SPHERICALLY SYMMETRIC SIMULATION WITH BOLTZMANN NEUTRINO TRANSPORT OF CORE COLLAPSE AND POSTBOUNCE EVOLUTION OF A 15 $M_\odot$ STAR

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ABSTRACT

We present a spherically symmetric, Newtonian core collapse simulation of a 15 $M_\odot$ star with a 1.28 $M_\odot$ iron core. The time-, energy-, and angle-dependent transport of electron neutrinos ($\nu_e$) and antineutrinos ($\bar{\nu}_e$) was treated with a new code that iteratively solves the Boltzmann equation and the equations for neutrino number, energy, and momentum to order $O(v/c)$ in the velocity $v$ of the stellar medium. The supernova shock expands to a maximum radius of 350 km instead of only $\sim$240 km as in a comparable calculation with multigroup flux-limited diffusion (MGFLD) by Bruenn, Mezzacappa, & Dineva. This may be explained by stronger neutrino heating due to the more accurate transport in our model. Nevertheless, after 180 ms of expansion the shock finally recedes to a radius around 250 km (compared to $\sim$170 km in the MGFLD run). The effect of an accurate neutrino transport is helpful but not large enough to cause an explosion of the considered 15 $M_\odot$ star. Therefore, postshock convection and/or an enhancement of the core neutrino luminosity by convection or reduced neutrino opacities in the neutron star seem necessary for neutrino-driven explosions of such stars. We find an electron fraction $Y_e > 0.5$ in the neutrino-heated matter, which suggests that the overproduction problem of neutron-rich nuclei with mass numbers $A \approx 90$ in exploding models may be absent when a Boltzmann solver is used for the $\nu_e$ and $\bar{\nu}_e$ transport.

Subject headings: elementary particles — hydrodynamics — methods: numerical — supernovae: general

1. INTRODUCTION

The mechanism of supernova explosions of massive stars is still not satisfactorily understood. Detailed numerical models showed that the hydrodynamic shock, which is launched when the collapsing stellar core bounces abruptly by the stiffening of the equation of state (EOS) at nuclear densities, cannot propagate out promptly but stalls because of energy losses due to photodisintegration of iron group nuclei and neutrino emission from the shock-heated matter (e.g., Bruenn 1985, 1989a, 1989b; Myra et al. 1987). Early suggestions that energy deposition by neutrinos might cause an explosion reach back to Colgate & White (1966). The modern version of the neutrino-driven “delayed” explosion mechanism is due to Wilson (1985), who found that neutrino energy deposition can revive the stalled shock on a timescale of several hundred milliseconds after the bounce (Bethe & Wilson 1985). Because of the complexity of the involved physics and the low efficiency of the neutrino energy transfer, it remained unclear for years whether the explosions are sufficiently energetic and whether the delayed mechanism works for a larger range of stellar masses (Wilson et al. 1986; Bruenn 1993). Recognizing that neutron finger convection in the newly formed neutron star could increase the neutrino luminosities, Wilson & Mayle (1988, 1993) managed to obtain healthy explosions. However, the question of neutron star convection is not finally settled, and currently it is not clear whether neutron finger instabilities or Ledoux convection (Burrows 1987; Pons et al. 1999) or quasi-Ledoux convection (Keil, Janka, & Müller 1996; Janka & Keil 1998) or none of these (Bruenn, Mezzacappa, & Dineva 1995; Bruenn & Dineva 1996; Mezzacappa et al. 1998a) occur and how they affect the explosion.

Multidimensional hydrodynamic models (Herant et al. 1994; Miller, Wilson, & Mayle 1993; Burrows, Hayes, & Fryxell 1995; Janka & Müller 1996; Mezzacappa et al. 1998b) have demonstrated the existence and the importance of convective overturn in the neutrino-heating layer behind the supernova shock. Driven by a negative entropy gradient that emerges behind the weakening prompt shock and is enhanced by the neutrino energy deposition, the convective motions transport energy from the region of strongest heating to the shock, thus raising the postshock pressure and pushing the shock farther out. At the same time, cold, low-entropy matter is advected out with serious simplifications of the neutrino transport. Even the most advanced spherically symmetric postbounce models have employed only multigroup flux-limited diffusion (MGFLD; Bruenn 1993; Bruenn et al. 1995) until recently. The significance of an accurate neutrino transport for the delayed explosion mechanism, however, has long been recognized (Janka 1991; Messer et al. 1998; Yamada, Janka, & Suzuki 1999; Burrows et al. 2000). It is therefore a natural step that a new generation of supernova models will employ schemes based on a solution of the Boltzmann equation. In fact, Mezzacappa et al. (2000) have published results for a 13 $M_\odot$ star that show that a better transport can make a qualitative change to the outcome of the simulations. However, they considered a model with an exceptionally small iron core of 1.17 $M_\odot$ (Nomoto & Hashimoto 1988), and the explosion energy was only $(4.1 \times 10^{50})$ ergs at a postbounce time of $\sim$550 ms. The growth rate of this energy of $0.05 \times 10^{50}$ ergs per 100 ms cannot easily be extrapolated in time and will probably not increase the explosion energy significantly, because the density
around the mass cut drops rapidly and the heating region is evacuated by the developing bifurcation between the neutron star and ejecta.

In this Letter we present results for a Newtonian simulation of a 15 $M_\odot$ star with a 1.28 $M_\odot$ iron core (Woosley & Weaver 1995), which show that an accurate neutrino transport does not produce an explosion for this star in spherical symmetry.

2. NUMERICAL METHODS

We have developed a new transport code that determines the neutrino phase-space distribution by iteratively solving the radiation moment equations for neutrino energy and momentum coupled to the Boltzmann equation. The code takes into account effects due to the motion of the stellar medium to order $v/c$ and determines the neutrino quantities in a comoving frame of reference (Rampp 2000; M. Rampp & H.-Th. Janka 2000, in preparation). It allows a general relativistic treatment, but for comparison with published results we have restricted ourselves to the Newtonian case. The angle dependence of the distribution function is accounted for by the use of a grid of tangent rays that exploits spherical symmetry. Closure of the set of moment equations is achieved by a variable Eddington factor calculated from the solution of the Boltzmann equation, and the integrodifferential character of the latter is tamed by making use of the integral moments of the neutrino distribution as obtained from the moment equations. The method is similar to the one described by Burrows et al. (2000). In order to fulfill lepton number conservation, we employ additional moment equations for neutrino number density and number flux. Severe time step restrictions are avoided and proper establishment of equilibrium is ensured by integrating the set of transport equations implicitly in time. The stiff character of the source terms for neutrino energy and lepton number requires a simultaneous implicit update of the temperature and electron fraction of the stellar medium.

The transport is coupled to the hydrodynamics code PROMETHEUS, which integrates the continuity equations for mass, momentum, energy, and particle species in a conservative way on a moving radial grid by explicit time stepping. The integration is accurate to second order in space and time. Shocks are treated as local Riemann problems at the zone interfaces (Fryxell, Müller, & Arnett 1989). The source terms for energy and momentum due to gravity and neutrinos and for lepton number due to neutrino emission/absorption are handled by an operator-splitting technique. The stellar background and the neutrinos are evolved on different radial grids and with different time steps, which are constrained by changes per transport step (which is typically larger than the hydrodynamical step) of at most 10% for the neutrino quantities and 5% for the fluid quantities. Interpolation between both grids is done in a conservative manner.

We used the EOS of Lattimer & Swesty (1991; with nuclear incompressibility modulus of $K = 180$ MeV), which is extended to densities and temperatures below the regime of nuclear statistical equilibrium by an ideal gas EOS, corrected for Coulomb lattice effects, that includes arbitrarily relativistic and degenerate electrons and positrons, photons, and a mixture of predefined nuclear species. Nuclear burning was not taken into account in the present simulation.

The hydrodynamics was solved on a grid with 400 radial zones out to 20,000 km, which were moved with the matter of the iron core during collapse to ensure good spatial resolution at all times and kept fixed later. For the transport we used a Eulerian grid with 210 geometrically spaced radial zones, 230 tangent rays, and 27 energy bins geometrically distributed between 0 and 380 MeV, the zone center of the first zone being at 1 MeV. The quality of the energy conservation limits the error in the net energy deposition by neutrinos to less than $5 \times 10^{48}$ ergs, and the lepton number is globally conserved to better than 0.1%.

The present simulation includes only $\nu_e$ and $\bar{\nu}_e$. The corresponding rates for charged current and neutral current reactions with nucleons and nuclei and for neutrino-electron scattering were taken from Bruenn (1985), Mezzacappa & Bruenn (1993), and Bruenn & Mezzacappa (1997). We neglect production and annihilation of $\nu_\mu \bar{\nu}_e$ pairs, which are of minor importance compared to the charged current reactions with nucleons. A detailed comparison of core collapse results with published models of Bruenn & Mezzacappa (1997) showed excellent agreement. Disregarding muon and tau neutrinos and antineutrinos and $\nu_\mu \bar{\nu}_e$ pair processes has virtually no effect on the neutrino heating (see Bruenn 1993).

3. RESULTS

Figure 1 shows the trajectories of selected mass shells as a function of time. The bounce shock forms 211.6 ms after the onset of the collapse at a radius of 12.5 km with an enclosed mass of $\sim 0.62 M_\odot$. The central density at this time is $\rho_c = 3.3 \times 10^{14}$ g cm$^{-3}$ (cf. Bruenn & Mezzacappa 1997). By the rapid accretion of mass (Fig. 2) the shock is pushed out to $\sim 240$ km. When the accretion rate drops significantly at $\sim 120$ ms after the bounce, neutrino heating is able to support further shock expansion to a radius of 350 km. After some time, however, the shock retreats again and finally turns into a standing accretion shock around 250 km, still within the collapsing sil-
icon shell of the progenitor star. No indication for the possibility of an explosion was visible when the simulation was terminated at 350 ms after the bounce. At this time the shock was stagnant and enclosed a mass of 1.5 $M_\odot$ with increasingly negative postshock velocities. The decreasing density in the neutrino-heating region and the decay of the $\nu_e$ and $\bar{\nu}_e$ luminosities do not give hope for a later rejuvenation of the shock. The overall evolution in our simulation is very similar to model WPE15ls(180)Newt20 in Bruenn et al. (1995), who used MGFLD for the neutrino transport. The most obvious difference is a larger maximum radius of the shock: 350 km compared to only $\sim$240 km in the calculation by Bruenn et al. (1995). Also, the shock is able to stay near its maximum radius for a longer time and afterward does not recede as far as in model WPE15ls(180)Newt20.

The $\nu_e$ and $\bar{\nu}_e$ luminosities and the rms energies at 1000 km are shown as functions of time in Figure 2. The prompt $\nu_e$ burst with a peak luminosity of $3.36 \times 10^{52}$ ergs s$^{-1}$ arrives at this radius only $\sim$6 ms after the core bounce. About 50 ms after the bounce the $\nu_e$ and $\bar{\nu}_e$ luminosities have become roughly equal with a fairly stable value of $(2.5-3) \times 10^{52}$ ergs s$^{-1}$. By the end of our simulation they begin to decrease slowly, different from the mean energies, which show a gradual rise to 11.2 MeV for $\nu_e$ and 15.5 MeV for $\bar{\nu}_e$.

In Figure 3 we present profiles of the net energy deposition rate by $\nu_e$ and $\bar{\nu}_e$, $Q$ (top), of the electron fraction $Y_e$ (middle) and of the entropy per baryon, $s$ (bottom), at times 119 ms (thin lines), 169 ms (medium lines), and 350 ms (thick lines) after the core bounce. The positions of the shock and of the $\nu_e$ and $\bar{\nu}_e$ spheres are indicated.

because of the decreasing mass accretion rate. The negative entropy gradient implies potential instability against convective overturn in the region between maximum heating and supernova shock. In this layer $Y_e$ climbs to values larger than 0.5 and also develops a negative gradient. Values $Y_e > 0.5$ were also found by Mezzacappa et al. (2000) in the neutrino-heated ejecta behind the outgoing shock for the successful explosion of a 13 $M_\odot$ star. The neutronization of the neutrino-heated medium is determined by the absorption of $\nu_e$ on neutrons and of $\bar{\nu}_e$ on protons and the inverse processes. It is sensitive to the luminosities and spectra but also to the angular distributions of the neutrinos in the heating region, which govern the efficiency of energy deposition as well as the lepton exchange with the medium. Since $\nu_e$ decouple at a larger radius than $\bar{\nu}_e$, their distribution is more isotropic in the heating region, leading to a higher probability of $\nu_e$ absorption and thus to an increase of $Y_e$. This is enhanced by the recombination of alpha particles (Fuller & Meyer 1995).

4. CONCLUSIONS

Our spherically symmetric, Newtonian simulation of a 15 $M_\odot$ star with a 1.28 $M_\odot$ iron core, using a new Boltzmann solver for the neutrino transport, did not give an explosion until 350 ms after the core bounce, although the shock reached a larger maximum radius than in a comparable MGFLD simulation of Bruenn et al. (1995). This is probably explained by stronger neutrino heating of the postshock medium with the more accurate Boltzmann transport. Since both simulations were done with the same progenitor, EOS, and neutrino opacities and excellent agreement during the core collapse phase was found, uncertainties due to the different numerics seem to be minimized. Although we have included only $\nu_e$ and $\bar{\nu}_e$ in our simulation, we consider our conclusions as solid, because muon and tau neutrinos would drain energy from the $\nu_e$ and $\bar{\nu}_e$ lu-
minosities but contribute to the postshock heating only at an insignificant level because of the lack of charged current interactions. The main effect of adding pair processes would be a weakening of the early shock propagation by additional energy losses. Also, general relativity would probably hamper an explosion (Fryer 1999), but the situation is still ambiguous (De Nisco, Bruenn, & Mezzacappa 1998; Baron 1988).

The importance of an accurate $\nu_e$ and $\bar{\nu}_e$ transport is emphasized by the finding that $Y_e > 0.5$ in the region of net neutrino energy deposition. This is interesting because $Y_e \lesssim 0.48$ was obtained in the neutrino-heated ejecta in supernova models, e.g., by Herant et al. (1994), Burrows et al. (1995), and Janka & Müller (1996), causing a large overproduction of neutron-rich nuclei around and (Sr, Y, Zr). This is in conflict with measured Galactic abundances. With values $Y_e > 0.5$ this problem disappears (Hoffman et al. 1996).

Using their Boltzmann solver for the neutrino transport, Mezzacappa et al. (2000) obtained a successful but weak explosion in the case of a $13 M_\odot$ progenitor with an extraordinarily small iron core of 1.17 $M_\odot$. For a 15 $M_\odot$ star with a larger core (and therefore most likely also for more massive progenitors), we cannot confirm a qualitative difference from spherically symmetric simulations with MGFLD transport, although we find important quantitative differences with our more accurate neutrino transport. In order to obtain explosions via the neutrino-heating mechanism, multidimensional simulations seem indispensable for stars with typical iron core masses. Convection inside the neutron star (Keil et al. 1996) or lower neutrino opacities—due to suppression relative to the standard description by nucleon correlation effects (e.g., Janka et al. 1996; Burrows & Sawyer 1998; Reddy et al. 1999)—could raise the neutrino emission significantly on the relevant timescale of a few 100 ms after the bounce, and convective overturn in the postshock region has been shown by several groups to support the explosion.

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