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THREE-DIMENSIONAL SIMULATION OF A ROTATING CORE-COLLAPSE SUPERNOVA

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ABSTRACT

Multi-dimensionality in the inner working of core-collapse supernovae has long been considered one of the most important ingredients to understand the explosion mechanism. We perform a series of numerical experiments to explore how rotation impacts the 3-dimensional hydrodynamics of core-collapse supernova. We employ a light-bulb scheme to trigger explosions and a three-species neutrino leakage scheme to treat deleptonization effects and neutrino losses from the neutron star interior. We find that the rotation can help the onset of neutrino-driven explosions for models in which the initial angular momentum is matched to that obtained from recent stellar evolutionary calculations (~ 0.3 - $3\,\mathrm{rad\,s^{-1}}$ at the center). For models with larger initial angular momenta, a shock surface deforms to be oblate due to larger centrifugal force. This makes a gain region, in which matter gains energy from neutrinos, more concentrated around the equatorial plane. As a result, the preferred direction of the explosion in 3-dimensional rotating models is perpendicular to the spin axis, which is in sharp contrast to the polar explosions around the axis that are often obtained from 2-dimensional simulations.

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1. INTRODUCTION

Ever since SN1987A, multi-dimensional hydrodynamic simulations have been carried out extensively in a variety of contexts. They give us confidence that multi-dimensional hydrodynamic motions associated with proto-neutron-star (PNS) convection, neutrino-driven convection, and the standing accretion shock instability (SASI) can help onset of neutrino-driven explosions.

One of the remaining problems is that the explosion energies obtained from two-dimensional (2D) models from first principles (although some of them were reported before their explosion energies became saturated) are typically smaller by one order of magnitude compared to what is needed to explain the canonical supernova kinetic energy ($\sim 10^{51}$ erg).

Many researchers are now seeking for some possible physical ingredients to make these underpowered explosions more energetic. One of the major candidates is three-dimensional (3D) effects on the neutrino-driven mechanism. Another prime candidate is general relativity, which has been found to help neutrino-driven explosions in both 2D and 3D models. The impacts of nuclear equations of state (EOS) have been investigated in 2D models, and these studies reached an agreement that a softer EOS leads to easier explosions.

In this article, we investigate the roles of rotation as a possible ingredient to foster explosions. We performed a series of simplified numerical experiments to explore how rotation impacts the 3D hydrodynamics of the CCSN core that produces an explosion by the neutrino mechanism. For our systematic study, we employed a light-bulb scheme to trigger explosions and a three-species neutrino leakage scheme to treat deleptonization effects and neutrino losses from the neutron star interior. We made pre-collapse models by parametrically adding the initial angular momentum to a widely used 15 $M_\odot$ progenitor (Woosley & Weaver, 1995). We carried out 3D special-relativistic simulations starting from the onset of gravitational collapse, through bounce, moving towards explosions (typically up to about ~ 1 s postbounce) and compared the results of 30 models, in which the input neutrino luminosity and the initial rotation rate are systematically varied.

2. RESULTS

In our simulations, we assume a shell-type rotation profile as

$$\Omega(r) = \Omega_0 \frac{R_0^2}{r^2 + R_0^2}, \tag{1}$$

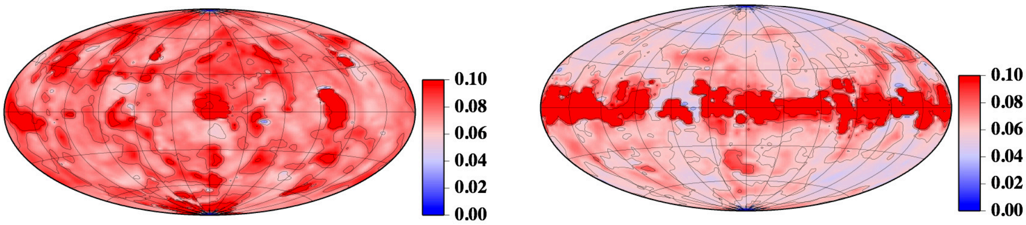

Figure 1. Mollweide maps showing the mass distributions in the gain region for the models with $\Omega_0 = 0.0$ (left) and 0.1π (right) at $t_{\rm pb} = 200$ ms postbounce. Concentration of the gain mass around the equatorial plane is clearly seen in the rotating model.

where $\Omega(r)$ is the angular velocity at the radius r, R_0 is set to be 2×10^8 cm, and the initial angular velocity at the origin Ω_0 is treated as a free parameter and we vary it as $\Omega_0 = 0$, $0.1\,\pi$, and $0.5\,\pi$ rad s^{-1}.

We found that the critical neutrino luminosity for obtaining neutrino-driven explosions generally becomes smaller for models with larger initial angular momenta. Our 3D models show a much wider variety in the explosion geometry than in two dimensions. In the 3D rotating models, we found that the preferred direction of the explosion is often perpendicular to the spin axis, which is in sharp contrast to polar explosions around the spin axis that were commonly obtained from previous 2D simulations. Details of our numerical scheme and results are in Nakamura et al. (2014). In this article, we summarize the results of two models with a different value of Ω_0 ($= 0$ and $0.1\,\pi$ rad s^{-1}) and with a common input neutrino luminosity $L_\nu = 2.5 \times 10^{52}$ erg s^{-1}.

In neutrino-driven explosions, the shock revival is governed by the mass in the gain region where material can gain energy by neutrino heating. Figure 1 shows the angular distribution of the gain mass for the non-rotating ($\Omega_0 = 0$, left panel) and the moderately rotating ($\Omega_0 = 0.1\pi$, right) models. We find that the gain mass of the rotating model begins concentrating around the equatorial plane ~ 150 ms postbounce. This feature has never appeared in the non-rotating model.

This gain mass concentration of the rotating model results in a different behavior of the shock compared to the non-rotating model. Figure 2 shows the time evolution of average shock radius for our two models. Without rotation, the bounce shock stalls at $r \sim 200$ km and never revives during our simulation time. When the model initially has moderate rotation ($\Omega_0 = 0.1\,\pi$,), the shock shows a clear deviation from the non-rotating model. This occurs after ~ 200 ms postbounce. This clearly demonstrates that even moderate pre-collapse rotation could affect the shock evolution. An additional model with very fast rotation ($\Omega_0 = 0.5\,\pi$,) is also shown in Figure 2 for reference.

3. CONCLUSIONS

We performed a series of simplified numerical experiments to explore how rotation impacts the 3D hydrodynamics of neutrino-driven CCSNe. We find that rotation can help the onset of neutrino-driven explosions for models, in which the initial angular momentum is matched to the one obtained from recent stellar evolutionary calculations. For models with larger initial angular momenta, the PNS and the shock surface deform to be more oblate due to the larger centrifugal forces. This not only makes the gain region much more concentrated around the equatorial plane, but also causes the mass in the gain region to become bigger. As a result, hot bubbles tend to be coherently formed in the equatorial region, which pushes the shock to ever larger radii. We found that these are the main reasons that the preferred direction of the explosion in the 3D rotating models is often perpendicular to the spin axis, which is in sharp contrast to the polar explosions around the axis that were obtained from previous 2D simulations.

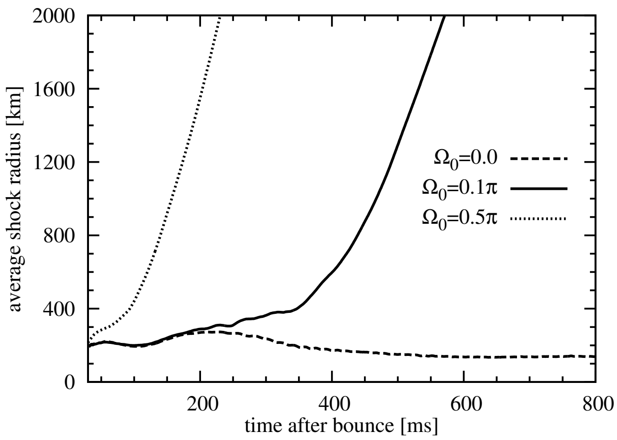

Figure 2. Time evolution of average shock radius. We can see that rotating models (solid and dotted lines) present shock revival, which is in contrast to the non-rotating model (dashed line).

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