

From supernovae to neutron stars

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A core-collapse supernova is a generation site of a neutron star as well as one of the largest explosions in the universe. This article gives a brief overview of the studies on supernova explosion mechanism. Basic picture of the explosion mechanism, the method to solve neutrino transfer equation, the impact of the nuclear equation of state on the explosion, and long-term simulation of neutron star evolution from the onset of the explosion are presented.

KEYWORDS: supernova, neutrino, equation of state

1. Introduction

Supernovae (SNe) have been supposed to be made by neutron star (NS) formation [1]. This basic picture was validated by neutrino observations from SN 1987A (e.g., [2]), which was done 30 years ago. In total ~ 20 neutrinos were detected and they implied the total amount of energy carried out by neutrinos is $\sim 10^{53}$ erg, which is perfectly consistent with the binding energy of a NS.

Although the above basic picture was proposed more than 80 years ago, the exact mechanism of SN explosion is still unclear. This is because understanding the explosion mechanism requires knowledge of all known physical interactions, i.e. gravitational, electromagnetic, weak and strong interactions. The strong interaction governs the nuclear equation of state, which provides the NS structure. Therefore, SN is a good experiment for the strong interaction and the nuclear physics.

The standard scenario of SN explosion is shown in Figure 1. Each panel shows six phases of supernova explosion: the first panel (left top) shows the onion-like structure at the end point of stellar evolution of massive stars, which gives the onset of core collapse; the second panel (middle top) shows the formation of neutrinosphere (the last scattering surface of neutrinos) at the central density being $\sim 10^{11}$ g cm⁻³; the third panel (right top) indicates the formation of a NS and the shock generation at the surface of the NS; the fourth panel (left bottom) presents the shock stall due to photodissociation of iron elements and neutrino cooling; the fifth (middle bottom) shows “shock revival” that is mandatory to produce supernova explosions; and the sixth panel (right bottom) is supernova explosion! The most important and mysterious part is from fourth to fifth panels, that is, *how is the shock revived?*

To revive the shock, a mechanism that transfer energy from inside to outside is needed. The most promising scenario is so-called “delayed explosion scenario”, which is driven by neutrino heating. A SN emits $O(10^{58})$ of neutrinos with ~ 10 MeV. These neutrinos transfer energy from the vicinity of a NS (see Figure 2). Most of them are just escaping from the system, which act as cooling. Part of them are absorbed in the outer layer than a *gain radius*, where the cooling and the heating equate. The reason why this kind of structure forms is the different radius dependences of cooling and heating functions. The neutrino cooling rate is given by $Q_{\nu}^{-} \propto T^6 \propto r^{-6}$, where T is the temperature, r is the radius. Here, $T \propto r^{-1}$ is used. On the other hand, the neutrino heating rate is given by $Q_{\nu}^{+} \propto L_{\nu} r^{-2}$, where L_{ν} is the neutrino luminosity. These relations imply that the neutrino cooling dominates over