

# Role of hyperons in black hole formation

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**Abstract.** A phase transition from hadronic to exotic phases might occur in the early post-bounce phase of a core collapse supernova. We investigate the role of strange baryons in the dynamical collapse of a non-rotating massive star to a black hole using 1D General relativistic simulation *GR1D*. We choose a  $40M_{\text{solar}}$  progenitor of Woosely and follow the dynamical formation of a protoneutron star and its subsequent collapse to a black hole. We also study the neutrino signals that may be used as a probe to core collapse supernova. We adopt the newly constructed Shen hyperonic EoS for the simulation and compare the results with those of Shen nuclear EoS and understand the role of strange baryons in the core collapse.

## 1. Introduction

The core collapse supernova explosion mechanism is being investigated over the last five decades [1]. Still, the detailed theory of a successful supernova explosion is beyond our reach and is a challenging problem. The massive stars at their final journey implode so quickly that the inner core rebounds, a shock wave is said to form [2]. The shock soon loses its energy and stalls after traversing a few hundred kilometers. The massive star directly ends up in a black hole without an explosion, this falls in the category of failed supernova [3]. However, there are different ideas to revive the shock, which could eventually trigger a delayed supernovae explosion. The second shock is very important in understanding a successful core collapse supernova explosion.

In recent years existence of strange matter in the high-density core of neutron stars has been the subject of extensive research [4,5]. It may so happen that the phase transition from hadronic to exotic phases might have already occurred in the early post-bounce phase of a core-collapse supernova. This idea of appearance of strange particles has initiated intense interest lately. It is said that a quark-hadron phase transition could trigger the explosion and revive the shock [6], that was stalled due to loss of energy. During the implosion, neutrinos could escape the surface of the star carrying off most of the energy and reach detectors on earth. The neutrino burst ceases once the shock is stalled. However, an additional burst of neutrino is released as the second shock passes through the neutrinosphere. Neutrinos could be a significant observational signature [6].

One of the main inputs in the study of evolution of core-collapse supernovae by numerical simulations, is the equation of state (EoS) for a wide range of density ( $10^4 - 10^{15} \text{g/cm}^3$ ), temperature ( $0 - 100 \text{MeV}$ ) and composition (proton fraction  $0 - 0.6$ ) [7]. For the supernovae simulations with non-strange particles like neutrons, protons, alpha-particles and nuclei, mainly two sets of EoS are used —Lattimer-Swesty (LS) [8] and Shen, Toki, Oyamatsu and Sumiyoshi (Shen) EoS [9]. Also there have been supernova EoS based on thermodynamically consistent nuclear statistical equilibrium model [7,10]. The first EoS with non-nucleonic degrees of freedom

was presented by Ishizuka et. al. [11]. They studied the emergence of the full baryon octet in the dynamical collapse of a massive static star to a black hole formation [12]. This EoS was recently utilised to study the behaviour of black hole formation and neutrino emission with hyperons and/or pions in Ref. [13]. Another set of EoS with hyperon degrees of freedom was constructed for supernova simulations [14] using the relativistic mean field model (RMF).

It is obvious that the inclusion of strange degrees of freedom softens the EoS. A stiffer EoS can sustain more mass against the collapse. A soft EoS on the other hand favors lower maximum masses compared to the stars having nucleonic degrees of freedom only. The recent measurement of the Shapiro delay in the radio pulsar PSR J1614-2230 which yielded a mass of  $1.97 \pm 0.04 M_{\text{Solar}}$ , puts an important constraint on the neutron star mass and may rule out most of the soft EoS [15]. However, it is at present not possible to rule out any exotica with this observation as many model calculations including hyperons and/or quark matter could still be compatible with it [14, 16, 17]. Many of these approaches are model dependent and can accommodate a NS as massive as two suns.

In this paper, we report the effect of hyperons on the black hole formation using the spherically-symmetric General relativistic hydrodynamic code, *GR1D* [18], designed to follow the evolution of stars beginning from the onset of core collapse. We adopt two sets of the Shen EoS—for nucleon (np) [9] and hyperon (npY) degrees of freedom [14]. We comment on the neutrino signal that might be observed as a result of phase transition from nucleonic to hyperonic matter.

The paper is arranged as follows. In Section 2, we briefly describe the EoS, adopted for the simulations. Section 3 is devoted to result discussion. Finally we summarise in Section 4.

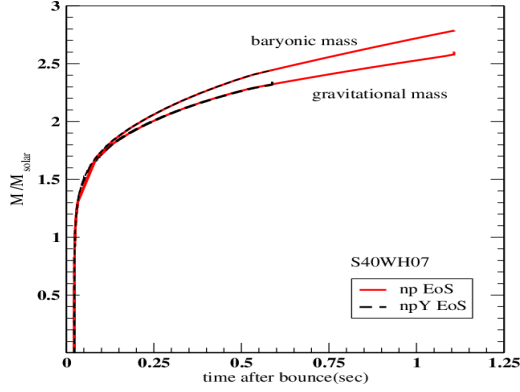
## 2. The equation of state (EoS) and the numerical simulation

We use the nuclear and hyperonic equation of state by Shen et. al [9, 14] for our simulations. Shen nuclear EoS is based on a relativistic mean field model at intermediate and high densities ( $\rho > 10^{14.2}$  g/cc). At low temperature ( $T \leq 14$  MeV), and  $\rho < 10^{14.2}$  gm/cm<sup>3</sup>, Thomas Fermi approximation is used. Leptons are treated as uniform non-interacting relativistic particles and their contributions are added separately. Minimisation of free energy is done at low density. The calculation has been done in the RMF model with the TM1 parameter set [19], the parameters of the model are obtained by fitting the experimental data for binding energies and charge radii of heavy nuclei. With the TM1 parameter set, the nuclear matter saturation density is  $0.145 \text{ fm}^{-3}$ , the binding energy per nucleon is 16.3 MeV, the symmetry energy is 36.9 MeV and the compressibility is 281 MeV [19]. Shen et. al. included the  $\Lambda$ s in their EoS table [14]. For the parameters of  $\Lambda$  hyperons, they use the experimental mass value  $M_{\Lambda} = 1115.7$  MeV. The coupling constant for hyperon-vector meson interaction is taken based on naive quark-model and that of hyperon-scalar meson interactions is determined by fitting experimental binding-energies data for single- $\Lambda$  hypernuclei [20].  $\Lambda$ s appear when the threshold condition  $\mu_n = \mu_{\Lambda}$  is satisfied, where  $\mu_n$  and  $\mu_{\Lambda}$  are the chemical potentials of the neutron and  $\Lambda$  respectively. Other hyperons,  $\Xi$  &  $\Sigma$  are excluded due to their relatively higher threshold and lack of experimental data.

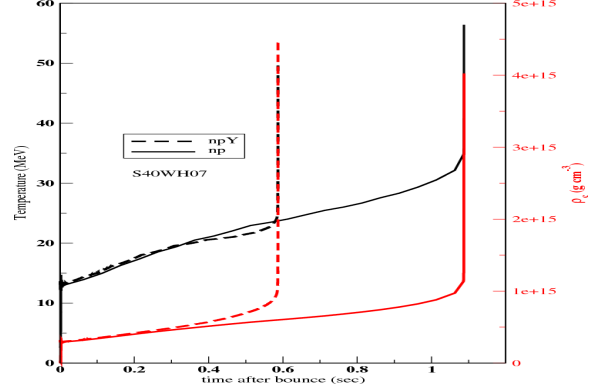
We use the open source code *GR1D* [18] for the supernova simulations. *GR1D* is a spherically-symmetric, general-relativistic Eulerian hydrodynamics code for low and intermediate mass progenitors. It is designed to follow the evolution of stars beginning from the onset of core collapse to black hole formation and makes use of several microphysical EoS.

## 3. Results & Discussion

We report our simulation results for a  $40 M_{\text{Solar}}$  progenitor model of Woosley et. al [21] using GR1D [18] for Shen EoS- nucleon (np) as well as and hyperon (npY) [9, 14]. We solved the Tolman-Oppenheimer-Volkov equation for zero temperature ( $T=0$ ) EoS of NS assuming  $\beta$  equilibrium. The maximum mass of the NS for np EoS is  $2.18 M_{\text{Solar}}$ , whereas for npY



**Figure 1.** Baryonic mass and gravitational mass vs. time after bounce

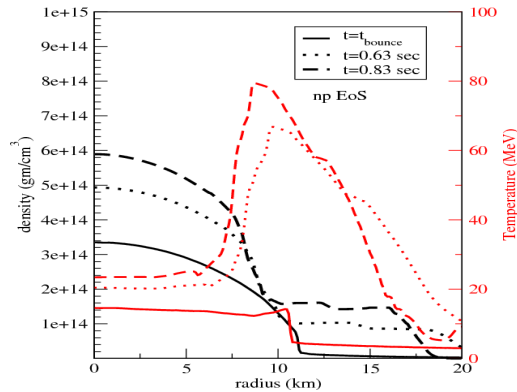


**Figure 2.** Central density ( $\rho_c$ ) & temperature (T) vs time after bounce

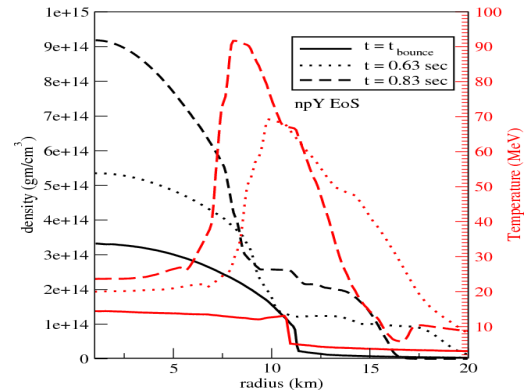
EoS, the maximum mass reduces to  $1.82M_{solar}$ . The corresponding radii are 12 and 12.5 km respectively.

In Fig. 1 we plot the baryonic and gravitational mass of PNS, obtained from simulations. The maximum mass is higher than that of NS. When accretion pushes PNS over its maximum mass, BH is formed. The spikes in the gravitational mass correspond to a blow-up and the BH formation. For the np EoS, this happens for a  $2.71M_{solar}$  star at 1.09 s after bounce, whereas for npY EoS (the black dashed lines) this happens much earlier at 0.57 s after bounce for a  $2.38M_{solar}$  star.

Fig. 2 shows the evolution of central density ( $\rho_c$ ) and temperature (T) for the np (solid lines) and npY EoS (dashed lines). The bounce corresponds to the spikes at real timeline  $t_{bounce} = 0.27$  s, which we take as  $t=0$  in the figure. The value of  $t_{bounce}$  is same for the np and npY EoS, we will see that the contribution of hyperon is not important at that time. The onset of BH formation is marked by a sharp rise in the value of  $\rho_c$  (the black lines). Similar trend is noticed in the temperature profile (red lines in online version). Owing to the hyperon emergence, the contraction of PNS is accelerated, which leads to quicker rise in temperature and central density. Or in other words, the stiffer EoS leads to larger post-bounce time to BH-formation.



**Figure 3.** Density and temperature profiles for np EoS

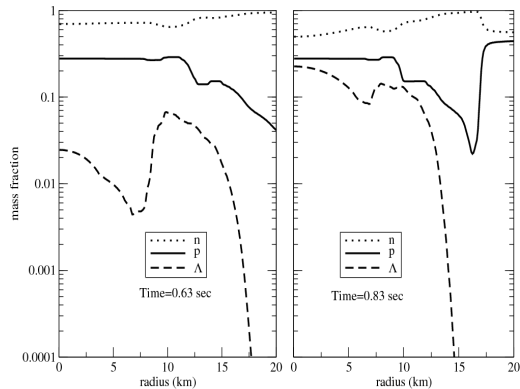


**Figure 4.** Density and temperature profiles for npY EoS

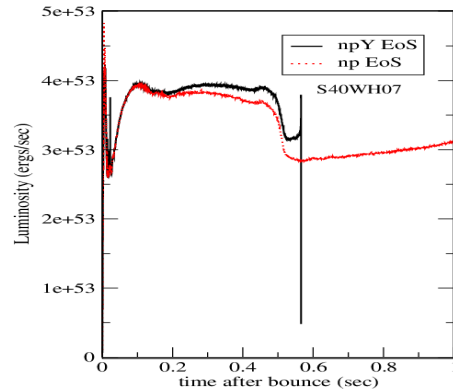
In Figs. 3 and 4, we compare the density (black lines) and temperature (red lines in online version) profiles for np and npY cases at  $t=t_{bounce}$ , 0.63 s and 0.83 s. The density rises from less

than  $\rho_0$  ( $\rho_0 \simeq 2.4 \times 10^{14} \text{gm/cm}^{-3}$ ) at the surface to a few times  $\rho_0$  at the core. The plateau in the density profile could be attributed to strong thermal pressure there. At core bounce, the core density is  $1.4\rho_0$ . With intense accretion, the central density shoots to  $2\rho_0$  at 0.63 s, and  $2.5\rho_0$  at 0.83 s for np EoS. The density and temperature profiles are similar in both the cases, the central density is slightly above that of the np case at  $t=0.63$  s, as  $\Lambda$  just starts appearing in the system. However, at  $t=0.83$  s, owing to substantial amount of  $\Lambda$ , the central density rises almost  $3.8\rho_0$ , which is 2.8 times its value at core bounce.

With time, the temperature also attains a peak at the mid-radius region. The peak rises from 66.8 Mev at 0.63 s to 79.35 Mev at 0.83 s in np case (Fig. 3). This is due to accretion and compression of shock heated material onto the PNS surface. At this region, the thermal pressure support is enough to flatten the density profile. In inner core ( $\sim 6\text{km}$ ) the material is not shock heated, rather is heated by adiabatic compression. The temperature peak is further raised to 91.7 MeV at 0.83 s in the presence of  $\Lambda$  hyperons (Fig. 4).



**Figure 5.** Snapshot of particle fraction vs. radius at  $t=0.63$  s and 0.83 s



**Figure 6.** Luminosity of total neutrinos as a function of time after bounce.

Next we compare the compositions of PNS in Fig. 5. We have noticed that initially at core bounce the system consists of neutron and protons only; hyperons appears first in the collapse at 0.16 s after core bounce (assuming  $10^{-3}$  considerable amount of fraction). The central density that was just above normal nuclear matter density (Fig 2) at bounce rises to  $3.79 \times 10^{14} \text{gm/cm}^{-3}$  at 0.16 s after bounce. We have seen that the appearance of  $\Lambda$  hyperon is delayed until the matter density reaches at least  $2\rho_0$ , the threshold shifts to lower density with increasing temperature [14]. The temperature also increases to 16.26 MeV. We display two snapshots at 0.63 s and 0.83 s in the two panels of Fig. 5. It is interesting to note that hyperons appear off-center owing to high temperature, although density is still on the plateau. At 0.63 s, the abundance of  $\Lambda$  becomes significant at  $R \simeq 10\text{km}$ , as temperature is maximum there (Fig. 5). It even falls sharply after reaching the peak due to fall in temperature, only to rise at the core again owing to high density there. At a later time, the high central density forbids it from dropping too low, once it reaches the peak at mid-radius region. Thus,  $\Lambda$  becomes one of the major components at the core.

In the final figure, the evolution of neutrino-luminosity is plotted for the np and npY EoS. We find a short neutrino burst ( $\sim 1$  s) before the PNS, born temporarily in a failed-supernova, terminates in a black hole. The resulting neutrino burst in np and npY cases are quite similar, differ only in earlier termination of burst in the latter. The soft npY EoS lowers the critical mass of PNS, thus accelerates the mass accretion onto it and triggers the gravitational instability at 0.63 s. However, no second neutrino burst is noticed as observed in quark-hadron phase transition [6]. The quark EoS is stiff while the npY is a soft one. So, npY though triggers black

hole formation, fails to generate second shock.

#### 4. Summary

We have studied the effect of hadron-hyperon phase transition in core-collapse supernova using general relativistic hydrodynamic simulation GR1D [18]. By following the dynamical collapse of a new-born proto-neutron star from the gravitational collapse of a  $40M_{solar}$  star adopting Shen hyperonic EoS table [14], we notice that hyperons appear just before bounce. It appears off center at first due to high temperature and prevails at the center just before the black hole formation, when the density becomes quite high. Hyperons triggers the black-hole formation, but fails to generate the second shock as the EoS is softened too much with the appearance of hyperons. Hyperon emergence in the collapse produces an intense but short neutrino burst, which terminates at the black hole formation. All these results match with those of Ref [10,12]. No second neutrino burst is observed as in quark-hadron phase transition [6].

There are possibilities for other strange degrees of freedom in the form of kaon condensates to appear in the highly dense matter. We have seen such a phase transition can support a maximum mass [5], which is well above  $2M_{solar}$  [15]. It would be intriguing to investigate if a hadron-antikaon condensed matter can revive the second shock. A successful shock revival would have observational consequence in the form of neutrino signatures. Until now, only one supernova, SN1987A, has been detected by its neutrinos. Post SN1987A, more advanced neutrino facilities, such as Ice-cube and Super-Kamiokande are expected to detect the neutrino signals more efficiently and frequently.

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