon as a stellar explosion.

2. THE ORIGIN OF THE LIGHT

Let us illustrate this with the appropriate numbers. Luminosity at maximum of a type I supernova (SN_I I) is variously estimated as 1-4 × 10^{43} ergs s^{-1} depending on whether H_0 equals 70 or 35 (Branch 1981). It rises to maximum light within roughly 10 days or 8 × 10^5 s and has a color temperature of 1.5 × 10^4 degrees with line blanking in the ultraviolet that prevents any (~ 1%) of the UV from escaping. (This is a near fluorescent converter.) Then the surface area of the matter that must be emitting no greater than the blackbody flux of 15,000 K in the optical, becomes

$$A = \frac{Lb}{c/4\ aT^4} \tag{1}$$

where b is the bolometric correction for radiation with a cutoff above the blue band, $\lambda > 3400$ Å, from a body at 15,000 K. An estimate of $\bar{b} \cong 6$, so that $A = 10^{31}$ cm^2 and the radius at maximum light is 10^{15} cm. The mass required to emit the radiation depends upon the opacity which in turn is dependent upon the material and the relatively new consideration of line blanking (Wagoner, R. 1981; Colgate and Petschek 1981; Karp et al 1974).

A relatively conservative value for the opacity corresponding to a typical heavy element at low density and this temperature is $\kappa = 0.03$ cm^2 g^{-1}. Line blanking enhances this by a factor of times 3 or $\kappa = 0.1$ cm^2 g^{-1} as estimated by Karp et al (1977). The enhancement of the opacity due to line blanking is due to the Doppler broadening of the lines in an expanding media. Then the surface layer becomes $A/\kappa = 10^{32}$ g or 1/20 $M_\odot$. The velocity of expansion is $R/t = v_{surface} = 1.2 \times 10^9$ cm s^{-1}. If we believe that radiation must diffuse out within the time of the width of the maximum of the light curve $\Delta T = 10^6$ s, then the optical thickness becomes

$$\tau = c/v_{surface} = 30 \tag{2}$$

and the mass becomes

$$M_{ej} = \frac{A\tau}{3\kappa} = 10^{33}\ g = \tfrac{1}{2}\ M_\odot \tag{3}$$

This is why a SN is interpreted as the explosion of an entire star.

Type II SN also have recently been observed in the UV (Panagia et al 1980) and the spectra show a combination of narrow and broad emission lines as well as a UV excess above the Planck value. This is interpreted as ejected matter colliding and accelerating an extended envelope, pre-SN stellar wind, $R > 10^{17}$ cm, (Fransson 1981). This collision then supplies the energy later emitted as optical and enhanced UV emission. But how does a type I emit light without such a collision source?

SN I's show no hydrogen in the spectra and as previously noted no UV emission. Since the kinetic energy supplied by the expansion velocity is so much $(M_{ej}\ v_{ej})^2/2 \gtrsim 5 \times 10^{50}$ ergs, compared to an optical emission of $\cong 2 \times 10^{49}$ ergs, we might naively believe that the original heat of the explosion would be adequate following expansion. Let us generously extimate this heat as being both the kinetic energy as well as an initial gravitational binding energy of $w = 5 \times 10^{51}$ ergs, i.e., times 10 greater than the kinetic energy. The radius corresponding to the gravitational energy is $R = M_\odot G/(M_{ej} v^2/2) = 10$ cm. We have already assumed no subsequent collisions of the ejected matter (until interstellar remnant formation) and so the expansion will be adiabatic and the internal energy will decrease at least as fast as 1/R for radiation dominated matter, $\gamma = 4/3$. Therefore, adiabatic expansion will decrease the internal energy by the ratio $R_{initial}/R_{optical} \cong 10^{-7}$. This is such a large decrease that no reasonable assumption of initial energy content can account for the optical radiation. A late time energy source is required. It is now almost universally agreed (Colgate and McKee 1969; Axelrod 1980; Weaver, Axelrod, and Woosley 1980; Colgate, Petschek, and Kriese 1980) that the late time energy must be derived from the radioactive decay of ^{56}Ni formed by nuclear synthesis in the exploding star. If we rearrange alpha particles by thermonuclear reactions of alpha particle nuclei, i.e., C, O, Si, carbon oxygen and silicon, then the minimum energy nucleus is ^{56}Ni. This decays as $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}$ (6.6 days) $\rightarrow {}^{56}\mathrm{Fe}$ (77 days) which accounts for the large abundance of iron in the universe. It also conveniently accounts for the peculiar optical decay curve of SN I when the transparency loss of radioactive gamma rays and positrons is included in the calculations of luminosity, Figs. 1 and 2.

There is still a disagreement as to whether the long-time optical decay of 56-day half-life is produced by positron loss (Arnette 1980; Colgate, Petschek, and Kriese 1980) or infrared emission (Axelrod 1980) but this uncertainty may be resolved by the calibration of the peak luminosity and H_0. This is because the two models of an SN I type I explosion collapse to a neutron star (NS) or a thermonuclear explosion (TN) produce ¼ $M_\odot$ ejected or 1.5 $M_\odot$ ejected, respectively, and the ejected mass in turn determines the density and hence late time infrared emission. The optical and UV emission by its spectra, time variation and intensity describe a star exploding with a velocity characteristic of the gravitational binding of the late stages of evolution.

3. THE INSTABILITY THAT STARTS EXPLOSION

The great success of stellar modeling using gravity, mass, radiation transport, and nuclear reactions leads one to the inevitable conclusion that the stellar explosion is the result of late nuclear evolution to some unstable end point.

There are now recognized three unstable end points of nuclear synthesis. These are, in order of decreasing mass of the parent star:

1. The electron positron pair instability (Fraley 1968) for stars heavier than ~ 75 $M_\odot$. Here at a late stage in evolution with an oxygen or heavier core, the radiation pressure support is weakened by the specific heat of the rest mass of the near relativistic pairs and collapse to a

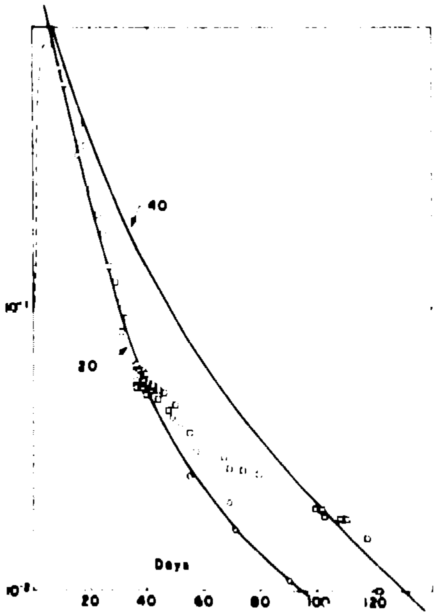


Fig. 1. The calculated luminosity at early and intermediate times for $M_{Ni} = 0.25$ solar masses and the corresponding deposition functions for $\pi = 1$ at 20 days and 40 days. Gamma-ray deposition and the Ni → Co → Fe decay determine the solid curves. The dashed curve is the modification of the deposition function due to diffusion and expansion (Colgate and McKee 1969). The extrapolation of the deposition curves reaches 2×10^{43} ergs s^{-1} at $t = 0$, and the difference between this and the dashed curve is due to heat energy converted to kinetic by expansion. The circles give NGC 5253 data (Kirshner and Oke 1975), and squares give NGC 4182 data (Baade and Zwicky 1938; Van Hise 1974).

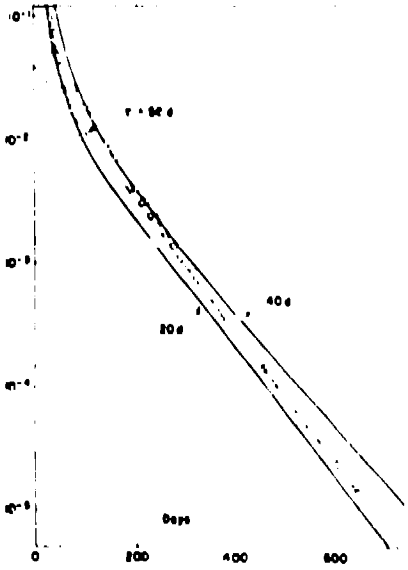
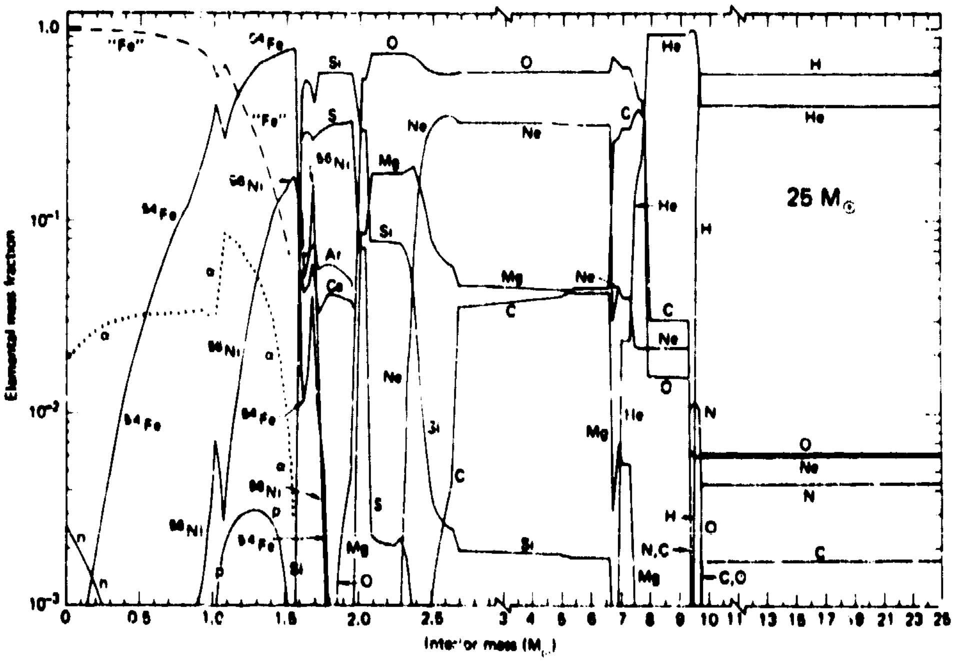


Fig. 2. Same as Fig. 1 for times out to 700 days. Here the curves are primarily determined by the deposition of positrons from the Co → Fe decay. The dashed curve is a fit to the data with a slope corresponding to a 56-day half-life.

neutron star or black hole results. The number of such massive stars, according to the present stellar mass function (Miller and Scalo 1979) are too few to account for either type of SN and more particularly supernova type II's and neutron stars.

2. A more reasonable mass for SN II's is ~ 25 $M_\odot$ and then the original suggestion of Burbidge, Burbidge, Fowler, and Hoyle 1957) applies and collapse is initiated by the thermal decomposition of iron back to alphas and neutrons. The extensive nuclear systhesis calculation of Arnette (1977); Weaver, Zimmerman, and Woosley (1978) confirm the evolution to the instability. A still more recent calculation of stellar nuclear synthetic structure is given in Fig. 3 from Weaver and Woosley (1980). This nuclear structure is exceedingly complex and would be very different if convection were driven by rotation or magnetic fields. Following collapse, an explosion of the star results presumably by the energy from the creation of a neutron star. However, despite the desire by theorists to explain this explosion, a truly convincing description is still illusive.

3. Finally, a type I SN is most likely a thermonuclear instability, but with two possible outcomes. The thermonuclear instability is associated with the thermonuclear burning of a carbon-oxygen stellar core. This may be initiated off center in a mantle of helium that detonates. This then leads to the detonation of the high density core and therefore an off-center explosion (Nomoto, Mariai, and Sugimoto 1979; Nomoto 1980; and Weaver, Axelrod, and Woosley 1980). The helium mantle is most likely formed by accretion from a helium star companion onto a white dwarf. Alternately, the core may initiate carbon-oxygen burning at the center by pico-nuclear reactions. Then a detonation or deflagration may result and this may have two very different outcomes as indicated in the section on light curves. The detonation or deflagration may result in the entire disruption of this star or following deflagration only the beta decay via electron capture of the heavy nuclei may be fast enough such that collapse results before explosion (Buchler, Mazurek, and Colgate 1979). In this case a collapse to a neutron star would result and an explosion would occur similar to the SN II explosion.



(From Weaver and Woosley, 1980, Annals of N.Y. Acad. Sci., 336, 335.)

Fig. 3. Presupernova composition profile of a 25 $M_\odot$ Population I star as a function of the interior mass coordinate as given by WZW.[8] The structure is shown at the point at which collapse velocities in the iron core have nearly reached 1000 km/s and are rapidly increasing. In the region interior to 1.61 $M_\odot$ where a 131-isotope quasiequilibrium nuclear-burning network was used to treat quasistatic silicon burning and neutronization, the curve labeled ^{56}Ni includes minor contributions from other A ≅ 2Z iron peak nuclei; the curve labeled ^{54}Fe includes those iron peak isotopes with A = 2(Z + 1), while that labeled "Fe" includes all other isotopes with Z > 22 (e.g., ^{56}Fe, ^{58}Fe, and major contributions from highly neutronized iron peak species such as ^{48}Ca, ^{64}Ni, ^{50}Ti, etc.). For additional details and a similar plot for a 15 $M_\odot$ star, see WZW.[8]

The mass ejected in the case of collapse would be only ~ 0.5 $M_\odot$ and perhaps 0.25 $M_\odot$ of ^{56}Ni. The thermonuclear explosion on the other hand would eject 1.5 $M_\odot$ of which at least 1 $M_\odot$ would be ^{56}Ni. Possibly the liht curve from early SN I's will tell the difference. Possibly a more accurate budget of iron in the galaxy will tell the difference. Also the current estimate of the galactic rate of SN is 1 per 20 to 40 years (Tammann 1981) and the error in the neutron star production rate in the galaxy is also 1 per 20 to 40 years (Hills 1980). This then also allows either possibility, namely, neutron stars may result from SN II only or from both types of SN.

4. STATISTICS OF NEUTRON STARS AND SUPERNOVAE

Certainly many neutron stars as seen in the Galaxy and a few, the Vela and the Crab, are uniquely associated with SN events. Unfortunately, all the historical SN do not uniquely have neutron stars and their types cannot be uniquely determined from the records (Clark and Stephenson 1981 and 1977) and furthermore, all neutron stars might not be expected to be visible because of possible beaming of the superluminal pulsar radiation.

To summarize, stellar instability at the end point of evolution has two significantly divergent possibilities; i.e., collapse to a neutron star or a thermonuclear detonation. These alternatives are not yet resolved. We will now discuss these alternative mechanisms in greater detail.

5. THERMONUCLEAR EXPLOSION AND COLLAPSE

The off-center explosion depends upon the slow accretion from a red giant envelope of a helium companion star to a helium envelope building up on a white dwarf star. This accretinG layer of helium burns at its base, building up A carbon-oxygen core. Depending upon the core mass, helium accretion rate, and core density, the helium shell may or may not detonate before ignition of carbon burning at the center. The carbon burning may also be initiated at high density by pico-nuclear reactions which depend upon the electron degeneracy. In either case the central density of the ignition will be roughly 10^{10} g cm^{-3}. At this high density, the electron degeneracy pressure is significantly greater, times 10, than the incremental pressure arising from complete thermonuclear burning of a carbon-oxygen core of ^{56}Ni. Hence, the pressure wave arising from the thermonuclear energy is only a strong sound wave and a very weak shock. Hence a detonation wave is not self-supporting and only in the case of the helium ignition is a driven shock likely to be strong enough to initiate the near simultaneous TN ignition of the entire core. The subsequent history of the core is then determined by the competition between electron capture which rapidly decreases the pressure by removing electrons from the top of the Fermi sea (7 to 8 MeV) and disassembly that occurs at a fraction, (~ 1/3) of sound speed. The radius of the core is 3×10^7 cm and sound speed is 2×10^8 cm s^{-1}, or a time of 0.05 s. Since the core must bounce, the total time is ~ 1/10 s. In this time the electron capture is just about rapid enough to remove 10% of the pressure and collapse to a neutron star would ensue. Collapse or TN explosion therefore depends sensitively upon the electron capture rates as well as the hydrodynamics of the helium detonation shock core compression. The capture rates depend sensitively upon the Fermi level, hence, density and hence radius, roughly as (radius)^5 yet the core is close to unstable collapse due to gravity and relativistic degeneracy. Hence, the issue of collapse or TN explosion requires very detailed knowledge of the equation of state, core structure, beta decay rates, and finally the hydrodynamics of an off-center explosion.

Recently, Fuller, Fowler, and Newman (1980,1981) have significantly revised the electron capture rates due to "beta decay blocking." This results in an increase in the capture rate at the pre-collapse density, ≅ 10^{10} g cm^{-3} and a large decrease in the rates at early collapse, a few 10^{11} g cm^{-3}.

Finally, if carbon-oxygen burning initiates at the center of the star, the burning leads to a deflagration rather than detonation because of the weak, ≅ 10%, overpressure from TN burn. Deflagration consumes a core at the rate of turbulent plume mixing which will take considerably longer than a sound wave traversal time by roughly the ratio of the solid angle of a plume to that of the full sphere, or by roughly a factor of 4π. Hence, the deflagration time is closer to 1 s allowing more time for electron capture than shock wave initiation. This leaves the issue of collapse or TN detonation for type I SN uncertain.

6. TYPE II SUPERNOVA

Type II SN are more massive stars that evolve a higher adiabat, i.e., more temperature for a given density, and hence burn carbon and oxygen nondegenerately and stably to a core Fe as shown in Fig. 3. (Weaver and Woosley 1980). The collapse of the core when all available fuel is burned is inevitable. The results may be a neutron star or a black hole. The existence of neutron stars would dictate that the usual result is a neutron star, but just how is still slightly uncertain.

Bethe, Applegate, and Applegate (1980) have recently completed the most exhaustive analysis of the problem of forming a supernova explosion from the formation of a neutron star. This work takes into account the latest understanding of the equation of state, neutron trapping and diffusion, hydrodynamics of collapse and core bounce shock formation. We give only a brief description of this phenomenon, but with some emphasis on the points of uncertainty.

7. SUPERNOVA TYPE II COLLAPSE

The iron core of a reasonably massive star, 6 TO 10 $M_\odot$ is partially degenerate at the end of TN burning with a low entropy $S/k \cong 1$. As collapse proceeds, almost all the leptons are trapped because 1. blocking reduces electron capture and early collapse, and 2. neutral current neutrino scattering traps the neutrinos. The lepton fraction Y_ℓ, decreases from that of iron ≅ 0.48 to

$Y_\ell = 0.35$ and hence the pressure is significantly reduced. (Nuclei do no contribute significantly to the pressure.) Hence, a fraction of the core collapses homologously (~ 0.75 $M_\odot$) the mass corresponding to the new Chandrasekhar limit associated with the reduced Y_ℓ. This new homologous core bounces at just above nuclear density (nuclear matter is stiff) initiating a shock wave at the homologous core boundary.

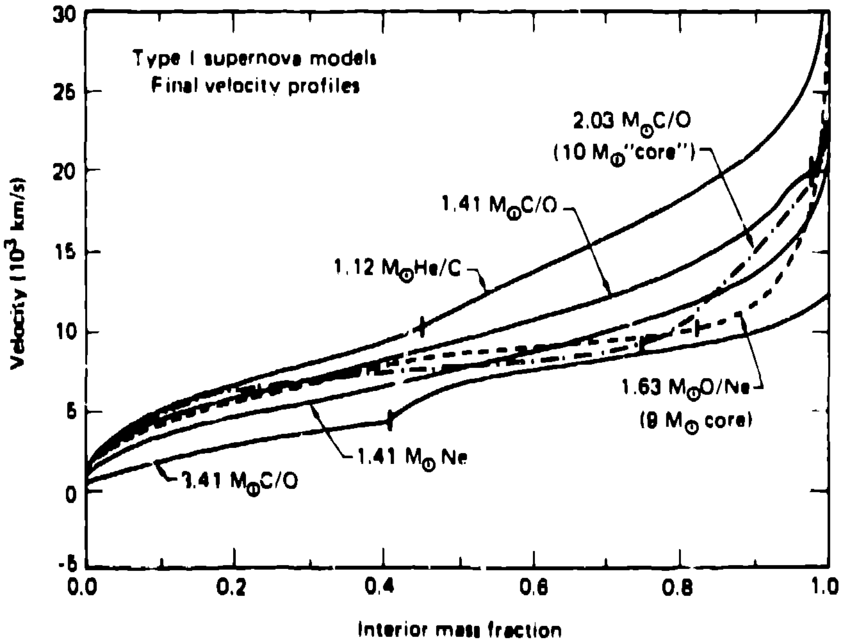
8. THE BOUNCE SHOCK

It is presumed that this shock causes the SN explosion. This core bounce shock climbs out through the imploding matter heating it to a high temperature kT ≅ 10 MeV in high entropy S/k ≅ 7 to 10 which dissociates the nuclei back to free nucleons. The shock is weakened by dissociation and lepton degrees of freedom. It is strengthened by the density gradient. Numerical calculations indicate a weakening due to neutrino emission. Analysis would say that neutrino diffusion behind the shock should strengthen or aid the shock because diffusion allows thermal conduction to transport heat from the inner higher density, higher temperature regions to the outer, lower density regions behind the shock, i.e., forming a near isothermal shock. On the other hand, neutrino leakage (at low energy, small cross section) should definitely weaken the shock. Further out beyond where neutrinos will be trapped, thermonuclear burning will aid the shock as well as the recombination (thermonuclear burning) of the previously shocked decomposed nuclear matter. These gains and losses are so complicated that an unequivocal prediction is not possible but is certainly plausible that this is the mechanism of SN created from collapse.

There are several further complexities like degenerate lepton-driven core convection and violent overturn, post ejection, rarefaction collapse, and neutrino luminosity stress that have yet to be fully resolved. Nevertheless, the great advance is the detailed analytical reproduction of much of the numerical modeling. This has strengthened the physics basis of the understanding of SN.

9. EJECT VELOCITY DISTRIBUTION

The optical evidence and its interpretation is the reason for believing that supernova eject roughly a solar mass at high velocity. A shock wave inevitably precedes such an explosion, and depending upon the structure of the mantle of the presupernova star, i.e., a compact star for type I SN, this shock can become relativistic before reaching the surface of the star (Colgate and White 1966). The extended envelope models of SN II, as already pointed out, give good agreement with observation and particularly UV observations, and in these models no high velocity ejecta is formed. Hence only in the case of SN I's do we foresee a possibility of relativistic ejecta. The mass fraction that becomes relativistic can be estimated from the solution of shock waves in density gradients and these estimates are confirmed by the numerical hydrodynamics (Colgate and White 1966). Recently this phenomenon of the shock wave speeding up in the envelope has been confirmed by calcualtions by Weaver, Axelrod, and Woosley (1980)for compact models of SN I, Fig 4. The mass fraction that becomes relativistic after the expansion of the post shock energy density is then roughly 10^{-5} to 3×10^{-6} and so the total energy in reltivistic matter becomes 10^{-5} c^2 $M_\odot$ = 10^{49} ergs. This is adequate to power cosmic rays



(From Weaver, S. A., Axelrod, T. S., and Woosley, S. E., 1980, in proceedings of the Texas Workshop on Type I Supernova, ed. J. C. Wheeler, Univ. of Texas Press, Austin, Texas.)

Fig. 4. Final velocity profiles for Type I supernova models as a function of interior mass fraction. As in Fig. 1, major abundance discontinuities are indicated by bars.

in our galaxy provided the relativistic matter can escape from the region of the SN without degradation and with the appropriate energy distribution. The escape is a question of the effectiveness of Alfvén wave trapping (Kulsrud 1979) and the spectrum is determined by relativistic shock hydrodynamics (Colgate and Petschek 1978, Fig. 5). A summary of these questions with references is given in Colgate (1981).

10. REMNANT FORMATION

Remnant formation starts with THE first interaction of the SN ejecta with the interstellar medium. The first indication of this may be the detection of the SN II 1979 c in radio emission, (Weiler et al 1980). Pacini and Salvati (1980) have interpreted this as pulsar emission, but the early time of detection (less than one year) would result in a high enough density of the SN ejecta such as to prevent the observation of an embedded source. There are not yet models that would predict this very early remnant emission by nonthermal electrons.

Later stages of remnant formation are concerned with the development of a collisionless shock in the ISM. This structure of such a shock is still problematic (McKee 1974) yet extensive modeling of the origin of cosmic rays depends upon such a collisionless shock (Bell 1978a,b; Blanford and Ostriker 1978, 1980; Axford, Lear, and Skadron 1977).

11. SUMMARY

The whole of the supernova phenomenon is rich in physics as well as astrophysics and the observations and interpretation test our ability to model the most extreme observable phenomenon of the universe.

12. ACKNOWLEDGEMENT

I am indebted to Albert Petschek for the many collaborations and discussions that has led to this work. This work has been supported by the University of California, Los Alamos National Laboratory; and by the National Science Foundation, Astronomy Section.

13. REFERENCES

1. Arnett, W. D., 1977, Ap. J. 218, 815.
2. Arnett, W. D., 1980, Ap. J. 230, L37.
3. Axelrod, T. S., 1980, Proceedings of the Texas Workshop on Type I Supernova, Univ. Texas Press, ed. J. C. Wheeler, Austin, TX.
4. Axford, W. I., Lear, E., and Skadron, G., 1977, Proc. 15th Int. Conf. on Cosmic Rays, Plodiv, Bulgaria.
5. Baade, W. and Zwicky, F., 1938, Ap. J., 88, 411.
6. Bell, A. K., 1978a,b, Mon. No. T. R. Astr. Soc. 182, 147 (a), 443 (b).
7. Bethe, H. A., Applegate, J. H., and Brown, S. E., 1980, Ap. J. 241, 343.
8. Blanford, R. D. and Ostriker, J. P., 1978, Ap. J. 221, L229.
9. Blanford, R. D. and Ostriker, J. P., 1980, Ap. J. 237, 793.
10. Branch, D., 1980, Proceedings of the Texas Workshop on Type I Supernova, Univ. Texas Press, ed. J C. Wheeler, Austin, TX.
11. Branch, D., 1981, NATO-sponsored Supernova Workshop, Cambridge, England.
12. Buchler, J. R., Mazurek, T., and Colgate, S. A., 1979, "The Afterclap of Degenerate Carbon Ignition Revisited," International Colloquium on the Physics of Dense Matter, Paris, France.
13. Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F., 1957, Rev. Mod. Phys. 29, 547.
14. Clark, D. H. and Stephenson, F. R., 1977, "The Historical Supernova," Pergamon Press, Oxford, England.
15. Clark, D. H. and Stephenson, F. R., 1981, NATO Supernova Workshop, Cambridge, England.
16. Colgate, S. A., 1981, 17th Int. Conf. on Cosmic Rays, Paris, France, O.G. (11.2) 232.
17. Colgate, S. A. and McKee, C., 1969, Ap. J. 157, 623.
18. Colgate, S. A. and Petschek, A. G., 1981, NATO sponsored Supernova Workshop, Cambridge, England.
19. Colgate, S. A., Petschek, A. G., and Kriese, J. T., 1980, Ap. J. 237, L81.
20. Colgate, S. A. and White, R. H., 1966, Ap. J. 143, 626.
21. Fraley, G. S., 1968, Astrophys. and Space Sci. 2, 96.
22. Fransson, C., 1981, "UV-Emission from Supernova Shock Waves in Stellar Winds," preprint, Lund Observatory, Lund, Sweden.
23. Fuller, G. M., Fowler, W. A., and Newman, M. J., 1980, Ap. J. Suppl. 42, 447; and 1981 preprint, Orangeade, Caltech.
24. Hills, J. G., 1980, Ap. J. 240, 242.
25. Karp, A. H., Lasher, G., Chan, K. L., and Salpeter, E. E., 1977, Ap. J. 214, 161.
26. Kirshner, P. P. and Oke, J. B., 1975, Ap. J. 200, 574.
27. McKee, C. F., 1974, Ap. J. 188, 335.
28. Miller, G. E. and Scalo, J. M., 1979, A. J. Suppl. 41, 513.
29. Nomoto, K., 1980, Proceedings of the Texas Workshop on Type I Supernova, Univ. Texas Press, ed. J. C. Wheeler, Austin, TX.
30. Nomoto, K., Mariai, K., and Sugimoto, D., 1979, Publ. Astron. Soc. Japan, 31, 287.
31. Pacini, F. and Salvati, M., 1980, preprint Univ. of Florence, Italy
32. Panagia, N., Vettolani, G., Boksenberg, A., Ciatti, F., Ortolani, S., Rafanelli, P., Rosino, L., Gordon, C., Reimers, D., Hempe, K., Beuvenuti, P., Clavel, J., Heck, A., Penston, M. V., Michetto, F., Stickland, D. J., Bergeron, J., Tarenghi, M., Marano, B., Paulumbo, G. G. C., Parmar, A. N., Pollard, G. S. W., Sanford, P. W., Sargeant, W. L. W., Stramek, R. A., Weiler, K. W., Mutzik, P., 1980, Monthly Notices Roy. Astron. Soc. 86, 459.
33. Tammann, G., 1981, NATO Supernova Workshop, Cambridge, England.
34. Van Hise, Jr., 1974, Ap. J. 192, 657.
35. Wagner, R., 1981, NATO Supernova Workshop, Cambridge, England.
36. Weaver, T. A., Axelrod, T. S., and Woosley, S. E., 1980, Proceedings of the Texas Workshop on Type I Supernova, Univ. Texas Press, ed. J. C. Wheeler, Austin, TX.

37. Weaver, T. A. and Woosley, S. E., 1980, Annals of NY Acad. Sci. 336, 335.
38. Weaver, T. A., Zimmerman, G. B., and Woosley, S. E., 1978, Ap. J. 225, 1021.
39. Weiler, K. W., van der Hulst, J. M., Sramek, R. A., and Panagia, N., 1980, preprint NRAO, Socorro, NM.