Emergence of hyperons in failed supernovae with short neutrino bursts

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Abstract

We present that the appearance of hyperons plays a crucial role in failed supernovae from massive stars of ~40M$_\odot$. The quick dynamics from the gravitational collapse to the black hole leads to extreme conditions, reaching high densities and temperatures to have strangeness particles, within 1 s after the core bounce. The associated neutrino bursts are short and energetic, being different from ordinary supernova neutrinos, and may provide the information on the strangeness in dense matter. The end point of the duration of neutrino burst is determined by the stiffness of EOS and the appearance of new particle is the trigger of the termination due to the black hole formation. By measuring the duration of burst and the energy spectrum, one can constrain the appearance of exotics. The event numbers of neutrinos from the black-hole-forming collapse at the terrestrial detector are found large enough to utilize this phenomena as a target of neutrino astronomy and a probe of dense matter with strangeness.

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1. Dense matter with strangeness in astrophysics

When and where hyperons appear in compact stars? This is a fundamental question for nuclear physics as well as astrophysics. Inside neutron stars, there are interesting possibilities to have hyperons and/or quarks [1]. The possible existence of strangeness in the neutron star actually originates from the gravitational collapse of a massive star. Starting from the collapse of the iron core of a 20M$_\odot$ star, it leads to the core bounce and its explosion in ~1 s [2, 3, 4]. A hot and nascent neutron star, i.e. a proto-neutron star is born at center [5]. This stage of the proto-neutron star is the place where hyperons/quarks first appear [6, 7, 8, 9]. Since neutrinos are produced during the collapse and trapped inside, this object cools down by emitting neutrinos for ~20 s. The neutrino emission during the cooling of the proto-neutron star is the supernova neutrinos, which carry the information of central core. After many hundred years through the slowly cooling phase, we have a cold neutron star with the possible mixture of strangeness.

The scenario described above is actually a part of the whole story of massive stars. In fact, the mass of massive stars has a wide range from ~10M$_\odot$ to ~100M$_\odot$ [10]. The ordinary supernovae, leading to the cold neutron stars, originate from the massive stars of 10–30$M_\odot$. There are more massive stars beyond 30$M_\odot$, which consists about 30% of all massive stars. They lead to the black hole formation and appear as hypernovae or failed supernovae, depending on their mass and rotational rate [11]. It is important to note that the collapse of these massive stars is also associated with neutrino bursts. Naturally, they are the target of neutrino astronomy and equally important as compared with the ordinary supernovae.

We focus here on this massive branch of the stars, a quiet death through the core collapse [12]. In this case, it starts from the collapse of iron core of a 40$M_\odot$ star, for example. Since the iron core is too large, the explosion is not possible after the bounce. A proto-neutron star is born also in this case, but its mass increases rapidly. Since the explosion is not successful, the matter falls to the surface of proto-neutron star. When the mass reaches the critical mass, it dynamically collapses to the black hole. During this evolution, the density and temperature become very high inside the massive proto-neutron star. Therefore, there is a chance to have the appearance of hyperons and/or quarks. Since the neutrinos are emitted during the short life of proto-neutron star, the neutrino burst may carry the information on the appearance of strangeness in the black-hole-forming collapse.

In this contribution, we demonstrate that the collapse of massive star of 40$M_\odot$ leads to the condition of very high density and temperature, which lead to the mixture of hyperons [13]. We perform numerical simulations of the gravitational collapse, the core bounce, and the following evolution of compact object toward the black hole formation. We show that the emergence of hyperons in dense matter triggers the re-collapse of the proto-neutron star to the black hole due to a sudden softening of the equation of state (EOS). Consequently, the neutrino burst from the proto-neutron star is terminated within a short period. We argue that this short neutrino signal may be used as a probe of EOS with strangeness through the neutrino observation at the terrestrial neutrino detectors [14].

2. Numerical simulations with the EOS tables

In order to perform the numerical simulations of core-collapse supernovae, the data set of physical EOS for extreme conditions must be implemented. One has to develop the nuclear many body framework to cover the wide range of density, temperature and electron fractions in a consistent manner while the framework should be checked by the experimental data. One needs the thermodynamically consistent and smooth data tables for the wide range of conditions. Since the construction of such EOS table is a difficult task, there are limited sets of EOS tables up to now [15, 16, 17].

One of the recent developments is the relativistic EOS table [17, 18]. The so-called Shen-EOS is becoming popular in these years in astrophysical applications [19]. This EOS table is constructed by the relativistic mean field (RMF) theory with the local density approximation. The framework treats the inhomogeneous distribution of nucleons as well as homogeneous one, considering the mixture of neutron, proton, alpha and nuclei. The lagrangian of the RMF theory is based on the relativistic Brueckner Hartree-Fock theory. The interaction is determined by the experimental data of neutron-rich unstable nuclei as well as stable ones. The nuclear masses, charge radii and neutron skin thickness are used to fix the interaction [20]. With the parameter set, TM1 interaction, thus determined and checked, the data table[1] for supernova simulations have been constructed.

[1] `http://user.numazu-ct.ac.jp/~sumi/eos/index.html`

Recently, the extension of Shen-EOS has been made to include hyperons in addition to nucleons [21]. The table of Hyperon-EOS is constructed by the RMF extended to flavor SU(3) using the lagrangian by [22]. On top of the TM1 interaction, the meson-hyperon couplings are determined by the depth of potential for hyperons in nuclear matter. We adopt $U_\Lambda = -30$ MeV, $U_\Sigma = +30$ MeV and $U_\Xi = -15$ MeV as a standard choice. There are additional sets of Hyperon-EOS table using the different values for U_Σ and with/without pion contributions[2]. The extension of Shen-EOS table to the quark degrees of freedom (Quark-EOS) has been done recently within the MIT bag model [23].

The counter part, within the nucleon degree of freedom, of Shen-EOS is the Lattimer-Swesty EOS (LS-EOS) [16]. This EOS set, which is provided by the subroutine program, is based on the extension of the compressible liquid drop model. The functional form for the energy of nuclear matter is based on the form in the Skyrme interaction. The parameters of the function are determined by the bulk properties at the saturation. The LS-EOS has been used for the supernova simulations as a conventional choice.

When we compare the representative sets of EOS, Shen-EOS is stiffer than LS-EOS within the nucleon degree of freedom [19]. This is a characteristic behavior of the EOS by relativistic many body frameworks with respect to the EOS by non-relativistic counter parts. The maximum mass of cold neutron stars is $2.2M_\odot$ for Shen-EOS whereas $1.8M_\odot$ for LS-EOS with a choice of the incompressibility, K=180 MeV, which is used frequently for the supernova simulations [24, 25]. When we compare Hyperon-EOS with Shen-EOS, the mixture of hyperon softens the EOS and reduces the maximum mass down to $1.6M_\odot$.

Adopting the sets of EOS described above, we perform numerical simulations of the gravitational collapse of massive stars. The numerical simulations are performed by the numerical code to solve the general relativistic neutrino-radiation hydrodynamics [26, 27]. We solve the Boltzmann equation for neutrino distribution function under the spherical symmetry [28]. The code has been used to study the supernova explosion [27] and is applied to study the black hole formation [12, 13, 29, 30, 31]. The set of neutrino reactions with the composition of matter [32] is implemented in the code as collision terms. Since we solve the Boltzmann equation, we can evaluate the neutrino flux and energy spectrum in detail to predict the properties of neutrino emission. We adopt the profile of iron core inside the massive stars of 40–$50M_\odot$ from the stellar evolutionary calculations as initial models. We present here a case of the $40M_\odot$ star by Woosley and Weaver [33]. The dependence on the progenitor models (stellar mass, metallicity and evolution models) can be found in [30, 34]. We compare the four cases with Shen-EOS, Hyperon-EOS, Quark-EOS and LS-EOS to see the influence of the EOS and the mixture of strangeness.

3. Dynamical collapse to the black hole

We describe here the extreme condition during the rapid evolution toward the black hole formation from the massive star. Starting from the gravitational collapse, the core bounce launches the shock wave. However, the explosion is not successful and the shock wave goes down to the surface of compact object. The proto-neutron star is born at center and gradually contracts. Because of the falling matter (accretion), the proto-neutron star mass increases rapidly and reaches the critical mass. The dynamical collapse occurs again at this point and the black hole is formed at 1.3 s after the bounce for the case of Shen-EOS. If we switch to Hyperon-EOS, the dynamics

[2] http://nucl.sci.hokudai.ac.jp/~chikako/EOS

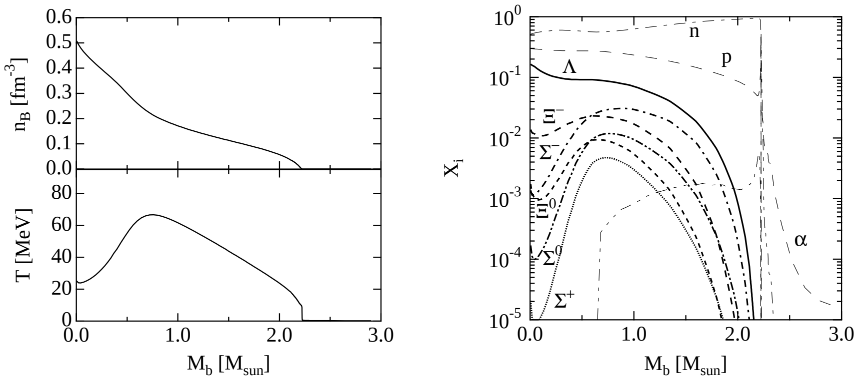

Figure 1: Profiles of density, temperature (Left) and mass fractions of hyperons (right) at 0.68 s after the bounce are shown as functions of radial coordinate in mass for the case of Hyperon-EOS.

becomes more quick. Starting with the same initial model, the core bounce, the launch and recession of shock wave, the proto-neutron star formation and the accretion of matter occur in the same way as the case of Shen-EOS. However, the dynamical collapse to the black hole occurs much earlier than before. The hyperons appear around 0.7 s after the bounce and they make the EOS softer. This appearance of hyperons triggers the dynamical collapse to the black hole [13].

The timing of the black hole formation is determined by the increase of proto-neutron star mass. We remark here that the proto-neutron mass (in baryon mass) in the supernova explosion is constant whereas it increases in the failed explosion. Figure 2 (left) shows the mass of the central object as a function of time after the bounce. The mass increases rapidly within 0.1 s and grows steadily due to the accretion. The curves for two EOS cases are similar due to the same accretion rate while the durations are different due to different critical masses. For Hyperon-EOS case, it reaches $2.2M_\odot$, where the re-collapse to the black hole occurs whereas it goes up to $2.7M_\odot$ for Shen-EOS case. Therefore, the maximum supportable mass by the EOS of hot and dense matter determines the end point of curves. The emergence of new particles is crucial in the case of Hyperon-EOS.

It is dramatic to see the hyperon emergence during the dynamical evolution. The density at the core bounce is actually not so high, reaching just above the nuclear matter density. A half second later, the density becomes higher and it reaches about 3 times the nuclear matter density at just before the re-collapse. Figure 1 (left, upper panel) shows the profiles of density inside the core at 0.68 s after the bounce for the case of Hyperon-EOS. Meanwhile, the temperature becomes high during the evolution. Starting from $\sim$10 MeV at the core bounce, the temperature increases beyond 50 MeV and even higher toward the end as shown in Fig. 1 (left, lower panel). Under these circumstances, the appearance of hyperons occurs. Although the hyperons are almost negligible at the core bounce, they emerge at off-center due to the temperature effect at 0.5 s after the bounce. The hyperon fraction is appreciable at center just before the re-collapse as seen in Figure 1 (right). In summary, the mixture of hyperons occurs shortly after the bounce and determines the early re-collapse to the black hole. This short life of proto-neutron star is associated with a short neutrino burst, which can be a probe of EOS as we discuss below.

4. Short bursts of energetic neutrinos

Now that we have hyperons at the end of life of massive stars, we discuss the neutrino astronomy to explore the EOS with strangeness.

In the case of the supernova explosion from the massive stars of ~20$M_\odot$, the proto-neutron star emits an enormous number of neutrinos in ~20 s. As it happened in the case of SN 1987A, the supernova neutrinos are detected at the terrestrial neutrino detectors. There were 11 neutrino events at the Kamiokande facility [35] at that time and $\sim 10^4$ neutrino events will be detected from a next Galactic supernova at the Super-Kamiokande facility. Since neutrinos are emitted from the hot and dense matter inside the proto-neutron star, we can probe EOS by neutrino signals and may examine whether hyperons and/or quarks appear during the event of supernova explosion.

The mixture of strangeness in proto-neutron stars has been investigated by Pons et al. [7] and by the following studies with exotic particles [8, 9]. They have found that the hyperon (and quarks etc.) appear at the late phase of the evolution of proto-neutron star. Since the neutrinos are trapped inside the core, the balance under the chemical equilibrium makes the matter to remain proton-rich mixture, therefore, the threshold for hyperon appearance becomes high. For a typical case of proto-neutron star, the fraction of hyperons is very small at the beginning and becomes appreciable after 10 s or more. The resulting neutrino signals carry the information of hyperons, however, the difference due to the hyperons can be seen only at the tail of decaying neutrino luminosities. The neutrino luminosity from proto-neutron stars generally decreases fast exponentially as a function of time. Therefore, the effect of hyperons appears at the late phase where the flux is already small. The difference of the average energy amounts to a few MeV depending on the choice of EOS in the decreasing time variation. To summarize, we can see the EOS difference, however, it is rather difficult to detect them in the ordinary supernovae leading to the neutron star.

Coming back to the neutrinos from failed supernovae, it starts from massive stars with ~40$M_\odot$ leading to the black hole. In this case, we do not have any optical display, but we have $\sim 10^4$ neutrino events for a Galactic incident. The neutrino signal is actually different from that of ordinary supernovae, having the short duration within 1 s. The energy and luminosity increase rapidly, as shown in Fig. 2 (right), being different from the long-term decay of those from the proto-neutron star cooling. Therefore, this branch of massive stars is the chance to see the emergence of hyperons and a possible transition to quarks as well as to identify the birth of black hole.

We show in Fig. 2 (right) the time evolution of average energy of neutrinos for the cases of Shen-EOS (lower panel) and Hyperon-EOS (upper panel). The average energies for three flavors increase rapidly due to the temperature increase in the contracting proto-neutron stars. The neutrino burst ends up at 0.7 s and 1.3 s for Hyperon-EOS and Shen-EOS case, respectively, when the black hole formation occurs. This termination corresponds to the end point of the increasing curve of the proto-neutron star mass shown in Fig. 2 (left). Therefore, if we measure the duration of neutrino burst, we identify the timing of the black hole formation. Moreover, if we discriminate the time difference, we may be able to examine the emergence of hyperons.

In order to judge the hyperon emergence, we need to distinguish it from the effect of soft nucleonic EOSs. If we compare the case of Hyperon-EOS with the case of LS-EOS, the duration of burst is around 0.6 s for both cases, which make the two signals similar at a glance. However, there is a difference in μ- and τ-type (anti-)neutrinos. The average energy for $\nu_{\mu/\tau}$ ($\bar{\nu}_{\mu/\tau}$) increases faster in the case of LS-EOS than that in the case of Hyperon-EOS, reflecting the fast increase of temperature inside. This difference can be seen in energies and luminosities and is detectable at

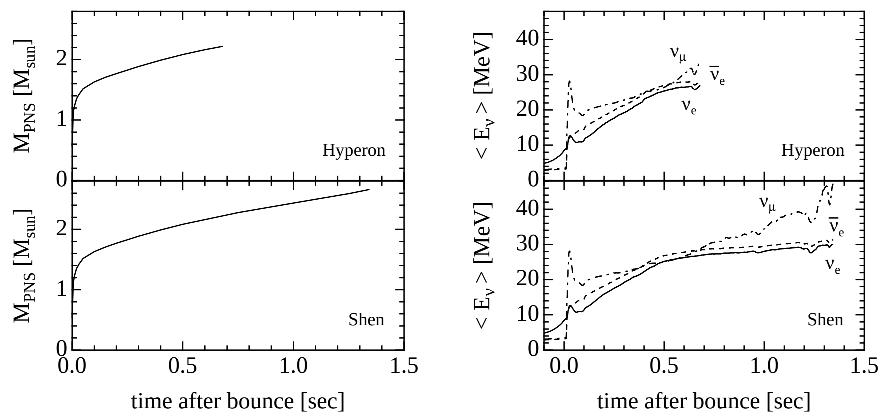

Figure 2: Time profiles of the mass of proto-neutron star (left) and the average energy of neutrinos (right) are shown as functions of time after the bounce for the case of Shen-EOS and Hyperon-EOS.

the terrestrial neutrino detectors after the conversion by the neutrino oscillations [23]. Therefore, it is possible to distinguish Hyperon-EOS from the soft nucleonic EOS.

We report briefly the recent results using Quark-EOS. Nakazato et al. have done the numerical simulations of the gravitational collapse from the 40$M_\odot$ star adopting the extended table of Shen-EOS with quark mixture [36]. The calculation of EOS is based on the RMF with the MIT bag model [31]. The bag constant is chosen to be $B^{1/4}$=209 MeV to support the maximum cold neutron star of 1.8$M_\odot$. The resulting evolution is similar to the one with Shen-EOS and lasts till the black hole formation for 1.1 s after the bounce. The quarks appear only at the final moment with this choice of parameter and the hyperons may appear fast.

5. Observational prospects of black-hole-forming collapse

In order to show that the neutrino burst toward the black hole formation is detectable, we evaluated the event numbers of neutrinos at the currently working detector at the Super-Kamiokande [23]. We assume an event at the center of our Galaxy (∼10kpc) and calculated the event numbers by taking into account the conversion of flavors via neutrino oscillations. We found that the resulting event numbers are large enough to detect, being comparable to those of ordinary supernovae. We expect that more than 10^4 neutrinos will be detected.

Since the duration of neutrino burst is different, the total number is different depending on the EOS. Hence, the total event number can be used to distinguish the different EOS, especially regarding the softness. For Shen-EOS (stiff EOS), we detect more than 3×10^4 neutrinos, while we detect less than 2×10^4 neutrinos for Hyperon-EOS and LS-EOS (soft EOSs). To distinguish the composition (hyperon mixture), the information of the total number is not enough. We need to examine the difference of average energies between the two cases of soft EOSs as we mentioned above. With the predicted size of energy difference between the cases of LS-EOS and Hyperon-EOS, it should be able to distinguish the difference within the resolution of the Super-Kamiokande. We can see the difference also in the cumulative event numbers. The time profiles of the increasing event number are different each other between the cases of LS-EOS and

Hyperon-EOS. Nakazato et al. have made the statistical analysis to judge the two time profiles and concluded it is possible to distinguish the two for galactic events having $\sim 10^4$ events [14].

We stress that this phenomenon is a feasible target in astronomy. The number of massive stars beyond $30M_\odot$ amounts to ~30% of all massive stars. Actually, there are two faint supernovae from massive stars in this range observed so far [11]. A black hole with the mass of 24–$33M_\odot$ has been identified already [37]. In order to find a quiet death of massive stars, which leads to the black hole formation, there is a planned survey to monitor $\sim 10^6$ massive stars [38]. By regularly making observations of nearby galaxies, they compare the images to find out the disappearance of stars. They estimate that they can find the events yearly.

If we extend our search of supernovae to far galaxies, we will be able to have more events [39]. Within our Galaxy and the Large Magelanic Cloud, the supernova event rate is about ~0.03 year^{-1} though we can detect 4×10^2–10^4 events. If we go further to Andromeda (M31) at ~1Mpc or even beyond 4Mpc, we have supernova event rates 0.08–0.3 year^{-1}, therefore, we may have one supernova per several years. In order to detect enough number of neutrinos, we need to construct larger neutrino detectors. Such a proposal has been made as Deep-TITAND [40] and the event number of 10–10^2 is expected. Therefore, the collapse of massive stars to black hole is a plausible target of neutrino astronomy and it is feasible to use as a probe of EOS.

6. Summary

We present the appearance of hyperons in failed supernovae and its associated signal of neutrino bursts as a new probe of dense matter in astrophysics. Being different from supernovae, the collapse of massive stars of $\sim 40M_\odot$ leads to the failed explosion and the birth of proto-neutron stars with *increasing* mass. The emergence of hyperons in dense matter plays a decisive role to trigger the re-collapse toward the black hole formation by terminating the proto-neutron star epoch due to a sudden softening of the equation of state (EOS).

We demonstrate that the black hole formation due to the emergence of hyperons can be examined by the detection of neutrino bursts at the terrestrial detectors. During the evolution of the accreting proto-neutron star, a bunch of neutrinos are emitted within a short period of ~1 s (cf. ~20 s for supernova neutrinos) until the black hole formation. We show that the duration of neutrino burst, which is determined by the softness of the EOS of dense matter, becomes further short with the hyperon emergence.

In order to predict the characteristics of neutrino bursts, we performed the numerical simulations of neutrino-radiation hydrodynamics adopting a new EOS table of hyperonic matter, which is constructed recently with the recent experimental information. We evaluated the event number of neutrinos at the SuperKamiokande detector with the effect of neutrino oscillation using the detailed calculation of neutrino bursts. The event number for a failed supernova event in our Galaxy amounts to $\sim 10^4$, which suggests that the neutrinos from the black-hole-forming event is a candidate for neutrino astronomy like the supernova neutrinos. Moreover, it is shown that one can distinguish a hyperon EOS from a soft nucleonic EOS by the statistical analysis of neutrino signals.

Further studies using more sets of EOS and the progenitor models of massive stars are apparently necessary to constrain the EOS in detail by neutrino bursts toward the black hole formation. It is especially urgent to study the uncertainties on the hyperon mixture in different many body approaches and hyperon interactions [41, 42]. However, it is exciting already to find how this phenomenon involves crucially the physics of strangeness and provides the clue to assess the properties of dense matter at extreme conditions.

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