Cutting-edge issues of core-collapse supernova theory

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Abstract. Based on multi-dimensional neutrino-radiation hydrodynamic simulations, we report several cutting-edge issues about the long-veiled explosion mechanism of core-collapse supernovae (CCSNe). In this contribution, we pay particular attention to whether three-dimensional (3D) hydrodynamics and/or general relativity (GR) would or would not help the onset of explosions. By performing 3D simulations with spectral neutrino transport, we show that it is more difficult to obtain an explosion in 3D than in 2D. In addition, our results from the first generation of full general relativistic 3D simulations including approximate neutrino transport indicate that GR can foster the onset of neutrino-driven explosions. Based on our recent parametric studies using a light-bulb scheme, we discuss impacts of nuclear energy deposition behind the supernova shock and stellar rotation on the neutrino-driven mechanism, both of which have yet to be included in the self-consistent 3D supernova models. Finally we give an outlook with a summary of the most urgent tasks to extract the information about the explosion mechanisms from multi-messenger CCSN observables.

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INTRODUCTION

Supported by accumulating supernova observations of the blast morphology (e.g., [1, 2], and references therein), it is now almost certain that multidimensionality is a key to understanding the explosion mechanism of core-collapse supernovae (CCSNe). In fact, a number of neutrino-driven explosions have been recently obtained in the following first-principle two-dimensional (2D) simulations in which spectral neutrino transport is solved at various levels of approximations (see [3, 4, 5] for recent reviews). Among them are the work by the Garching team (e.g., [6, 7]) who included one of the best available neutrino transfer approximations by the ray-by-ray variable Eddington factor method, by the Oak Ridge team [8] who included a ray-by-ray multi-group flux-limited diffusion transport with the best available weak interactions, and by our team [9, 10] who employed a ray-by-ray isotropic diffusion source approximation (IDSA) [11] with a reduced set of weak interactions.

This success, however, is giving rise to further new questions. One of the outstanding problems is that the explosion energies obtained in these 2D models (though some of them were reported before their explosion energies saturated) are typically underpowered by one or two orders of magnitudes to explain the canonical supernova kinetic energy (∼10^51 erg, see table 1 in [12] for a summary). With an indefatigable spirit, most researchers are now seeking for some possible physical ingredients to make these underpowered explosions more energetic.

Among them, three-dimensional (3D) effects on the neutrino-driven mechanism are attracting a paramount attention. Unfortunately, however, experimental 3D models that employed a light-bulb scheme (e.g., [25]), have provided divergent results so far. The basic result of [13] who were the first to point out that 3D leads to easier explosions than 2D, has been supported by the follow-up studies (e.g., [14]), but not by [15]. On top of the urgent task to make a detailed comparison between these idealized models, self-consistent 3D simulations should be done in order to have the final word on the 3D effects.

In this contribution, we first summarize our recent results [17], in which we performed 3D Newtonian simulations with spectral neutrino transport. In the section, we focus how the explosion dynamics will differ from 3D to 2D by systematically changing numerical resolutions and initial seed perturbations in both our 2D and 3D radiation-hydrodynamic simulations. We then move on to report our recent results based on full 3D general relativistic simulations including a more approximate neutrino transport (e.g., [18, 19]). Finally, based on our recent parametric studies
using the light-bulb scheme, we exploratory seek possible ingredients to help the onset of neutrino-driven explosions, which includes nuclear energy deposition behind the supernova shock [20] and stellar rotation [21].

3D NEWTONIAN SIMULATIONS WITH SPECTRAL NEUTRINO TRANSPORT

In this section, we briefly summarize results from our multigroup (via the IDSA scheme), radiation-hydrodynamic core-collapse simulations in both 2D and 3D [17] for an 11.2 $M_\odot$ progenitor star of Woosley et al. [23].

The left panel of Figure 1 shows the blast morphology of our fiducial 3D model for the 11.2 $M_\odot$ star computed with highest numerical resolutions in [17] at $t_{pb} = 230$ ms (postbounce) when the revived shock is reaching an angle-average radius of 400 km (e.g., red dashed line in the right panel of Fig. 2). As seen from the side wall panels (left panel of Fig. 1), a bipolar explosion is obtained for this model. The middle panel (red regions) shows that the ratio of the residency timescale to the neutrino-heating timescale (e.g., Equations (6) and (7) in [16]) exceeds unity behind the shock, which presents evidence that the shock revival is driven by the neutrino-heating mechanism. The right panel of Figure 1 depicts spatial distribution of the net neutrino heating rate at $t_{pb} = 150$ ms. Small scale inhomogeneities (colored as red or yellow) are seen, which predominantly comes from neutrino-driven convection and anisotropies of the accretion flow, but the shape of the gain region is very close to be spherical before the onset of an explosion. This suggests that the bipolar geometry of the shock is produced not by the global anisotropy of the neutrino heating in the vicinity of the neutrino sphere, but by multi-D effects such as by neutrino-driven convection and the standing-accretion-shock instability (SASI) in the gain regions after the explosion (gradually) sets in.

Reflecting the stochastic nature of the multi-D neutrino-driven explosions, the blast morphology changes from models to models. The left and middle panels of Figure 2 show that a stronger explosion is obtained toward the north direction (model 3D-H-2) and the south pole (model 3D-H-3), respectively. In all our 3D models, seed random perturbations are added at 10 ms postbounce behind the shock with the amplitude of 1% relative to the unperturbed velocity. For the model-series 3D-H-1 (Figure 1), 3D-H-2 (left panel of Figure 2), and 3D-H-3 (middle panel of Figure 2), the difference comes only from the random seed perturbations (with the perturbation amplitudes being the same in all cases).

The right panel of Figure 2 shows the evolution of the average shock radius for our 1D (blue line), 2D (green lines), and 3D (red lines) models, respectively. Before the onset of shock revival (before 100 ms after bounce), the evolution of the shock is all similar to that of the 1D model (blue line). After that, the shock systematically expands more energetic in 2D (green lines) than in 3D (red lines). This feature is qualitatively consistent with [16], and also with [22] who recently reported 2D vs. 3D comparison based on a single 3D model but employing more detailed neutrino transport

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1 Our fiducial 3D run is computed on a spherical polar grid with a resolution of $n_r \times n_\theta \times n_\phi = 320 \times 64 \times 128$, in which non-equally spacial radial zones covers from the center to an outer boundary of 5000 km. For the spectral transport, we use 20 logarithmically spaced energy bins ranging from 3 to 300 MeV and we take a ray-by-ray approximation, in which a ray is cast for every angular zone.
than ours. Our findings could be taken as encouraging because our 3D self-consistent models for the 11.2 $M_\odot$ star are (at least) very likely to produce an explosion. If all the (exploding) 2D models would turn to be non-exploding in 3D, it may be very disappointing to CCSN practitioners. Above results showing that the neutrino-driven shock expands more energetically in 2D than in 3D may simply lead us to move on to seek some missing physical ingredients to assist neutrino-driven explosions in 3D. In the rest of this contribution, we will discuss several possible candidates to this end. First we discuss roles of general relativity (GR) in the next session.

**FIGURE 2.** Same as the top panel in Figure 1 but for models 3D-H-2 (left panel) and 3D-H-2 (middle panel), which produces stronger explosions closely toward the north (left panel) and south pole (middle panel), respectively. Note that models 3D-H-2 and 3D-H-3 are computed in the same computational setting as the 3D model in Figure 1, except for the difference of the seed random perturbations with the perturbation amplitudes being the same in all cases. Right panel shows the evolution of average shock radii for the high-resolution 2D (green lines) and 3D (red lines) models (the difference of the random perturbations are labeled by -1, -2, -3, -4, and so on, see Table 1 in [17] for more details).

### 3D FULL GR SIMULATIONS WITH AN APPROXIMATE NEUTRINO TRANSPORT

In this section, we summarize our first 3D-GR simulations of a 15 $M_\odot$ star based on [18] that include an approximate treatment of neutrino transport. We present also some new results for a 27 $M_\odot$ star [23], for which we just finished the data-transfer from our supercomputer until $\sim$200 ms after bounce. The spacetime treatment of our full GR code [24] is based on the Baumgarte-Shapiro-Shibata-Nakamura formalism. The hydrodynamics can be solved either in full GR or in special relativity (SR), which allows us to investigate the GR effects on the supernova dynamics. Using a M1 closure scheme with an analytic variable Eddington factor, we solve the energy-independent set of radiation energy and momentum (see [18] for more details).

The left panel of Figure 3 shows a snapshot at $t = 40$ ms postbounce for our 3D GR model. At this stage, the bounce shock stalls (seen as a greenish sphere) and the gain region forms at $\sim$80 ms after bounce in which neutrino heating dominates over neutrino cooling. The neutrino-driven convection gradually develops later on. The entropy behind the standing shock becomes higher with time due to neutrino-heating. The high entropy bubbles ($s[k_B/\text{baryon}] \geq 10$) rise and sink behind the standing shock. The shock deformation is dominated by unipolar and bipolar modes, which is a characteristic feature of the SASI. The size of the neutrino-heated regions grows bigger with time in a non-axisymmetric way, which is indicated by bubbly structures with increasing entropy (indicated by reddish regions in the right panel).

The left panel of Figure 4 shows evolution of the neutrino luminosities (for $\nu_e$ and $\bar{\nu}_e$) for all the computed models. After the neutronization burst ($t_{\text{neb}} \sim 10$ ms), the $\nu_e$ luminosity for the GR models slightly increases later on, while it stays almost constant for the SR models during the simulation time (green and blue lines). Although the luminosities change with time, the luminosities generally yield to the following order, for $\nu_e$, 3D-GR > 1DGR, 3D-SR > 1D-SR, for $\bar{\nu}_e$, 3D-GR > 1DGR, 3D-SR > 1D-SR, and for $\nu_x$, 3D-GR > 1DGR, 3D-SR > 1D-SR. To summarize, both 3D

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2 (or simply sad..)

3 The 3D computational domain consists of a cube of 10000$^3$ km$^3$ volume in the Cartesian coordinates. The maximum refinement AMR level is 5 in the beginning and then increment it as the collapse proceeds. The criterion to increment $L_{\text{AMR}}$ is set every time the central density exceeds $10^{12,13,13.5}$ g cm$^{-3}$ (see [24] for more details), yielding an effective resolution of $\Delta t \sim 600$ m at bounce.
FIGURE 3. Three dimensional plots of entropy per baryon for four snapshots (left: $t_{pb} = 40$ ms and right: $t_{pb} = 100$ ms) for our 3D-GR model of a 15 $M_\odot$ star (taken from [18]). The contours on the cross sections in the $x = 0$ (back right), $y = 0$ (back bottom), and $z = 0$ (back left) planes are, respectively projected on the sidewalls of the graphs to visualize 3D structures. For each snapshot, the arbitrary chosen iso-entropy surface is shown, and the linear scale is indicated along the axis in unit of km.

FIGURE 4. Neutrino luminosities for $\nu_e$, $\nu_x$ (left panel) as a function of postbounce time, respectively. Right panel shows the ratio of the residency timescale to the heating timescale for the set of our models as functions of post-bounce time (see [18] for the definition of the timescales). These figures are taken from [18].

and GR work to raise the neutrino luminosities in the early postbounce phase. As seen from the left panel in Figure 4, GR maximally increases the $\nu_e$ luminosity up to $\sim 50\%$ (in 3D), while the maximum increase by 3D is less than $\sim 20\%$ (compare the $\bar{\nu}_e$ luminosity between the 3D-GR and 1D-GR model). These results indicate that compared to the spacial dimensionality, GR holds the key importance to enhance the neutrino luminosities. This is also the case for the RMS neutrino energy. The reason for the higher neutrino energy is that the deeper gravitational well of GR produces more compact core structures, and thus hotter neutrino spheres at smaller radii.

The right panel of Figure 4 shows the ratio of the residency timescale to the neutrino-heating timescale for all the computed models. As seen, the shock revival seems most likely to occur for the 3D-GR model (red line) in our simulation time, which is followed in order by 3D-SR, 1D-SR and 1D-GR models. Thanks to a more degree of freedom, the residency timescale becomes much longer for the 3D models than for the 1D models. In addition, the increase of the neutrino luminosity and RMS energies due to GR enhances the timescale ratio up to the factor of $\sim 2$ for the 3D-GR model (red line) compared to the SR counterpart (blue line). These results suggest that GR could potentially help the onset of neutrino-driven explosions in 3D.

The left panel of Figure 5 shows a snapshot of our 3D-GR model for a 27 $M_\odot$ star at $t_{pb} = 194.6$ ms postbounce. From the sidewall panels, one would expect that this model exhibits a violent SASI activity with the sloshing (see vertical sidewall panels) and spiral modes (bottom sidewall panel). The right panel of Figure 5 supports this anticipation, which shows the clear oscillatory behavior of the $(\ell, m) = (1, 0)$ sloshing SASI mode as well as the $(\ell, m) = (1, 1)$ spiral SASI mode. This feature is in good agreement with the work by [22] who recently employed the same progenitor model in their 3D Newtonian model but with elaborate transport scheme.

For both the 15 $M_\odot$ and 27$M_\odot$ progenitors employed in our full-GR-3D simulations, 2D self-consistent models...
have so far predicted the onset of an explosion to be after $\sim 200 - 300$ ms postbounce at the earliest ([8, 22]) and it could be delayed after $\sim 600$ ms postbounce ([6]). Although it is very computationally expensive, we need to follow the postbounce dynamics in the much later time to have the final word on whether our 3D-GR models\textsuperscript{4} can or cannot produce an explosion finally.

**POSSIBLE INGREDIENTS TO FOSTER NEUTRINO-DRIVEN EXPLOSIONS: EXPLORATORY SIMULATIONS WITH A "LIGHT-BULB" SCHEME**

In the rest of this contribution, we discuss possible ingredients to help neutrino-driven explosions, which have yet to be included in self-consistent 3D models. For the sake of our systematic survey, we are now switching gears to parametrized models, in which neutrino heating and cooling is treated by a light-bulb scheme (see [25] for more detail). Following [25], we take the light-bulb neutrino luminosities for $\nu_e, \bar{\nu}_e$ to evolve exponentially with time as $L_{\nu_e} = L_{\bar{\nu}_e} = L_{\nu_0} \exp\left(-t_{pb}/t_d\right)$, where $L_{\nu_0}$ denotes the initial luminosity, $t_{pb}$ is the time measured after core bounce, $t_d$ is the decay time, respectively. $L_{\nu_0}$ and $t_d$ are treated as free parameters. Based on these parametrized models, we discuss possible impacts of nuclear energy deposition behind the supernova shock [20] and stellar rotation [21] on the neutrino-driven mechanism.

**Nuclear burning**

Figure 6 shows the mass-shell trajectory of a 15 $M_\odot$ model by Limongi-Chieffi [26] (LC15) with the different parameter set of $(L_{\nu_0.52}, t_d) = (2.2, 2.0)$ and $(L_{\nu_0.52}, t_d) = (2.0, 5.0)$, respectively. Note that $L_{\nu_0.52}$ represent the luminosity in unit of $10^{52}$ erg s$^{-1}$. By calculating a 13-isotope $\alpha$ network, we take into account energy deposition by nuclear burning in the hydrodynamic simulations. Without nuclear burning (left panel of Figure 6), the stalled shock (red line), showing several oscillations, does not turn into expansion finally. With nuclear burning (right panel), the shock expansion can be seen to take place when the shock front passes through the Si-rich layer (see the behavior of the thick red line in the green region in the right panel) or later it touches to the O-rich layer (e.g., right panel of Figure 4 in [20]). These results show that energy input due to nuclear burning of the postshock material can energize the shock expansion in models that fail to produce an explosion (if not for nuclear burning).

\textsuperscript{4} Of course, it is urgent for us to update our GR transport scheme from gray to multi-energy and to include more detailed neutrino opacities.
FIGURE 6. Evolution of model LC15 with a parameter set of \((L_{\nu0}, t_d) = (2.2, 2.0)\) visualized by the mass-shell trajectories. The thick red line starting at \(t = 0\) denotes the position of the shock. Both cases either without (left) or with (right) the energy feedback from nuclear reactions are shown. The regions colored by gray, green, and red correspond to the iron, silicon, and oxygen layers, respectively. Thick gray lines correspond to the mass coordinates from 1.3 to 1.8 \(M_\odot\) with every 0.1 \(M_\odot\) (thin gray lines with every 0.02\(M_\odot\)).

FIGURE 7. Parameter maps of the initial neutrino luminosity \((L_{\nu0})\) and its decay time \((t_d)\) that separates the non-exploding regime (blue region) from the exploding one (red regime) in 2D light-bulb simulations for the LC15 progenitor. The dashed lines represent the critical curves in 1D.

Figure 7 shows the parameter region on the \((L_{\nu0}, t_d)\) plane, in which 2D explosions are obtained only if the network calculation is performed (e.g., the yellow region between the exploding and the non-exploding regime). In the same way, we have investigated the impacts of nuclear burning for three more progenitor models, namely, 15 \(M_\odot\) star by Woosley & Weaver (1995), and 11.2\(M_\odot\) and 15\(M_\odot\) stars by Woosley et al. (2002). Among them, the parameter region in which an explosion is obtained when nuclear burning is taken into account (yellow region) was clearly visible only for the LC15 progenitor. This is because the LC progenitor model possesses a massive oxygen layer and the oxygen shell is positioned closest to the center among the four progenitor models, so that the shock can touch to the rich (burning) fuel on a shorter timescale after bounce (before the neutrino luminosity becomes smaller). Considering that there still remain a number of uncertainties in the progenitor modelings (such as about the treatment of mass-loss, mixing, and weak interaction rates [27]), our results indicate that nuclear burning (which has yet to be included in self-consistent 3D models) should remain as one of the key ingredients to foster the onset of neutrino-driven explosions.

Rotation

Finally, we discuss possible impacts of rotation based on our 3D special relativistic models [18] that employ the light-bulb scheme for neutrino heating and a leakage scheme for neutrino cooling [21]. Note in this session, the input neutrino luminosity (for heating) is taken to be constant with time. To model precollapse rotational profile, we assume a shell-type rotation law \(\Omega(r) = \Omega_0 R_0^2/(r^2 + R_0^2)\), where \(\Omega(r)\) is the angular velocity at the radius of \(r\), and \(\Omega_0\) is...
the model parameter, and $R_0$ is set as $2 \times 10^8 \text{cm}$, which is reconciled with results from stellar evolution calculations suggesting uniform rotation in the precollapse core.

The left panel of Figure 8 shows time evolution of average shock radius $\langle R_{sh} \rangle$ for models with $L_{\nu, 52} = 2.5$ (red lines) and 2.7 (blue lines) as a function of post-bounce time $t_{pb}$. For the non-rotating $L_{\nu, 52} = 2.5$ model (thin red line), the shock stalls at $r \sim 200 \text{ km}$ after bounce, stays around $r \sim 300 \text{ km}$, then starts to shrink to $r \sim 150 \text{ km}$ and never explodes. The corresponding rotating model with $\Omega_0 = 0.1 \pi \text{ rad s}^{-1}$ (thick red line) shows similar behavior to the non-rotating model (thin red line) till $t_{pb} \sim 200\text{ms}$. Then the shock for the rotating model (thick red line) gradually expands to $r \sim 400 \text{ km}$, and revives to expand more energetically afterward. It should be mentioned that $\Omega_0 = 0.1 \pi \text{ rad s}^{-1}$ is in agreement with the outcomes of most recent stellar evolution models that were evolved with the inclusion of magnetic fields ($\Omega_0 = 0.2 \sim 0.3 \text{ rad s}^{-1}$ of models m15b4 and m20b4 in Heger et al. [28]). This means that such slow rotation can impact on the onset of an explosion. This feature is qualitatively the same for models with different input luminosity (e.g., blue curves in the left panel of Figure 8).

Without rotation, the explosion geometry has no preferential direction, so that the blast morphology tends to be spherical (especially for models with lower input neutrino luminosity, see the middle panel of Figure 8 showing a roundish (average) shock surface). On the other hand, with rotation (of course, depending on the initial rotation rates), the proto-neutron star (PNS) and the shock surface deforms to be oblate due to the centrifugal forces (right panel of Figure 8). As a result, the gain region becomes more concentrated around the equatorial plane (see right panel of Figure 9) for models with larger initial angular momentum, while the gain mass is randomly distributed behind the shock for the non-rotating model (left panel of Figure 9). Moreover, the gain mass tends to be bigger for models with higher initial angular momentum. These are the main reasons that rotation can help the neutrino-driven explosions as demonstrated in the left panel of Figure 8. Here it should be noted that for rapidly rotating models the neutrino flux from the oblatey deformed PNS is not isotropic any more [29]. This means that the time-independent isotropic neutrino flux assumed in the light-bulb scheme is no longer valid. To elaborate the effects of rotation on the neutrino-driven mechanism, we are currently performing self-consistent 3D models with rotation, which will be submitted elsewhere very soon (Takiwaki and Kotake in preparation).

**FIGURE 8.** The left panel shows evolution of the average shock radius as a function of the postbounce time $t_{pb}$ for 3D light-bulb models with moderate rotation ($\Omega_0 = 0.1 \pi \text{ rad s}^{-1}$, thick lines), and no rotation (thin lines). Different electron-neutrino luminosity (labeled in the plots in unit of $10^{52} \text{ erg s}^{-1}$). The color-coded panels shows snapshots of 3D entropy distribution for $L_{\nu, 52} = 2.5$ models. Shown are the cases with two different rotational velocity, $\Omega = 0.0$ (left column) and $\Omega = 0.1 \pi \text{ rad s}^{-1}$ (right), at $t_{pb} = 450 \text{ ms}$ postbounce. Note that spacial scale is different between left ($600^3 \text{ km}^3$) and right ($2000^3 \text{ km}^3$).

**FIGURE 9.** Mollweide map of gain mass distributions for $L_{\nu, 52} = 2.5$ models with $\Omega_0 = 0.0$ (left column) and $0.1 \pi$ (right). Shown are snapshots of the gain mass in each solid angle normalized by total gain mass at $t_{pb} = 200 \text{ ms}$. 
OUTLOOK

Finally it is worth mentioning that the combined effects of 3D, GR, and rotation (which we have rather separately discussed in this contribution) should affect not only the supernova dynamics, but also the observational signatures of gravitational-waves (GWs), neutrino emission and explosive nucleosynthesis (e.g., [30] for a review). To draw a solid conclusion to these important observables, the energy and angle dependence of neutrino transport should be accurately incorporated in our full GR simulations with the use of more detailed set of weak interactions. This work is only the very first step that leads us to the long and winding road.

It is true that the goal for such ultimate SN models (3D-GR models with 6D Boltzmann transport) is still miles away, but one could at least say that (from an optimistic point of view) our understanding of the explosion mechanism can progress in a step-by-step manner at the same pace as our available computational resources will be growing bigger and bigger from now on. Since 2009, several neutrino detectors form the Supernova Early Warning Systems (SNEWS) to broadcast the alert to astronomers to let them know the arrival of neutrinos. Currently, Super-Kamiokande, LVD, Borexino, and IceCube contributes to the SNEWS, with a number of other neutrino and GW detectors planning to join in the near future. This is a very encouraging news towards the high-precision multi-messenger astronomy that targets CCSN events. The interplay between detailed numerical modeling, advancing supercomputing resources, and multi-messenger astronomy, will remain as a central issue for advancing our understanding of the CCSN theory. What we presented here in the OMEG12 workshop is nothing but an only snapshot of the moving (long-run) documentary film that records our endeavors for making the dream come true.

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