Collapse of rotating very massive stellar core to a black hole and a disk

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Abstract. Recent studies of modeling a progenitor of long gamma-ray bursts (LGRBs) suggest that progenitors of LGRBs might have a core with higher entropy than that of ordinary presupernove. Based on the above suggestion, we performed fully general relativistic, two-dimensional simulations of collapse of higher entropy core to a black hole and an accretion disk taking account of important microphysics. The initial core is simply modeled by a equilibrium configuration with constant entropy and electron fraction. We clarified that the formation dynamics depends even qualitatively on the amount of angular momentum. As a novel feature, we discovered that accretion disks formed after collapse can be convectively unstable.

1. Introduction
Gamma-ray bursts (GRBs) have been one of the outstanding problems in astrophysics since their discovery. Although progenitors of LGRBs have not been fully clarified yet, a number of progenitor models of LGRBs have been proposed (for a review, see[1]). Some authors [2, 3, 4, 5] proposed interacting binary models, in which the tidal force in a close binary keeps a helium star in synchronous, rapid rotation. Fryer and Heger [6] proposed a binary-merger model and showed that a merger of two helium cores during the common-envelope inspiral phase can produce a rapidly rotating core which may produces a LGRB. On the other hand, it has been showed that a single star can fulfill the requirements of the collapsar models if it is initially rapidly rotating (>50% of the Keplerian velocity at the equatorial surface) and of low metallicity (Z/Z⊙ < 0.1) (chemically homogeneous evolution model [7, 8, 9]).

All of these progenitor cores are anomalous in the sense that they are quite different from those of ordinary supernovae. Qualitatively speaking, the progenitor models have larger angular momentum and a higher entropy core (and hence, the core is more massive). The chemically homogeneous models predict a well-mixed, larger core with higher central entropy. It is also expected that the object formed after the binary merger will have a higher entropy, if the mass ratio of merging stars is not far from unity [10, 11]. Such a massive stellar core may collapse directly to a black hole without producing any explosion. In this article, we perform fully general relativistic simulations of collapse of rapidly rotating, higher entropy core, taking into account detailed microphysics.

2. Setting
Recently, we developed a fully general relativistic hydrodynamic code implementing a realistic equation of state, self-consistent electron and positron captures, and neutrino cooling by a
general relativistic leakage scheme [12, 13]. We follow this paper for hydrodynamic equations for which the readers may refer to the details.

We construct approximate initial models in the following manner. We first calculate a spherical equilibrium configuration with a constant electron fraction and with a constant entropy per baryon ($Y_e = 0.5$ and $s = 8k_B$ in this article). We set the central density to be $\rho_c \approx 10^8$ g/cm$^3$. Following Nakazato et al. [14], we define the boundary of the iron core to be where the temperature is $5 \times 10^9$ K. Then the mass and the radius of the iron core are $M_{\text{iron}} \approx 13M_\odot$ and $R_{\text{iron}} \approx 7000$ km. We adopt a wider region of $R_{\text{init}} \approx 14000$ km for simulation.

At the current status, little is known about the angular momentum distribution in the progenitor core. Therefore we add the rotation profile according to $\Omega(\varpi) = \Omega_0 \exp[-R_c^2/(2(\varpi^2 + R_0^2))] \exp[-\varpi^2/R_0^2]$, where $\varpi = \sqrt{x^2 + y^2}$. $\Omega_0$, $R_0$ and $R_c$ are parameters which control the degree of differential rotation. We fix the values of $R_0$ and $R_c$ as $R_0 = R_{\text{init}}/5$ and $R_c = R_{\text{init}}/8$ and vary $\Omega_0$ as 0, 0.4, 0.5 and 0.6 (hereafter referred to as spherical, slowly rotating, moderately rotating, and rapidly rotating models).

3. Results

The general feature of collapse until black hole formation can be summarized as follows. Gravitational collapse is triggered by the photo-dissociation of heavy nuclei and the electron capture. As the collapse proceeds the pressure is dominated by thermal gas pressure, and a weak bounce occurs at a subnuclear density forming a weak shock wave which is to be stalled quickly. Because the weak bounce is weak and ram pressure is strong, a black hole is formed soon after the bounce. Soon after the black hole formation neutrino luminosities decrease drastically because the main neutrino-emission region is swallowed by the black hole. After the black hole formation, on the other hand, the dynamics and feature of neutrino emission depend on the amount of angular momentum.

3.1. Slowly Rotating Model

In the slowly rotating model, a geometrically thin (but optically thick) accretion disk is formed soon after the black hole formation. A part of the material that falls onto the disk produces shock waves in the inner part of the disk (see the left panel of Figure 1). Thermal energy generated at the shock is not efficiently stored and the disk remains geometrically thin for a long time.
The left panel of Figure 2 plots the time evolution of neutrino luminosities for the slowly rotating model. It is found that the geometrically thin accretion disk emits $10^{53}$ erg/s by neutrinos. The efficiency of neutrino emission is very small as $\frac{L_{\nu,\text{tot}}}{(\dot{M}_{\text{BH}}c^2)} \approx 0.002-0.003$, which indicates that only small amount of material experiences the shock heating, and that most of energy is advected into the black hole before released by neutrinos.

### 3.2. Moderately Rotating Model
The feature of collapse is similar to that of slowly rotating model until formation of a geometrically thin disk. However, as the material with higher specific angular momentum in the outer region falls onto the disk, the density and mass of the disk increases. As the thermal energy is stored, the disk height $H$ increases according to the balance relation $(P_{\text{disk}} - P_{\text{ram}})/H \sim GM_{\text{BH}}\rho_{\text{disk}}H/R_{\text{disk}}^3$. The density and the temperature inside the disk increase and the ram pressure decreases. Consequently, $H$ increases to be $\sim R_{\text{disk}}$. The approximate balance relation is now written as $P_{\text{disk}} - P_{\text{ram}} \sim GM_{\text{BH}}\rho_{\text{disk}}/H$. Because the binding due to the gravitational force by the black hole decreases as $H$ increases, the disk expands forming shock waves [15]. The neutrino opacities decrease as the disk expands, and accordingly, the cooling timescale becomes shorter. Then, the shock wave is stalled and the disk relaxes to a new geometrically thick state. Note that neutrino luminosities are significantly enhanced after the thick torus formation.

After the formation of the geometrically thick torus, convective motions are excited in the torus and near the shocked region (see the middle panel of Figure 1). The origin of the convection is explained as follows. The shock heating is more efficient in an inner part of the disk because kinetic energy of infalling material is larger. On the other hand, the neutrino cooling is less efficient in an inner part of the disk because of its larger optical depth. Thus, regions of negative entropy gradient along the radial direction near the equatorial plane are developed. Such configurations are known to be unstable to convection.

As a natural consequence of the convective activities of the accretion flow, neutrino luminosities vary violently in time (see the middle panel of Figure 2). If GRBs are driven by the pair annihilation of neutrinos and anti-neutrinos, such time-variability may be associated with the observed time-variability of GRB light curves.

### 3.3. Rapidly Rotating Model
In the rapidly rotating model, the disk formation process is qualitatively different from that in the moderately rotating model: A geometrically thick torus is formed immediately after the
black hole formation because the pressure gradient and the angular momentum of the fluid near the equator are large enough that it retains an orbit outside the ISCO. Shock waves formed at the weak bounce is not swallowed into the black hole and a torus-shaped standing accretion shock remains around the black hole.

After the black hole formation, the luminosities decrease slightly. However, a dense torus surrounding the black hole is formed in a short time scale resulting in large total luminosity of $3 \times 10^{54}$ erg/s (see the right panel of Figure 2).

Convective motions are also observed in the rapidly model as in the moderately rotating model. However, strong large-scale circulations, appeared in the moderately rotating model, do not occur in the rapidly rotating model, although small-scale convective activities are driven (see the right panel in Figure 1). This is due to the stabilizing effect of the epicyclic frequency. Due to the absence of large-scale convective modes, effects of the convection on neutrino luminosities are likely to be minor. Indeed, no violent time-variability is observed after the thick torus formation.

4. Summary
We performed axisymmetric simulations of massive stellar core collapsing to a system composed of a rotating black hole and surrounding disk in full general relativity.

In the moderately rotating model, a geometrically thin accretion disk is first formed around the black hole and shocks are formed on its surface. As the thermal energy is stored in the disk, the disk expands to be a geometrically thick accretion torus. After the thick torus formation, convective activities set in because a region with negative entropy gradient emerges in the inner part of the torus. As a consequence the neutrino luminosities show violent time-variability with $L_\nu \sim 10^{54}$ erg/s.

The evolution of the accretion disk and neutrino emissivity depend strongly on the degree of initial rotation. In the slowly rotating model, the disk remains geometrically thin for a long time, and hence, the neutrino emissivity also remains relatively small ($\sim 10^{53}$ erg/s). In the rapidly rotating model, by contrast, a geometrically thick torus is immediately formed after the black hole formation, and luminosities of neutrinos emitted from the torus are as high as $10^{54}$ erg/s even at its formation. However, the convection is suppressed by the stabilizing epicyclic mode due to the rapid rotation and no violent time-variability is observed in the neutrino luminosities.

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References
[1] Fryer C L et al. 2007 Publ. Astron. Soc. Pacific 119 1211
[2] Izzard R G et al. 2004 Mon. Not. Roy. Astron. Soc. 348, 1215
[3] Podsiadlowski et al. 2004 Astrophys. J. 607, L17
[4] van den Heuvel E P J and Yoon S C 2007 Astrophys. Space Sci. 311 177
[5] Cantiello M et al., 2007 Astron. Astrophys. 465, L29
[6] Fryer C L and Heger A 2005 Astrophys. J. 623, 302
[7] Yoon S C and Langer N 2005 Astron. Astrophys. 443 643
[8] Yoon S C, Langer N and Norman C 2006 Astron. Astrophys. 460 199
[9] Woosley S E and Heger A 2006 Astrophys. J. 637 914
[10] Suzuki T K et al. 2007 Astrophys. J. 668 435
[11] Gaburov E, Lombardi J C and Portegies Zwart S 2008 Mon. Not. Roy. Astron. Soc. 383 L5
[12] Sekiguchi Y 2010 Class. Quant. Grav. 27 114107
[13] Sekiguchi Y 2010 Prog. Theor. Phys. 124 331
[14] Nakazato K, Sumiyoshi K and Yamada S 2007 Astrophys. J. 666 1140
[15] Sekiguchi Y and Shibata M 2007 Prog. Theor. Phys. 117 1029