Type-II Supernovae from Prompt Explosions

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Evidence is cited that supernova 1987A involved a large explosion energy, $\simeq(2-3)\times10^{51}$ ergs. Such a large explosion energy has not come from delayed shocks to date, nor is it likely to. Improved physics in the presupernova evolution, especially the inclusion of Coulomb interactions, has brought the iron-core mass down by $\gtrsim 0.1 M_\odot$ in the $13 M_\odot$ star which has recently been evolved. We find that supernova explosion energies up to 3×10^{51} ergs can be obtained by the prompt-explosion mechanism, provided that a somewhat soft equation of state is used at supranuclear densities.

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Many calculations have been made[1-5] to explain the light curve of supernova SN1987A. The authors consider explosion energies of (1 to 3)$\times10^{51}$ ergs. The most recent and extensive calculations by Woosley, Pinto, and Ensman[3] indicate that explosion energies (1.5 to 3) $\times10^{51}$ ergs can give a good representation of the light curve.

In most of these calculations it was assumed that the progenitor originally had a mass of (15 to 20)$M_\odot$, although some of the hydrogen envelope may have been lost before the explosion. Shigeyama *et al.*[5] assumed a mass of $13M_\odot$. The $1.18M_\odot$ iron core of this later star, the part relevant for the supernova explosion, is, however, only slightly less than the $1.27M_\odot$ core for the $15M_\odot$ star evolved by Woosley, Pinto, and Ensman.[3] Recent evidence has made Shigeyama *et al.*[5] believe in a larger explosion energy (2.5 to 3)$\times10^{51}$ ergs.[6] The evidence from the time at which the light curve began to increase (about 25 days after the explosion). This increase was predicted by Woosley *et al.*[4] to come from the radioactivity of ^{56}Co, the daughter of ^{56}Ni which was originally formed in the supernova. The heating of the outer part of the supernova by the γ rays resulting from this radioactivity is expected to become strong when the H envelope has become transparent, and this permits an estimate of the mass of H, somewhere between (5 and 10)$M_\odot$. Later on, further evidence on this may be obtained from the time when the light curve reaches a maximum. From the later decay, we shall get a better estimate of the amount of ^{56}Ni formed.

Evolutionary calculations depend mainly on the mass of the He core, without the H envelope. With a distance to the Large Magellanic Cloud of 55 kpc [distance modulus $(m-M)_0=18.7$], Woosley *et al.*[4] find a luminosity $L_{\rm bol}\simeq6\times10^{38}$ erg/s. In recent determinations[7] this distance has come down to 44 kpc [$(m-M)_0 = 18.2\pm0.2$] from which we find $L\simeq3.8\times10^{38}$ erg/s. This would correspond to a star of mass $\simeq15M_\odot$.[4,8] Very-long-baseline interferometry observations should soon pin down this distance more precisely. For the moment, we consider the $15M_\odot$ stars evolved in Refs. 1-3 and the $13M_\odot$ star from Ref. 5 to be within an acceptable range.

The bright stars in the Large Magellanic Cloud are mostly blue (not red) supergiants. Brunish and Truran[8] have calculated the evolution of massive stars of low metallicity, $Z=Z_\odot/4$ which is appropriate for the Large Magellanic Cloud, and found that, after spending a time as red supergiants, they shrink and become blue when carbon is ignited. This was confirmed by Woosley *et al.*[4] The short time ($\lesssim1$ h) between neutrino emission and arrival of the shock at the photosphere[1,5] indicates a small radius for the progenitor, $R\simeq2\times10^{12}$ cm. This small initial radius is responsible for the relatively low plateau of the light curve of SN1987A, four or five magnitudes below typical supernovae of type II.

Two mechanisms of supernova explosions have been extensively calculated during the last decade. The first uses the prompt shock due to the rebound after the collapse of the core. The second, due to Wilson,[9] is based on delayed heating of the mantle of the star by the neutrinos from the hot core. Wilson's delayed-shock mechanism[9] gave an energy of only 0.35×10^{51} ergs for a $15M_\odot$ progenitor.[10] It has been claimed[11] that convection might substantially increase this energy. Convection should occur if the prompt shock fails and thereby establishes a negative entropy gradient. Effects of convection on the neutrino emission have been computed by Burrows.[12] Comparison with the results of the Kamioka neutrino experiment[13] shows, however, a good fit without convection.[14] Wilson and Mayle[15] have examined the "salt-finger" instability, which they consider to be most effective, and find that it only doubles the delayed shock energy to at most 10^{51} ergs. It would appear difficult, from the delayed mechanism, to reach the energy of $(2-3)\times10^{51}$ ergs which present calculations suggest for SN1987A.

On the other hand, Baron, Cooperstein, and Kahana[16] (BCK) produced a viable prompt shock, showing that with a softening of the equation of state of neutron-rich matter at high density and with the inclusion of general relativity, the energy of the shock, E_{shock}, varies from (1 to $3)\times10^{51}$ ergs depending upon the degree of softness. The total explosion energy E_{expl} is somewhat larger, by about 0.5×10^{51} ergs, when the extra energy from further burning is added, and the binding outside the core is accounted for.

We report here on calculations of a prompt shock with an improved $13M_\odot$ progenitor which was recently evolved by Nomoto and Hashimoto.[17] Whereas the progenitor may turn out to be slightly too small for SN1987A, it is the best evolved core available, as we discuss below. The mass of the iron core in stars in this mass region evolved to date increases only slowly with progenitor mass, and we expect this calculation to be prototypical.

Using the Nomoto-Hashimoto $13M_\odot$ progenitor,[17] we have carried out numerical hydrodynamical calculations and have obtained the results described in Table I, which lists the variations used in several different hydrodynamical runs. No attempt was made to vary the equation of state at supranuclear densities here, which—as we know from Ref. 16—can substantially change the explosion energy. The general-relativistic hydrodynamical code, equation of state, and neutrino transport utilized are described in Ref. 16. In earlier, Newtonian calculations with stiffer equations of state, Cooperstein, Bethe, and Brown[19] had found that an iron core of $1.35M_\odot$ could not be exploded by the prompt mechanism, but one of $1.25M_\odot$ could be. BCK,[16] through softening the equation of state, taking into account the neutron excess of supernova matter, and using general relativistic dynamics, were then able to explode the larger cores of $\simeq1.35M_\odot$ obtained by Woosley and Weaver.[18]

Examination of Table I shows that the progenitor evolved by Nomoto and Hashimoto[17] is easily exploded by the prompt mechanism. The chief improvement over the cores of Ref. 18 is that the Coulomb interaction has been taken into account in the presupernova modeling. This lowers the core mass by about $0.1M_\odot$. Furthermore, Ref. 17 does not include the convective overshoot and semiconvection of Ref. 18. As noted earlier, the effective iron core of Ref. 17 is only $1.18M_\odot$.

TABLE I. Description of calculations. Model 43 is based on Woosley and Weaver's $15M_\odot$ model (Ref. 18). Models 59, 61, 62, and 63 use Hashimoto and Nomoto's (Ref. 17) $13M_\odot$ star. The bulk-symmetry coefficient W_s is given in megaelectronvolts. The effective trapping density, ρ_{trap}, is given in units of 10^{12} gm/cm^3. This is obtained by adjustment of the parameters of the leakage scheme to simulate a simple transport cutoff density. All calculations employ full general relativity, and use the BCK phenomenological EOS for high density (Ref. 16) with $K_0(N=Z)=180$ MeV and $K_0(N=2Z)=140$ MeV, with $\gamma=2.5$. $Y_{L,f}$ is the final trapped lepton fraction during the collapse phase. $\rho_c^{\max}$ is the maximum central density achieved just prior to bounce and is given in units of its ratio to $\rho_0(0.33)=2.4\times10^{14}$ g/cm^3 appropriate for neutron-rich matter. The explosion energy E_{expl} is obtained from E_{shock} by accounting for the binding energy of the mantle and envelope and the additional input from explosive nuclear burning. E_{lost} is the total neutrino loss when the calculation was stopped (roughly 30 msec after bounce). These energies are given in units of 10^{51} ergs.

Model	W_s	ρ_{trap}	$Y_{L,f}$	$\rho_c^{\max}/\rho_0(0.33)$	E_{shock}	E_{lost}
43	29.3	0.4	0.390	4.1	1.7	3.4
59	29.3	1.0	0.365	4.1	···	4.6
61	29.3	0.4	0.390	4.1	1.9	4.9
62	36.0	1.0	0.385	4.1	2.1	2.1
63	34.0	1.0	0.375	4.1	1.4	4.6

Woosley, Pinto, and Ensman,[3] in their new evolution calculation for a $15M_\odot$ star, find that agreement with the light curve of SN1987A is improved if they leave out convective overshoot and semiconvection. Their new calculation, which includes Coulomb interactions, gives an Fe core of $1.27M_\odot$, down from the $1.35M_\odot$ in Ref. 18. With the assumption as in Arnett[1] of a low metallicity $Z=Z_\odot/4$, their star first became a red giant during helium burning. It then moved back into the blue at carbon ignition and became a supernova. At collapse the radius was 2.0×10^{12} cm, about the radius needed for SN1987A.[4] With the inclusion of convective overshoot and semiconvection they obtained the much too large radius $R=3\times10^{13}$ cm. They conclude that the supernova is apparently teaching us a lesson about stellar evolution. As we shall discuss in a more detailed publication, we believe the initial assumptions of convective overshoot and semiconvection to be doubtful anyway. This conclusion is supported by detailed calculations of Langer.[20]

Another difference between the Nomoto-Hashimoto calculation[17] and that of Ref. 18 is that the former includes electron capture on oxygen from the beginning, whereas in the latter it is only turned on when the oxygen mass fraction reaches $\simeq 0.01$. By this time Y_e has dropped to 0.48 in the Nomoto-Hashimoto[17] calculation. Since the Chandresekhar mass goes as Y_e^2, this could lower the Woosley-Weaver[18] core by another $\simeq 0.05 M_\odot$. The two cores would then be in reasonable agreement, but perhaps some dependence on main-sequence mass will remain.

In our models 43, 59, and 61, a bulk-symmetry energy coefficient, $W_s = 29.3$ MeV was used. Such a value for W_s is considerably lower than the empirical value $W_s \simeq 34-36$ MeV deduced[21] for the neutron-rich iron region. In models 62 and 63 we have employed these latter values. Furthermore, in the benchmark calculations 43 and 61, a neutrino-leakage scheme was used[16] which gave an effective trapping density $\rho_{\rm trap} \simeq 4\times 10^{11}$ g/cm^3. However, it has been pointed out by Bruenn,[22] on the basis of detailed neutrino-transport methods, that a value of $\rho_{\rm trap} \simeq 10^{12}$ g/cm^3 is more appropriate, and this has been confirmed in detailed transport calculations some of us are presently pursuing. Therefore we adjusted the leakage scheme to model such behavior, and thus produced the results given in Table I for models 59, 62, and 63. The leakage scheme, tuned to give the higher trapping density, may very well overestimate the losses from directly behind the shock wave as it breaks out through the neutrinosphere. Thus, the marginal failure of model 59, our most conservative calculation, should not be viewed as a problem.

All of the calculations, except model 59 as noted above, produce quite strong explosions, with energies $E_{\rm shock} = (1-2)\times 10^{51}$ ergs and hence $E_{\rm expl}$ between $\simeq (1.5 \text{ and } 2.5)\times 10^{51}$ ergs. With a smaller compression modulus it is clear that the explosion would be much more energetic. It is also clear that stars of mass substantially greater than $12M_\odot$ or $15M_\odot$ can be blown up by the prompt mechanism, given the smaller iron cores the presupernova evolution calculations are now furnishing.

We do not believe the assertion in many papers that neutrino losses stall the shock. The high effective trapping density of $\rho_{\rm trap} = 10^{12}$ g/cm^3 corresponds well to Bruenn's very detailed calculations,[22] and ensures we have not underestimated neutrino losses during the infall. Stalled shock waves induce quicker deleptonization, but this is an effect of the shock wave's failure rather that its cause. Note that models 61 and 63 in Table I, which produced successful explosions, have lost almost 5×10^{51} ergs in neutrinos, the same as the marginal failure, model 59.

One can understand why the explosion mechanism is so sensitive to core changes of $\simeq 0.1 M_\odot$ by noting that most of the outer core must be dissociated and the dissociation energy of 2×10^{51} ergs per $0.1 M_\odot$ is comparable to the entire shock energy.

Baron, Cooperstein, and Kahana[16] showed that the $1.35 M_\odot$ cores of the $(12 \text{ and } 15) M_\odot$ stars could be exploded promptly while they used an equation of state consistent with the analysis of the giant monopole resonance.[23,24] The acceptable range for the saturation compressibility of symmetric matter in these calculations was $K_0(Z/A=\frac{1}{2}) = 180$ to 200 MeV, with the high-density adiabatic index Γ between 3.0 and 2.0. For comparison, the Friedman-Pandharipande[25] equation of state (EOS) has $K_0(\frac{1}{2}) = 240$ MeV, and $\Gamma \simeq 3.5$ for high density.

Early analyses of relativistic heavy-ion collisions seemed to indicate that the EOS might be even stiffer than the Friedman-Pandharipande[25] one, with the results of detailed calculations yielding $K_0 \gtrsim 380$ MeV and $\Gamma \gtrsim 3$. It was pointed out,[26] however, that heavy-ion experiments at high energy investigated chiefly the momentum dependence of the interactions, and had little or no bearing on the EOS. More recent analysis of the heavy-ion data[27,28] have borne out that the momentum dependence added to a conventional EOS, roughly that of Friedman and Pandharipande,[25] produces sufficient momentum dependence to describe the sideways flow in the heavy-ion reaction. It is therefore clear that the heavy-ion results are consistent with a soft EOS for the essentially cold matter encountered in stellar collapse.

We will not detail the many papers which claim that the prompt-shock mechanism will fail. Few of these have incorporated full general relativity, which BCK found essential. None of these foresaw the small presupernova cores now obtained with improved physics. Furthermore the EOS preferred by BCK[16] is fully in accord with existing nuclear physics data, as well as the newest theoretical studies of dense matter, and is in no way too soft.

We do not believe that the present models of $25 M_\odot$ stars will explode by the prompt mechanism; the iron cores are simply too large. For these, the delayed-explosion mechanism should be used, but it has to be recalculated with the smaller cores resulting from the inclusion of Coulomb interactions and with appropriate treatment of convection. For the present, we consider the physics of the prompt explosion to be a firmer basis than that of the delayed one.

We conclude that SN1987A most likely results from the prompt-explosion mechanism. The high energy in the explosion argues against stiff equations of state at supranuclear densities. If a somewhat more massive star than the $13 M_\odot$ one considered here was the progenitor, or if the explosion energy is appreciably higher than 3×10^{51} ergs, then we may need an even softer equation of state than that used here. Such soft equations of state are certainly not excluded and can be developed with reasonable assumptions about dependence of meson masses on the medium, and various possible phase transitions.

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