Supernovae: rotation, jets and neutrinos

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Abstract. I will give an overview of the current status of our understanding on the mechanism of collapse-driven supernovae and related phenomena, paying a particular attention to the asymmetry of dynamics and neutrino signals from them.

1. Introduction
The collapse-driven supernova is an explosive phenomenon which is supposed to occur at the end of the evolution of massive stars (≥8M⊙). The mechanism of collapse-driven supernovae has eluded our understanding for more than 40 years [1]. The difficulty in the modelling of collapse-driven supernova arises from the fact that it involves a complex combination of microphysics and macrophysics. In fact, weak interactions and nuclear physics are supposed to be dictating the dynamics in a critical way. It has also become a common sense that the collapse-drive supernova is in general not spherically symmetric.

The stellar rotation will be the most naive explanation for the asymmetric explosion. The rotation may be also an indispensable factor for gamma-ray bursts [2] and accompanying supernovae [3]. The interest in the role of magnetic field in the supernova is also growing [4] partly because of the existence of highly magnetized neutron stars, the so-called magnetars, and also in the expectation that the magnetic fields play a crucial role in the central engine of gamma-ray bursts.

The supernova explosion is supposed to occur for massive stars in the mass range of ~ 10 · · · ~ 30M⊙ [5]. Nowadays more massive stars are attracting much interest of researchers from beyond the supernova community. This is almost entirely due to the recognition that long gamma-ray bursts are somehow caused by the gravitational collapse of massive stars and subsequent black hole formation. It should be also mentioned that the interest in the first generation stars, or population III stars (POP III stars), is also growing rapidly these days thanks to the results of WMAP [6] as well as other observations of old stars [7]. It is generally supposed that not a small fraction of POP III stars had a very high mass of ~ 100 · · · ~ 1000M⊙ [8]. The future supernova research, thus, should be defined in the greater perspective of the gravitational collapse of massive stars.

In the following sections, I will focus on the particular issues mentioned above in turn.

2. Spherically Symmetric Models
Before going to the multi-dimensional issues, I will briefly summarize the spherical models. The theoretical research of the collapse-driven supernova has been done mainly in the context of the
so-called delayed explosion, in which a stalled shock wave is re-energized by neutrinos copiously emitted out of the proto neutron star.

It is known that there is a critical neutrino luminosity for the shock revival [9, 10]. Hence the issue is whether this critical value is realized in the evolution or not. The evaluation, however, requires a quantitative numerical modelling with all the relevant neutrino physics taken into account. Such sophisticated simulations have been done by a couple of groups over the years [11, 12, 13, 14]. Although the employed numerical techniques are different among them, different EOS’s are tried and various minor interactions and corrections have been explored, the results are consistently negative, that is, the neutrino heating is not high enough to produce successful explosions.

For example, figure 1 shows our latest results [14]. The evolutions were followed for more than a second after the core bounce for two realistic nuclear EOS’s. The left panel shows the mass trajectories for Shen’s EOS. As mentioned, there is no hint of shock revival. In fact, the shock stalls at around 200 km from the center and becomes an accretion shock and then starts to recede onto the proto neutron star later on. The evolution is not qualitatively different for the other EOS by Lattimer & Swesty and no explosion was found in this case, either, as found in the right panel.

Although the explosion mechanism is unknown, one particular feature of the neutrino signal can be predicted with some certainty as long as the rotation of the core is not very rapid. That is a so-called neutronization burst, which is a burst of electron-type neutrinos that occurs when the shock passes through the neutrino sphere. Kachelriess et al. [15] showed by numerical simulations that the neutronization burst is a robust signal affected little by the difference of the progenitor mass and uncertainties of microphysics. Since the signal observed on terrestrial detectors is subject to the neutrino oscillations in the stellar envelope and the earth, it will be a useful probe for the neutrino properties.

3. Rapid Rotation of Supernova Core and Global Asymmetry
If a collapsing star rotates rapidly, the accretion flow through the stalled accretion shock onto the proto neutron star becomes non-spherical due to the centrifugal forces. On the other hand, neutrinos are emitted anisotropically. A simple geometrical argument suggests that the neutrino flux is enhanced in the direction of the rotation axis. Then the neutrino heating and, as a result, the shock revival will be also affected. These effects can be seen qualitatively by solving steady
rotational accretion flows and observing how the critical luminosity is changed by the rotation [16].

The critical luminosity is lowered by rotation in two ways as shown in figure 2. Even if the neutrino-anisotropy is ignored, the critical luminosity is lower than that of the spherically symmetric flow with the same mass accretion rate. This clearly demonstrates that the rotation assists the revival of stalled shock. What is more, it is found that the condition of the shock revival is first satisfied at the rotation axis. This suggests that the shock revival is triggered on the rotation axis and a jet-like explosion is likely to ensue.

In the above models, it is assumed that neutrinos are emitted isotropically, which is no doubt unnatural. In fact, the centrifugal force renders the central core oblate, which also implies that the neutrino sphere becomes flattened. Then it is expected that neutrinos are emitted more preferentially in the direction of the rotation axis, which was indeed confirmed by recent simulations [17, 18]. We are naturally inclined to ask what is the influence of this anisotropic irradiation of neutrinos for the critical luminosity. Still preliminary results [19] suggest that this also tends to reduce the critical luminosity. In fact, we found that the rotation and anisotropic neutrino irradiation work additively to lower the critical luminosity as shown in figure 2. In these calculations we assumed that the neutrino temperature is given by $T_\nu \propto (1 + a \cos^2 \theta)$, where $\theta$ is a polar angle and $a = 0.1, 0.3$.

We have to wait for realistic multi-dimensional simulations before we can conclude if these effects are crucially important for the shock revival or not. Kotake et al. [17], for example, did 2D simulations of rotational collapse, varying the initial angular momentum and its distribution systematically. Although the neutrino transport was simplified, they found that the neutrino sphere becomes oblate in general indeed around the shock stagnation. More recently, Walder et al. [18] did 2D simulations of rotational collapse with the so-called multi-group flux-limited diffusion approximation for the neutrino transport. More importantly, they continued computations for about 200ms after the bounce, that is, up to the period where the neutrino heating is most efficient. They confirmed that the neutrino flux is enhanced in the direction of the rotation axis by a factor of $\sim 2$ for the rapidly rotating case ($\sim 1$rad/s prior to the collapse). It is incidentally mentioned that the authors did not claim a successful explosion in this paper although it is premature to say anything conclusive about the shock revival at this point, since

Figure 2. The critical luminosities for the rapidly rotating case. The left panel represents the case for the rotation without neutrino-anisotropy and the right panel shows the results with both the rotation and neutrino-anisotropy taken into account. The rotation frequency is 0.1 Hz at a radius of 1000 km.
the employed approximation tends to underestimate the anisotropy of the neutrino flux and the implementation of the neutrino transport is still incomplete.

For the last few years we have seen a remarkable rise of interest in the possible role of magnetic fields in the supernova mechanism [4, 20, 21, 22]. For example, Sawai et al. [23] did 2D MHD simulations of the collapse from the rapidly rotating and strongly magnetized core and found that the initial magnetic fields parallel to the rotation axis produced jet-like prompt explosions in the direction of the rotation axis irrespective of the distribution of field strength. So did the quadrupole-type fields. Note that the model with rotation but not magnetic field failed to produce an explosion, and hence that the magnetic field played a critical role in producing explosions. Interestingly, the model with a purely toroidal field at the beginning also failed. Hence the poloidal component of the magnetic field is crucially important.

It has been also advocated that initially weak magnetic fields will grow exponentially by the magneto-rotational instability (MRI) to the saturation level that is large enough to affect the dynamics. Bisnovatyi-Kogan and his collaborators have published [22] some results that claim the confirmation of MRI in the post-bounce core. Provided their crude approximation to the microphysics and the initial set up of the models, I think that it is premature to say something conclusive on the importance of MRI. It is incidentally mentioned that the strong magnetic fields produced by MRI should be somehow diminished by the time when young pulsars are observed to have a canonical dipole field strength if MRI were to be a key ingredient for ordinary supernovae.

So far we assumed in this section that the progenitor is a rapid rotator. This may not be the case, however. In fact, some stellar evolution models predict otherwise, and it is well known that young pulsars are supposed to be born as a slow rotator. Then the natural question is how the asymmetry of explosion as observed was produced. Hydrodynamical instabilities may be the answer. Recently, Blondin et al. [24] demonstrated numerically that a hydrodynamical instability other than convection may be operating to drive non-spherical motions in the flow below the shock wave. The so-called standing accretion shock instability (SASI) is supposed to be a non-local hydrodynamical instability possibly caused by the cycle of the inward advection of velocity- and entropy-perturbations and outward propagation of acoustic waves, with fluctuations amplified after each cycle (see their latest paper [25] for another interpretation). The interesting feature of SASi is the dominance of the \( \ell = 1 \) mode at first and \( \ell = 2 \) mode later, which will lead to the global deformation of the shock wave. Here \( \ell \) stands for the azimuthal index of the Legendre polynomials. One lesson to learn is that we should not impose the symmetry with respect to the equatorial plane in the simulations.

Figure 3 shows in the meridian section the distributions of entropy (the left half of the panel) and density (the right half) for the models with \( L_\nu = 5.5 \cdot 10^{52} \) erg/s after 1% of the \( \ell = 1 \) single-mode velocity perturbation is added. For both models, we observe the growth of the perturbations [26]. In the case of \( L_\nu = 5.5 \cdot 10^{52} \) erg/s, the shock surface is deformed at first by the increasing amplitude of the non-radial mode and then begins to oscillate with a large amplitude. In the case of \( L_\nu = 6.0 \cdot 10^{52} \) erg/s (right panels), on the other hand, in addition to the oscillations of the shock surface, we observe the substantial increase of the average shock radius as the time passes. In fact, after \( t = 400 \) ms, the shock radius continues to increase and appears to produce an explosion. Since the model is stable against radial perturbations as mentioned above, the non-radial instability and the neutrino heating therein are responsible for the explosion. We think that this is a reconfirmation of the claim that the instability, whatever the cause, behind the shock is helpful for the shock revival. It is also interesting to note that the modes with \( \ell = 1, 2 \) are dominant in the nonlinear regime.

We have to wait for realistic simulations before we judge if SASI can give enough boost for the shock revival. The numerical results [27] obtained so far are not very encouraging. If that is really the case, we had better find something more to obtain a successful explosion.
Figure 3. Entropy- (the left half of each panel) and density- (the right half) distributions in the meridian section for 1% of the $\ell = 1$ single-mode velocity perturbation. $L_\nu = 5.5 \times 10^{52}$ erg/s is assumed for the left panels and $L_\nu = 6.0 \times 10^{52}$ erg/s is for the right panels.

4. Gravitational Collapse of More Massive Stars

So far I have discussed theoretical researches on the collapse of $\sim 10 \cdot \cdots \sim 30 M_\odot$ stars, which are supposed to produce a supernova explosion eventually. As mentioned already, however, the fate of more massive stars ($\sim 30 \cdot \cdots \sim 100 M_\odot$), which will produce a black hole one way or another, is also attracting much interest these days. This is mainly because these massive stars are believed to produce long gamma ray bursts. On the other hand, the interest in POP III stars naturally motivates the study on the fate of very massive stars in the mass range of $\sim 100 \cdot \cdots \sim 1000 M_\odot$.

Neutrinos will be a useful probe for these high energy astrophysical phenomena. For example, it has been argued that high energy neutrinos of $10^{15} - 10^{17}$ eV are produced via photo-meson reactions in the internal shocks. Even higher energy neutrinos are also expected from the external shock through the same processes. Depending on the structure of the outer envelope of progenitors, the jet might produce precursor neutrinos by pp reactions before breaking out of the star [28]. These non-thermal high energy neutrinos are naturally a target for km$^2$ detectors.

Stars more massive than $\sim 30 M_\odot$ have large iron cores and will be intrinsically too massive to have stellar explosion. Then, the outcome will be a formation of black hole. The detection of neutrinos is a clear and unique identification of such events. In figure 4 we show our simulation of such an event [29]. As shown in the left panel, the second dynamical collapse starts when
the enclosed baryon mass reaches 2.66\(M_\odot\) (gravitational mass 2.38\(M_\odot\)) at \(t_{\text{pb}}=1.34\) s. The end points in the figure correspond to the formations of apparent horizon, i.e. the births of black hole. The time profile of luminosities is unique. Luminosities are dominated by the contributions from the accreted material. As the proto-neutron star contracts quasi-statically, the luminosities become higher and are dominated by \(\nu_e\) and \(\bar{\nu}_e\) originating from the accreted material. It is remarkable that the luminosities and average energies increase by a factor of two or more toward the formation of black hole. This increase will be used as a signal of black hole formation. The current generation of neutrino detectors will afford to detect the above-mentioned signal of the formation of black hole if it occurs in our own galaxy.

Population III (Pop III) stars are the first stars in the universe. They do not contain metals and their formation and evolution may be different from that of stars of later generations. In fact, according to the theory of star formation [8], Pop III stars might have very massive components (\(\sim 100 - 10000M_\odot\)). We evaluated the flux of relic neutrino from Pop III massive stars based on our numerical models [30]. We adopted the IMF of Pop III stars proposed by Nakamura & Umemura. As expected, the detection of these neutrinos is difficult for the currently operating detectors. To put it more precisely, the relic \(\nu_e\) fluxes from Pop III massive stars are overwhelmed by solar \(\nu_e\) below 18 MeV and relic neutrinos by ordinary supernova above \(\sim 10\) MeV. As for \(\bar{\nu}_e\), the emissions from nuclear reactors are the main obstacle below 10 MeV. Thus the existing detectors can not distinguish Pop III relic neutrinos from others. However, because the solar and reactor neutrinos are not isotropic, removing them is possible at least in principle. For \(\bar{\nu}_e\), in particular, Pop III massive stars are the largest cosmological sources. In the future, we may be able to discuss the Pop III star formation history with these diffuse neutrino fluxes.
5. Summary
In this talk I briefly summarized the current status of our understanding on the collapse of massive stars. For the mass range of $\sim 10 \cdots \sim 30M_\odot$, we expect the supernova explosion will result. Unfortunately, we are not yet able to claim what is the key element for successful explosions. Multi-dimensionality is thought to be crucially important one way or another.

For more massive stars, we expect a black hole formation at the end of evolutions. The neutrino signals from them will provide us with a valuable information on the phenomena as well as the microphysics of hot and dense matter.

We are now required to consider the physics of gravitational collapse of massive stars in this wide perspective.

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