with exact three-flavor Boltzmann neutrino transport, we simulate the stellar core collapse, bounce, and postbounce evolution of a 13 M⊙ star in spherical symmetry, the Newtonian limit, without invoking convection. In the absence of convection, prior spherically symmetric models, which implemented approximations to Boltzmann transport, failed to produce explosions. We are motivated to consider exact transport to determine if these failures were due to the transport approximations made and to answer remaining fundamental questions in supernova theory. The model presented here is the first in a sequence of models beginning with different progenitors. In this model, a supernova explosion is not obtained. We discuss the ramifications of our results for the supernova mechanism.

I. SUPERNOVA PARADIGM

Core collapse supernovae are among the most important phenomena in astrophysics because of their energetics and nucleosynthesis. 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—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]. 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 [2, 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.

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 [13]. Past simulations have implemented increasingly sophisticated approximations to Boltzmann transport, the most sophisticated of which is multigroup flux-limited diffusion [14, 15]. 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 [16, 17]. 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 [14, 15]. Moreover, the existence and vigor of proto-neutron star convection is currently a matter of debate [18, 19].

Wilson [20] implemented an approximation to Boltzmann neutrino transport by using order-of-magnitude parameterizations of the neutrino–matter weak interactions. His models failed to produce explosions. Core collapse simulations that implemented exact Boltzmann neutrino transport were completed by Mezzacappa and Bruenn [21, 22]. Following this work, we now present the findings of a core collapse, bounce, and postbounce simulation. Recognizing the need for more accurate time-dependent neutrino transport in supernova models, other groups have now developed Boltzmann solvers [23, 24].
II. FOUNDATIONS

We model the explosion of a 13 M\(_{\odot}\) star, beginning with the precollapse model of Nomoto and Hashimoto [26]. The core collapse, bounce, and explosion were simulated 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 [27,28], now extended to fully general relativistic flows [29]. 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 [29,30]. 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 [31] (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 \(^{28}\text{Si}\) 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 [32]; 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 \(^{28}\text{Si}\) and the composition determined by the LS EOS.

We investigated the convergence of the net neutrino heating rate as the number of Gaussian quadrature points and the number of neutrino energy groups in our Boltzmann simulations were varied, as in Messer et al [17]. In the heating region, the 4- and 6-point rates, the 6- and 8-point rates, and the 12- and 20-group rates differed by at most 5 percent, 3 percent, and 3 percent, respectively. Moreover, during the course of the important first 300 ms of our simulation, the maximum variation in the total energy is \(\sim 3 \times 10^{49}\) erg, which is a few percent of the total energy, and the total lepton number is conserved to within a fraction of a percent. Note that the numerical uncertainty in the net heating rate (which is at most 3 percent in our model) is no larger than the uncertainty in the total energy. Therefore, any further numerical convergence in the computation of this rate would be meaningless.

III. STELLAR CORE COLLAPSE, BOUNCE, AND POSTBOUNCE EVOLUTION

Figure 1 shows the radius-versus-time trajectories of equal mass shells (0.01M\(_{\odot}\)) in the stellar iron core and silicon layer during the first 600 ms of postbounce evolution. It also shows the shock and nuclear burning front trajectories. At 110 ms after bounce, the shock stalls at a radius of 230 km and then recedes for the duration of the simulation, and no explosion is launched. The shock and burning fronts divide the stellar core and silicon layer into three regions: A: Silicon. B: Iron produced by infall compression and heating. C: Free nucleons and alpha particles.

Figure 2 shows the three-flavor neutrino luminosities and rms energies at a radius of 500 km in the core as a function of time during our simulation.
In Figure 2, we plot the neutrino luminosities and rms energies at 500 km in the stellar core as a function of time. The electron neutrino luminosity decreases from its early “burst” value of $3.5 \times 10^{53}$ erg/s as we enter the postbounce accretion phase. (The early electron neutrino burst occurs as the shock passes the electron neutrinosphere in the core, liberating the trapped neutrinos behind it that are produced by electron capture during stellar core collapse.) In the accretion phase, the electron neutrino luminosity reaches a maximum of $3.6 \times 10^{52}$ erg/s and then decreases slowly as the mass accretion rate decreases. The electron antineutrino and muon/tau neutrino and antineutrino luminosities rise after a hot, deleptonized “mantle” forms beneath the shock (this is the region above the cold, degenerate, unshocked core, and includes the neutrinospheres). In this mantle, electron antineutrinos are produced by positron capture and all three flavors of neutrinos and antineutrinos are produced by electron–positron annihilation. The electron antineutrino luminosity reaches a maximum of $3.3 \times 10^{52}$ erg/s and exhibits the same subsequent decrease with decreasing mass accretion rate. The muon/tau neutrino and antineutrino luminosities on the other hand reach values of only $2.0 \times 10^{52}$ erg/s, and thereafter decrease with time. For all three flavors, the rms energies increase with time, owing to infall into an increasingly deep gravitational well. Relative to the electron neutrino and antineutrino rms energies, the muon/tau neutrino and antineutrino rms energies are larger, with values between 20–25 MeV: the muon/tau neutrinos and antineutrinos interact only via neutral currents and therefore decouple deeper in the core at higher densities. The electron neutrino rms energies lie in the range between 10–20 MeV. Relative to the electron neutrino rms energies, the electron antineutrino rms energies are slightly larger because the electron antineutrinos decouple at slightly higher densities: the core material is neutron rich; therefore, electron antineutrino absorption on protons is reduced relative to electron neutrino absorption on neutrons.

In Figure 3, we plot the mass density, entropy per baryon (in units of $k_B$), electron fraction, and velocity as a function of radius for various time slices in our simulation. In the velocity profiles, the initial outward propagation of the shock is evident, as is the subsequent decrease in radius at later times. Note the increasing infall velocities below the shock as it recedes, reaching values of -6000 km/s at 600 ms after bounce. Despite the decreasing shock radius and failed explosion, there remains a heating region behind the shock, where the entropies continue to increase. This is evident in the entropy profiles. Nonetheless, conditions remain such that an explosion does not occur in this model in the first second.

**IV. OUTLOOK**

We have presented results from the simulation of the stellar core collapse, bounce, and the first 600 ms of postbounce evolution of a 13 M$_\odot$ progenitor. Spherical sym-
metry was assumed, $O(v/c)$ Boltzmann neutrino transport was implemented, and gravity was Newtonian. No explosion was obtained. In light of our implementation of Boltzmann transport, if we do not obtain explosions in models initiated from other progenitors (see also Rampp and Janka [22]), it would indicate that improvements in our initial conditions (precollapse models) and/or input physics are needed, and/or that the inclusion of multidimensional effects such as convection, rotation, and magnetic fields are required ingredients in the recipe for explosion. In the past, it was not clear whether failures to produce explosions in spherically symmetric models were the result of transport approximations or the neglect of an important physical effect. We will report on the general relativistic case [23] and other models in subsequent papers.

Potential improvements in our initial conditions and input physics include: improvements in precollapse models [24–27]; the use of ensembles of nuclei in the stellar core rather than a single representative nucleus; determining the electron capture rates on this ensemble with detailed shell model computations [28]; the inclusion of nucleon correlations in the high-density neutrino opacities [29,30]; and the inclusion of new neutrino emissivities in dense matter [31]. These improvements all have the potential to quantitatively, if not qualitatively, change results [32,33] and other models in subsequent papers.

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