New Results in Core Collapse Supernova Theory

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In this paper, we present the results of the first core collapse supernova simulations to implement Boltzmann neutrino transport. We motivate the development of our Boltzmann solver in light of the sensitivity of the neutrino-heating paradigm to details in the neutrino transport, particularly near the neutrinospheres, where the neutrinos are neither diffusing nor free streaming and a kinetic description is necessary, and in light of the mixed outcomes and transport approximations used in all prior supernova models in both one and two dimensions. We discuss the implications of our findings for the supernova mechanism and future supernova research.

1. Introduction

Beginning with the first numerical simulations conducted by Colgate and White[1], three decades of supernova modeling have established a basic supernova paradigm. The supernova shock wave—formed when the iron core of a massive star collapses gravitationally and rebounds as the core matter exceeds nuclear densities and becomes incompressible—stalls in the iron core as a result of enervating losses to nuclear dissociation and neutrinos. The failure of this "prompt" supernova mechanism sets the stage for a "delayed" mechanism, whereby the shock is reenergized by the intense neutrino flux emerging from the neutrinospheres carrying off the binding energy of the proto-neutron star[2,3]. The heating is mediated primarily by the absorption of electron neutrinos and antineutrinos on the dissociation-liberated nucleons behind the shock. This past decade has also seen the emergence of multidimensional supernova models, which have investigated the role convection, rotation, and magnetic fields may play in the explosion [4–10].

Although a plausible framework is now in place, fundamental questions about the explosion mechanism remain: Is the neutrino heating sufficient, or are multidimensional effects such as convection and rotation necessary? Can the basic supernova observable, explosion, be reproduced by detailed spherically symmetric models, or are multidimensional models required? Without a doubt, core collapse supernovae are not spherically symmetric. For example, neutron star kicks[11] and the polarization of supernova emitted light[12] cannot arise in spherical symmetry. Nonetheless, ascertaining the explosion mechanism and understanding every explosion observable are two different goals. To achieve both, simulations in one, two, and three dimensions must be coordinated.

2. Convection

Supernova convection falls into two categories: (1) convection near or below the neutrinospheres, which we refer to as proto-neutron star convection and (2) convection between the gain radius and the shock, which we refer to as neutrino-driven convection. The gain radius is the radius at which neutrino heating and cooling via electron neutrino and antineutrino absorption and emission between the neutrinospheres and the shock balance. There is net neutrino heating above this radius and net neutrino cooling below it.

Proto-neutron star convection may aid the explosion mechanism by boosting the neutrinosphere luminosities. Hot, lepton-rich rich matter is convectively transported to the neutrinospheres. This mode of convection may develop owing to instabilities caused by lepton and entropy gradients established by the deleptonization of the proto-neutron star via electron neutrino escape near the electron neutrinosphere and by the weakening supernova shock (as the shock weakens, it causes a smaller entropy jump in the material flowing through it). Proto-neutron star convection is arguably the most difficult to investigate numerically because the neutrinos and the matter are coupled, and, consequently, multidimensional simulations must include both multidimensional hydrodynamics and multidimensional, multigroup neutrino transport. [Multigroup, i.e., multi-neutrino energy, transport is necessary because the neutrino opacities are strongly energy dependent and low and high energy neutrinos may be transported in very different ways (e.g., diffusion versus free streaming) at any given spatial point in the core at any given time.]

Neutrino-driven convection may aid the explosion mechanism by boosting the shock radius and the neutrino heating efficiency, thereby facilitating shock revival. It develops as the result of the entropy gradient established as the shocked stellar core material infalls between the shock and the gain radius, being continually heated in the process.

2.1. Proto-Neutron Star Convection (1D)

The fundamental difficulty in modeling convection in spherically symmetric models is apparent: convection is a three-dimensional phenomenon, and spherically symmetric models can incorporate convection only in a phenomenological way (e.g., via a mixing-length description). Moreover, because convection is not admitted by the one-dimensional hydrodynamics equations, some criterion for the existence of proto-neutron star convection must be used.

Neutron-finger convection has been invoked by Wilson et al.[13] in their one-dimensional models and has been deemed necessary to obtain supernova explosions. This mode of proto-neutron star convection arises in the presence of a negative electron fraction gradient and a positive entropy gradient in the postshock stellar core, resulting in higher-entropy, neutron-rich matter above lower-entropy, neutron-poor matter in the core. Under these conditions, and under the assumption that energy transport by neutrinos is more efficient than lepton transport, neutron fingers develop, resulting in (like salt fingers in the ocean) finger-like downflows of neutron-rich matter that penetrate deep into the stellar core. The assumption that energy transport is more efficient than lepton transport is justified in the following way: Three flavors of neutrinos (electron, muon, and tau) can transport energy, whereas only one (electron) can transport lepton number. However, detailed neutrino equilibration experiments carried out by Bruenn and Dineva[14] demonstrate that the muon and tau neutrinos do not couple strongly with the stellar core matter in energy, and therefore, there is only one flavor (electron) that transports both energy and lepton number efficiently in the core. Thus, the assumption breaks down and one should not expect neutron fingers to develop. Without them, Wilson et al. do not obtain explosions.

2.2. Proto-Neutron Star Convection (2D)

In certain regions of the stellar core, neutrino transport can equilibrate a convecting fluid element with its surroundings in both entropy and lepton number on time scales shorter than convection time scales, rendering the fluid element non-bouyant. This will occur in intermediate regimes in which neutrino transport is efficient but in which the neutrinos are still strongly enough coupled to the matter. Figures 1 and 2 from Mezzacappa et al.[7] demonstrate that this equilibration can in fact occur. Figure 1 shows the onset and development of proto-neutron star convection in a 25 $M_\odot$ model shortly after bounce in a simulation that did not include neutrino transport, i.e., that was a hydrodynamics-only run. Figure 2 on the other hand shows the lack of any significant onset and development of convection when neutrino transport was included in what was otherwise an identical model. Transport's damping effects are obvious. (The same result occurred in our 15 $M_\odot$ model.)

On the other hand, in the model of Keil et al.[15], vigorous proto-neutron star convection developed, which then extended deep into the core as a deleptonization wave moved inward, owing to neutrinos diffusing outward. In this model, con-

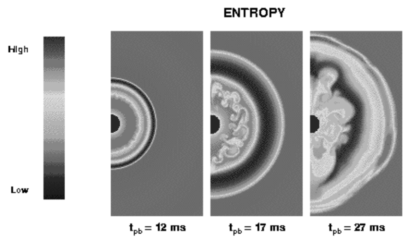

Figure 1. Two-dimensional entropy plots showing the evolution of proto-neutron star convection in our hydrodynamics-only 25 $M_\odot$ model at 12, 17, and 27 ms after bounce.

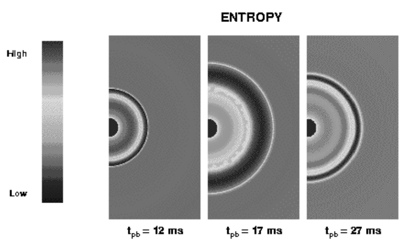

Figure 2. Two-dimensional entropy plots showing the evolution of proto-neutron star convection in our hydrodynamics-plus-neutrino-transport 25 $M_\odot$ model at 12, 17, and 27 ms after bounce.

vection occurs very deep in the core where neutrino opacities are high and transport becomes inefficient in equilibrating a fluid element with its surroundings.

It is also important to note in this context that Mezzacappa et al. and Keil et al. used complementary transport approximations. In the former case, spherically symmetric transport was used, which maximizes lateral neutrino transport and overestimates the neutrino–matter equilibration rate; in the latter case, ray-by-ray transport was used, which minimizes (zeroes) lateral transport and underestimates the neutrino–matter equilibration rate.

These outcomes clearly demonstrate that to determine whether or not proto-neutron star convection exists and, if it exists, is vigorous will require simulations coupling three-dimensional, multigroup neutrino transport and three-dimensional hydrodynamics. Moreover, realistic high-density neutrino opacities will also be needed.

2.3. Neutrino-Driven Convection (2D)

This mode of convection occurs directly between the gain radius and the stalled shock as a result of the entropy gradient that forms as material infalls between the two while being continually heated. In Figure 3, a sequence of two-dimensional plots of entropy are shown, illustrating the development and evolution of neutrino-driven convection in our 15 $M_\odot$ model[8]. High-entropy, rising plumes and lower-entropy, denser, finger-like downflows are seen. The shock is distorted by this convective activity.

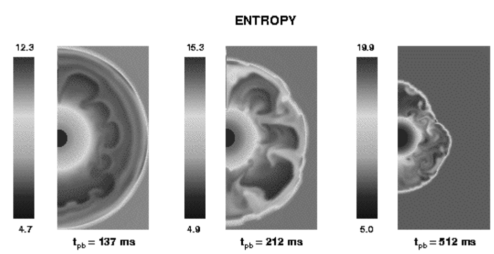

Figure 3. Two-dimensional entropy plots showing the evolution of neutrino-driven convection in our 15 $M_\odot$ model at 137, 212, and 512 ms after bounce.

In the Herant et al.[4] simulations, large-scale convection developed beneath the shock, leading to increased neutrino energy deposition, the accumulation of mass and energy in the gain region, and a thermodynamic engine that ensured explosion, although Herant et al. stressed the need for more sophisticated multidimensional, multigroup transport in future models. [They used two-dimensional "gray" (neutrino-energy–integrated, as opposed to multigroup) flux-limited diffusion in neutrino-thick regions and a neutrino lightbulb approximation in neutrino-thin regions. In a lightbulb approximation, the neutrino luminosities and rms energies are assumed constant with radius.] In the Burrows et al. simulations[5], neutrino-driven convection in some models significantly boosted the shock radius and led to explosions. However, they stressed that success or failure in producing explosions was ultimately determined by the values chosen for the neutrino spectral parameters in their gray ray-by-ray (one-dimensional) neutrino diffusion scheme. (In spherical symmetry (1D), all rays are the same. In a ray-by-ray scheme in axisymmetry (2D), not all rays are the same, although the transport along each ray is a 1D problem. In this latter case, lateral transport between rays is ignored.) Focusing on the neutrino luminosities, Janka and Müller[6], using a central adjustable neutrino lightbulb, conducted a parameter survey and concluded that neutrino-driven convection aids explosion only in a narrow luminosity window ($\pm 10\%$), below which the luminosities are too low to power explosions and above which neutrino-driven convection is not necessary. In more recent simulations carried out by Swesty[16] using two-dimensional gray flux-limited diffusion in both neutrino-thick and neutrino-thin regions, it was demonstrated that the simulation outcome varied dramatically as the matter–neutrino "decoupling point," which in turn sets the neutrino spectra in the heating region, was varied within reasonable limits. (The fundamental problem in gray transport schemes is that the neutrino spectra, which are needed for the heating rate, are not computed. The spectra are specified by choosing a neutrino "temperature," normally chosen to be the matter temperature at decoupling. In a multigroup scheme, the spectra are by definition computed.) In our two-dimensional models, the angle-averaged shock radii do not differ significantly from the shock trajectories in their one-dimensional counterparts, and no explosions are obtained, as seen in Figure 3. Neither the luminosities nor the neutrino spectra are free parameters. Our two-dimensional simulations implemented spherically symmetric (1D) multigroup flux-limited diffusion neutrino transport, compromising transport dimensionality to implement multigroup transport and a seamless transition between neutrino-thick and neutrino-thin regions.

In light of the neutrino transport approximations made, the fact that all of the simulations have either been one- or two-dimensional, and the mixed outcomes, next-generation simulations will have to reexplore neutrino-driven convection in the context of three-dimensional simulations that implement more realistic multigroup three-dimensional neutrino transport.

3. General Relativity, Rotation, and Magnetic Fields

For discussions of the role of general relativity, rotation, and magnetic fields in supernova models, the reader may begin with the papers by Bruenn et al.[17], Liebendörfer et al.[18],[19], Fryer and Heger[9], Khokhlov et al.[10], and MacFadyen and Woosley[20].

4. Boltzmann Neutrino Transport (1D)

The neutrino energy deposition behind the shock depends sensitively not only on the neutrino luminosities but also on the neutrino spectra and angular distributions in the postshock region, necessitating exact multigroup (multi-neutrino energy) Boltzmann neutrino transport. Ten percent variations in any of these quantities can make the difference between explosion and failure in supernova models[6,21]. Past simulations have implemented increasingly sophisticated approximations to Boltzmann transport, the most sophisticated of which is multigroup flux-limited diffusion[22,13]. A generic feature of this approximation is that it underestimates the isotropy of the neutrino angular distributions in the heating region and, thus, the heating rate[23,24]. Thus, the question arises whether or not failures to produce explosions in past one-dimensional models was the result of the transport approximations employed. It is important to note that, without invoking proto-neutron star (e.g., neutron finger) convection, simulations that implement multigroup flux-limited diffusion do not produce explosions[22,13] (as we have discussed, the existence and vigor of proto-neutron star convection is a matter of debate[7,14,15]).

To address the question posed above, we model the core collapse, bounce, and postbounce evolution of a 13 $M_\odot$ star, beginning with the precollapse model of Nomoto and Hashimoto[25], with a new neutrino radiation hydrodynamics code for both Newtonian and general relativistic spherically symmetric flows: AGILE–BOLTZTRAN. BOLTZTRAN is a three-flavor Boltzmann neutrino transport solver[26,27], now extended to fully general relativistic flows[18]. In this simulation, it is employed in the $O(v/c)$ limit with 6-point Gaussian quadrature to discretize the neutrino angular distributions and 12 energy groups spanning the range from 5 to 300 MeV to discretize the neutrino spectra. AGILE is a conservative general relativistic hydrodynamics code[18, 28]. Its adaptivity enables us to resolve and seamlessly follow the shock through the iron core into the outer stellar layers.

The equation of state of Lattimer and Swesty[29] (LS EOS) is employed to calculate the local thermodynamic state of the matter in nuclear statistical equilibrium (NSE). For matter initially in the silicon layer, the temperatures are insufficient to achieve NSE. In this region, the radiation and electron components of the LS EOS are used, while an ideal gas of ^{28}Si is assumed for the nuclear component. For typical hydrodynamic timesteps ($\sim$ .1 millisecond), silicon burning occurs within a single timestep for T $\sim$ 5 GK[30]; therefore, when a fluid element exceeds a temperature of 5 GK in our simulation, the silicon is instantaneously burned, achieving NSE and releasing thermal energy equal to the difference in nuclear binding energy between ^{28}Si and the composition determined by the LS EOS.

Figure 4, taken from the simulation of Mezzacappa et al.[31], shows the radius-versus-time trajectories of equal mass ($0.01 M_\odot$) shells in the stellar iron core and silicon layer in our Newtonian simulation. Core bounce and the formation and propagation of the initial bounce shock are evident. This shock becomes an accretion shock, decelerating the core material passing through it. At $\sim$ 100 ms after bounce, the accretion shock stalls at a radius $\sim$ 250 km and begins to recede, continuing to do so over the next several hundred milliseconds. No explosion has developed in this model during the first $\sim$ 500 ms.

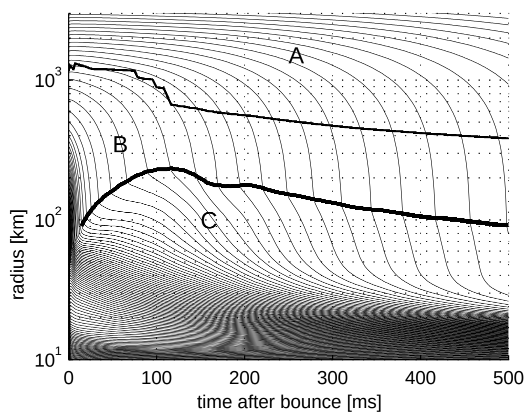

Figure 4. We trace the shock, nuclear burning, and dissociation fronts (the shock and dissociation fronts are coincident), which carve out three regions in the (r,t) plane. A: Silicon. B: Iron produced by infall compression and heating. C: Free nucleons and alpha particles.

Figure 5 shows the time evolution of the three-flavor neutrino signal, computed for the first time with Boltzmann neutrino transport, shortly after shock breakout in our general relativistic simulation[19]. We see the electron neutrino burst and the three-flavor emission develop from the hot, shocked mantle. This early evolution is a consequence of the time-dependent neutrino transport in semitransparent regions, requiring that we use Boltzmann neutrino transport to determine it accurately.

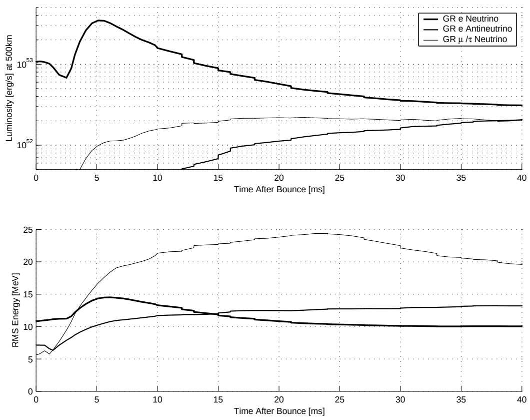

Figure 5. We plot the three-flavor neutrino luminosities and rms energies as a function of time over the first 40 ms after bounce.

5. Outlook

We are beginning to answer some fundamental questions in supernova theory. In this paper, we have shown results from the first ~ 500 ms of our Newtonian and general relativistic core collapse supernova simulations with Boltzmann neutrino transport, both initiated from a 13 $M_{\odot}$ progenitor. In light of our implementation of Boltzmann transport, if we do not obtain explosions in these models after completion, or subsequent models initiated from different progenitors (see also Rampp and Janka[32]), it would suggest that either changes in our initial conditions (precollapse models) and/or input physics or the inclusion of multidimensional effects such as convection, rotation, and magnetic fields are required ingredients in the recipe for explosion. With the implementation of Boltzmann transport, this conclusion can be made unambiguously. In the past, it was not clear whether failure or success in supernova models was the result of inadequate transport approximations or the lack of inclusion of important physics.

With regard to improved input physics, the use of ensembles of nuclei in the stellar core rather than a single representative nucleus; computing the neutrino–nucleus cross sections with detailed shell model computations[33]; the inclusion of nucleon correlations in the high-density neutrino opacities[34,35]; and improvements in precollapse models[36,37] all have the potential to quantitatively, if not qualitatively, change the details of our simulations. Thus, it is important to note that the conclusions drawn here are drawn considering the input physics used.

With regard to multdimensional effects such as convection, rotation, and magnetic fields, future simulations must be carried out in three dimensions and must implement realistic, three-dimensional, multigroup neutrino transport. Three-dimensional simulations will be necessary to assess, for example, the vigor of convection in the proto-neutron star, where the neutrinos and the matter are strongly coupled and the flow is three-dimensional, and to assess the character of neutrino-driven convection behind the shock in a stellar core that is both rotating and convecting.

We have developed a general relativistic neutrino Boltzmann transport/radiation hydrodynamics code, AGILE-BOLTZTRAN, that can now be used to study the supernova mechanism and nucleosynthesis, and to make accurate predictions of the neutrino signatures in supernovae and failed supernovae. In a model initiated from a 13 $M_{\odot}$ progenitor, we have computed, for the first time with general relativistic Boltzmann neutrino transport, the early three-flavor neutrino signal. We are currently running other models with different progenitor masses and will report on their dynamics and neutrino signatures in future papers.

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