THE ASTROPHYSICAL JOURNAL, 299:L19–L22, 1985 December 1

THE PROMPT MECHANISM OF TYPE II SUPERNOVAE

ADAM BURROWS[1]
Department of Physics, State University of New York, Stony Brook

AND

JAMES M. LATTIMER[1]
Department of Earth and Space Sciences, State University of New York, Stony Brook
Received 1985 August 5; accepted 1985 September 12

ABSTRACT

We report in this *Letter* on an extensive set of hydrodynamical simulations of the stellar collapse of the cores of massive stars. A new hydro technique and a series of state-of-the-art equations of state were employed. The purpose of this project was to understand in detail core implosion and immediate postbounce behavior (first 25 ms) and to investigate the viability of the hydrodynamic mechanism for Type II supernovae. We find that the bounce-shock always stalls upon encountering the massive infalling outer core for the calculated cores of stars between 8 and 25 $M_{\odot}$ and the standard input physics. In particular, it is found that Nomoto's 8.8 $M_{\odot}$ star and Woosley, Weaver, and Taam's 10 $M_{\odot}$ star do not explode via the prompt mechanism. Our conclusions appear to depend not on the details of the progenitor structures calculated by others but rather on the generic nature of these structures.

Subject headings: hydrodynamics — stars: supernovae

I. INTRODUCTION

That the events which lead to a Type II supernova begin with the gravitational collapse of the core of a massive star ($M > 8\ M_{\odot}$) at the end of its life is all but certain. What is still unclear, however, is just how core implosion leads to stellar explosions. A leading contender has been the so-called bounce-shock or hydrodynamic mechanism, whose chief virtue is its elegant simplicity (Colgate and Johnson 1960; Brown, Bethe, and Baym 1982). According to this scenario, the core, made unstable by photodisintegration and/or electron capture, collapses five orders of magnitude in central density to nuclear density. Since nuclear matter is very stiff, the inner core rebounds and drives a shock into the infalling outer core. This shock reverses the infall and, if successful, ejects the stellar envelope, leaving behind a proto–neutron star. There have been many hydrodynamical simulations of core collapse and bounce in recent years (e.g., Arnett 1983; Bruenn 1984; Baron, Cooperstein, and Kahana 1985; Bowers and Wilson 1982; Hillebrandt 1982; Lichtenstadt and Bludman 1984; Mazurek, Cooperstein, and Kahana 1980). Unfortunately, the prognosis for the bounce-shock has not been good. Due to a combination of electron capture during infall (Bludman, Lichtenstadt, and Hayden 1982), neutrino losses (Van Riper 1978), and dissociation (Mazurek 1982; Burrows and Lattimer 1983), the shock in these previous simulations has generally stalled into an accretion shock. The rebounding inner piston has not been energetic enough to reverse and eject the massive, supersonic, imploding outer core.

We set about to determine whether improvements in the equation of state and the hydro code employed for such numerical experiments could turn failure into success. To this end, we developed a Newtonian hydrodynamical code that is automatically conservative; uses a Riemann resolution technique, not artificial viscosity, to handle shocks; and is accurate to third order in space and second order in time. In addition, the code has a rezoning feature that in isentropic test collapses conserves entropy to one part in 10^5. Details of the code can be found in Yahil, Johnston, and Burrows (1985). In addition, we endeavored to devise a series of equations of state that incorporated as much of the relevant nuclear physics as was feasible. Different versions were developed and tested. The free energy of the nuclei generally included, in addition to the standard terms in the semiempirical mass formula, excluded volume effects, Coulomb pressure, thermal contributions to nuclear surface energies, and excited nuclear states. Species included were a representative heavy nucleus, alpha particles, free neutrons and protons, electrons, positrons, photons, and electron-type neutrinos. The thermodynamic variables, such as pressure, entropy, and energy, were obtained by minimizing the total free energy subject to charge and baryon conservation in a thermodynamically consistent fashion. The matter was in nuclear statistical equilibrium (Mazurek, Lattimer, and Brown 1979). Attempts were made to reproduce as closely as possible the Lattimer *et al.* (1985) equation of state. The neutrino transport module contained a leakage scheme which, while falling short of full transport, is more than adequate for testing the prompt mechanism.

II. RESULTS

We have performed simulations of the collapse and bounce of a variety of progenitor cores: Arnett's (1977) 4 $M_{\odot}$ He core; Weaver, Woosley, and Fuller's (1982, hereafter WWF)

[1]Alfred P. Sloan Research Fellow.

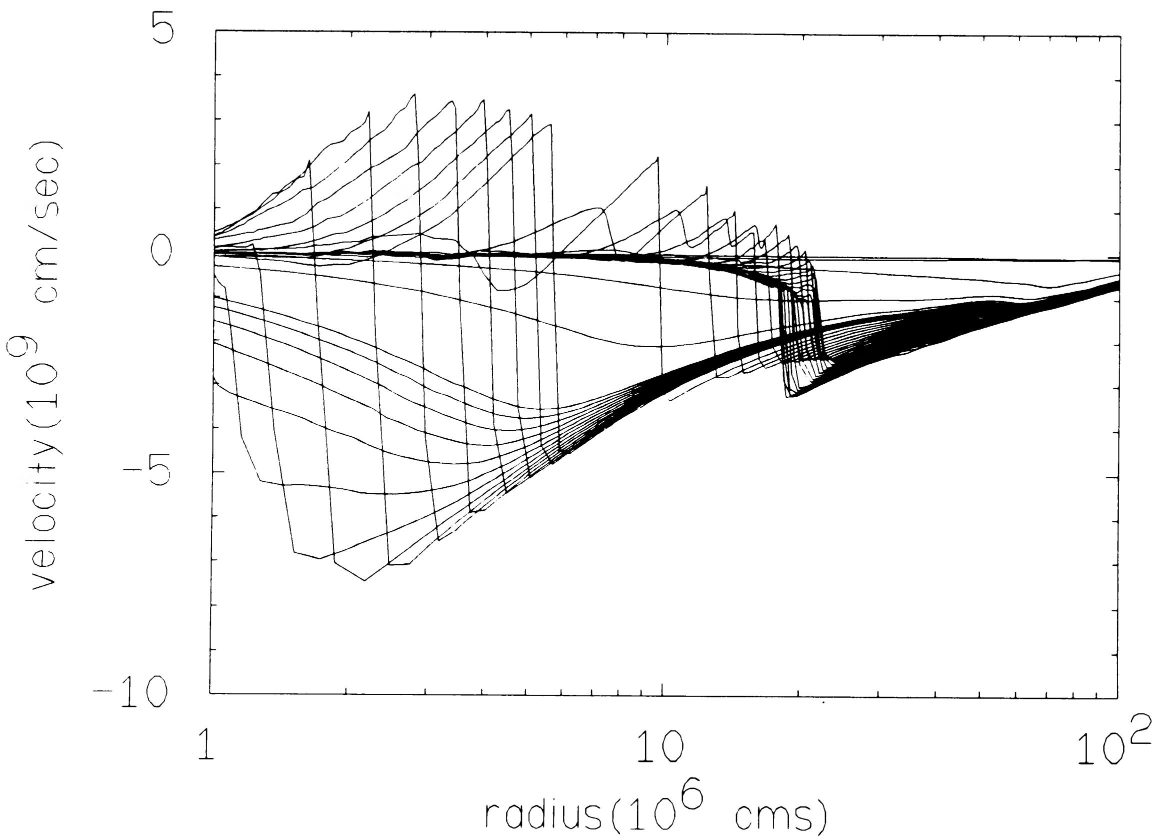

FIG. 1.—Snapshots of velocity vs. radius at various times for the collapse and bounce of WWF's 25 $M_\odot$ model. This figure encapsulates the entire evolution of a core up to 25 ms after bounce.

20 and 25 $M_\odot$ cores; Weaver, Zimmerman, and Woosley's (1978) 15 $M_\odot$ core; Weaver, Woosley, and Taam's (1980) 10 $M_\odot$ core; and Nomoto's (1982) 2.2 $M_\odot$ He core ($\equiv$ 8.8 $M_\odot$ star). All of the bounces in these numerical experiments produced shocks which stalled into accretion (i.e., postshock velocity ≤ 0) at a mass of between 1.2 and 1.25 $M_\odot$ and a radius of about 200 km. In other words, the direct mechanism aborted. Numerous artificial initial models of progenitor stars were constructed and followed and only those with the most unrealistic structures and parameters (e.g., $M_{\rm Fe} \approx 1.15$ $M_\odot$, $R_i \approx 2000$ km, and trapped lepton fractions $[Y_L] > 0.41$) exploded. Therefore, our results qualitatively confirm the results of most previous investigators (see above) and analytic theory (Lattimer, Burrows, and Yahil 1985; Burrows and Lattimer 1983). Neutrino losses and photodissociation in the outer mantle are too debilitating for the rebounding inner core to overcome them. In addition, we find that a shock, once stalled, will not be reenergized upon encountering a steep density gradient. It simply finds a new hydrostatic equilibrium. Further, we find that a decrease of the nuclear incompressibility at saturation densities from 220 MeV to 150 MeV merely pushes out the point at which the shock stalls from about 1.2 $M_\odot$ to 1.3 $M_\odot$.

The entire evolution of a core to 25 ms after bounce can be conveniently summarized in such composite graphs as are found in Figure 1. Each line in the figure is a snapshot of the velocity profile of the 1.4 $M_\odot$ core of WWF's 25 $M_\odot$ model at a specific instant after collapse ensues. These snapshots are taken first every decade in central density until 10^{14} g cm^{-3} is reached, then every *tenth* of a millisecond, and then, at an obvious break, every millisecond until about 25 ms past bounce. The horizontal lines are the shock front. The behavior represented in Figure 1 is typical for core collapses that lead to shock stagnation when the main-sequence mass of the progenitor is greater than or equal to 10 $M_\odot$. The reader is encouraged to scrutinize it for some time in order to decipher and understand this montage rich in information about the evolution. Pay special attention to the envelope of the curves. Some salient features to note are that the maximum speed attained during collapse is about 7.5×10^9 cm s^{-1} ($\sim c/4$), while the maximum postshock velocity does not exceed 4×10^9 cm s^{-1}. The initial shock speed is about 7×10^9 cm s^{-1}, but, as the figure clearly shows, this becomes zero (i.e., the shock stalls) about 10 ms after bounce, and even reverses direction (in Eulerian coordinates) as it settles into an accretion shock. Note also that the secondary bounce of the core generates a strong *sound* wave that soon catches up to the shock, but has only minor dynamical effect. After these two cycles of oscillation, the core settles into hydrostatic equilibrium. The shock is a very efficient damper of core pulsations (Brown, Bethe, and Baym 1982), the characteristic damping time being $\sim fM_c/\dot{M}_s$, where M_c is the core mass, $\dot{M}_s$ is the mass flux through the shock, and f is of order 1/3. $\dot{M}_s$ starts at about 500 $M_\odot$ s^{-1}, tapers off to 50 $M_\odot$ s^{-1} after

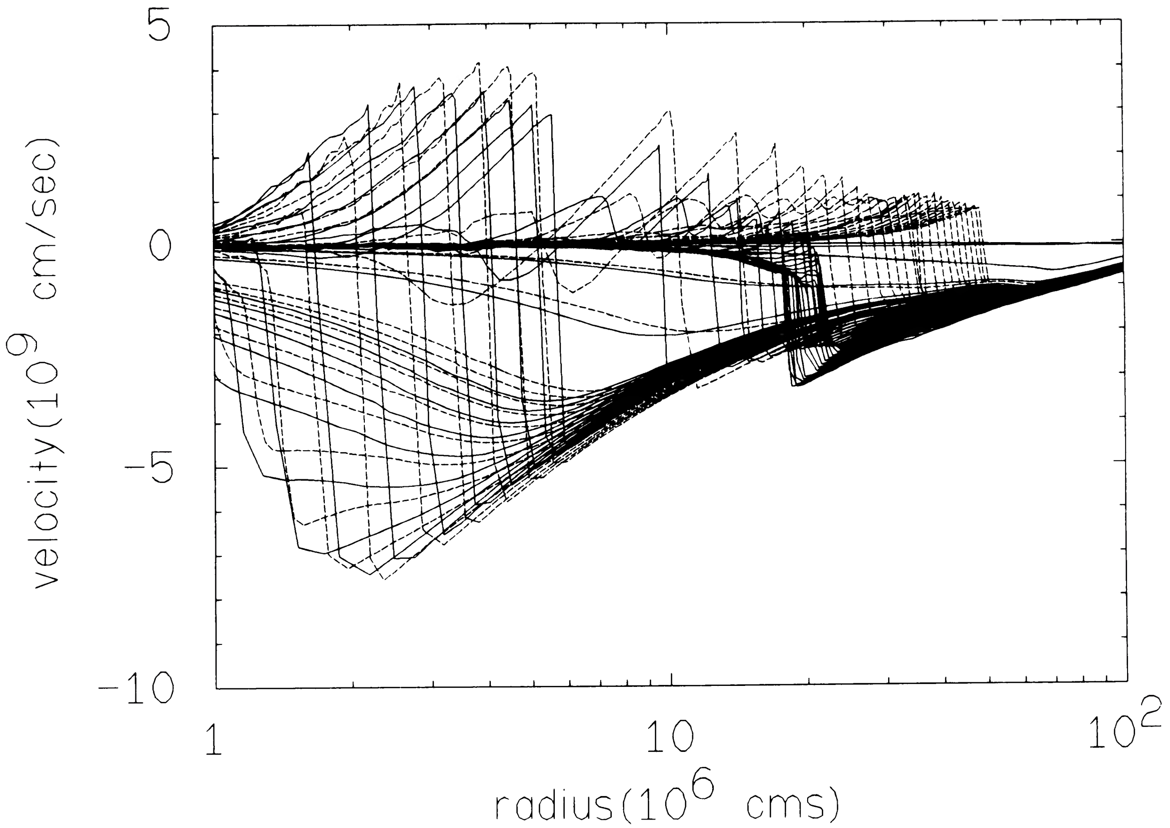

FIG. 2.—As in Fig. 1 (*solid lines*), with a similar sequence (*dashed lines*) superposed for which lepton loss was suppressed ($Y_L \equiv 0.43$)

3 ms, and is about 7 $M_\odot$ s^{-1} at the end of the calculation. The effective Γ ($= d \ln P / d \ln \rho$) for the central zone hovers around 1.3. The corresponding numbers for the core collapse of other progenitors whose main-sequence masses are larger than 10 $M_\odot$ are similar.

Those interested in gravitational wave production should note that the efficient damping of the core pulsations by the shock will significantly reduce both the gravitational radiation yield and duration from an asymmetrical collapse.

A successful bounce-shock can be generated by artificially suppressing lepton loss during infall so that $Y_L \approx 0.43$ (Burrows and Lattimer 1983). The results of such a calculation are shown in Figure 2 as the set of dashed lines superposed on the lines of Figure 1 for comparison. The immediate post-shock velocities for this sequence are always positive. Such a large Y_L is quite unrealistic, however, and of only academic interest.

As mentioned above, we have simulated the collapse of the core of Nomoto's 8.8 $M_\odot$ model. We find, that its bounce-shock also stalls. Most of the core (1.35 $M_\odot$) is within 700 km at the start of our calculation. The very compactness of this configuration alone would mitigate against success, but the burning of oxygen, neon, and magnesium on infall exacerbates the chances of a prompt explosion by entropizing the ashes to values of between 1 and 2 units (per baryon per Boltzmann's constant). This leads to a smaller Y_L, due to electron capture on the consequently more abundant protons, and, hence, a weaker shock. We also find that the stagnation at the burning front is of minor consequence. The magnitude of $\Delta\rho/\rho$ ($\sim -\Delta v/v$) at this front can be derived (Landau and Lifshitz 1959) to be approximately $[q/T_B]/[\eta_e Y_e(1 - M^2)]$, where q is the specific energy available from burning, T_B is the burning temperature, M is the Mach number of the flow in the frame of the front, and η_e and Y_e have their standard meanings and are taken when $T = T_B$. From this we can derive that $\Delta\rho/\rho \approx 0.1$, a small perturbation to the flow. The major effect of the burning on the hydrodynamics, other than the entropization, is the transformation of O-Ne-Mg matter on which the electron capture rate is very small into NSE matter on which the capture rate is significantly higher. Therefore, the burning front is also, in a sense, a "deleptonization front." There is a nontrivial pressure deficit associated with such electron capture.

III. CONCLUSIONS

Our studies have revealed that the simple hydrodynamic mechanism for Type II supernovae is not viable for any progenitor mass range, given the standard input physics. Baron, Cooperstein, and Kahana (1985) have demonstrated that if nuclear matter is sufficiently soft above nuclear density (cf. Brown and Osnes 1985), the combined action of such softness, general relativity, and a relatively high trapped Y_L *can* result in a direct explosion for the smaller progenitors (< 16 $M_\odot$) which have smaller cores (Woosley and Weaver

1985). The analytic arguments of Burrows and Lattimer (1983), when generalized from Newtonian to general relativistic hydrostatics, show graphically how this synergism can occur (Lattimer 1985). Whether nuclear matter is sufficiently soft is a subject of intense debate and scepticism. However, the challenge of a low nuclear incompressibility should be heeded. Nevertheless, there are advantages in failed bounces because they lead to the possibility of long-term mechanisms for Type II supernovae (Wilson 1985; Lattimer and Burrows 1984; Arnett 1985). These mechanisms may imply higher and more realistic neutron star masses (Burrows 1984) and ejecta compositions (Weaver 1985), though highly neutronized matter, perhaps necessary for *r*-process nucleosynthesis (Truran 1981), may not be produced. The actual mechanism for Type II supernovae has yet to be determined.

The authors would like to acknowledge conversations with Edward Baron, Hans Bethe, Gerry Brown, Jerry Cooperstein, Ken Nomoto, and Amos Yahil. In addition, thanks are extended to Stirling Colgate and the NMFECC for giving us Cray time without which these calculations would have been difficult indeed. We also appreciate the hospitality of the Aspen Center for Physics, where this paper was written. This work was supported in part by the USDOE under contract no. ACO2-80-ER10719.

REFERENCES

Arnett, W. D. 1977, *Ap. J. Suppl.*, **35**, 145.
———. 1983, *Ap. J. (Letters)*, **263**, L55.
———. 1985, in preparation.
Baron, E., Cooperstein, J., and Kahana, S. 1985, *Phys. Rev. Letters*, **55**, 126.
Bludman, S. A., Lichtenstadt, I., and Hayden, G. 1982, *Ap. J.*, **261**, 661.
Bowers, R. L., and Wilson, J. R. 1982, *Ap. J. Suppl.*, **50**, 115.
Brown, G. E., Bethe, H. A., and Baym, G. 1982, *Nucl. Phys.*, **A375**, 481.
Brown, G. E., and Osnes, E. 1985, preprint.
Bruenn, S. W., 1984, *Ap. J. Suppl.*, **58**, 771.
Burrows, A. 1984, *Comments on Ap.*, **10**, 149.
Burrows, A., and Lattimer, J. M. 1983, *Ap. J.*, **270**, 735.
Colgate, S. A., and Johnson, H. J. 1960, *Phys. Rev. Letters.*, **5**, 235.
Hillebrandt, W. 1982, in *Supernovae: A Survey of Current Research*, ed. M. D. Rees and R. J. Stoneham (Dordrecht: Reidel), p. 123.
Landau, L. D., and Lifshitz, E. M. 1959, *Fluid Mechanics* (New York: Pergamon), p. 350.
Lattimer, J. M. 1985, in preparation.
Lattimer, J. M., and Burrows, A. 1984, in *Problems of Collapse and Numerical Relativity*, ed. D. Bancel and M. Signore (Dordrecht: Reidel), p. 147.
Lattimer, J. M., Pethick, C. J., Ravenhall, D. G., and Lamb, D. Q. 1985, *Nucl. Phys.*, **A432**, 646.
Lichtenstadt, I., and Bludman, S. 1984, *Ap. J.*, **276**, 746.
Mazurek, T. J. 1982, *Ap. J. (Letters)*, **259**, L13.
Mazurek, T. J., Cooperstein, J., and Kahana, S. 1980, in *Dumand-80*, ed. V. J. Stenger (Honolulu: University of Hawaii), p. 142.
Mazurek, T. J., Lattimer, J. M., and Brown, G. E. 1979, *Ap. J.*, **227**, 713.
Nomoto, K. 1982, in *Supernovae: A Survey of Current Research*, ed. M. D. Rees and R. J. Stoneham (Dordrecht: Reidel), p. 205.
Truran, J. 1981, *Astr. Ap.*, **97**, 391.
Van Riper, K. A. 1978, *Ap. J.*, **221**, 304.
Weaver, T. A. 1985, in preparation.
Weaver, T. A., Woosley, S. E., and Fuller, G. M. 1982, *Bull. AAS*, **14**, 957 (WWF).
Weaver, T. A., Woosley, S. E. and Taam, R. (1980), in *Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p. 164.
Weaver, T. A., Zimmerman, G. B. and Woosley, S. E. 1978, *Ap. J.*, **225**, 1021.
Wilson, J. R. 1985, in *Numerical Astrophysics*, ed. J. Centrella, J. LeBlanc, and R. Bowers (Boston: Jones and Bartlett), p. 422.
Woosley, S. E., and Weaver, T. A. 1985, preprint.
Yahil, A., Johnston, M., and Burrows, A. 1985, *J. Comp. Phys.*, submitted.

ADAM BURROWS: Department of Physics, State University of New York, Stony Brook, NY 11794

JAMES M. LATTIMER: Department of Earth and Space Sciences, State University of New York, Stony Brook, NY 11794