Core-collapse supernova simulation using Λ hyperon EoS with density-dependent couplings

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Recently we generated an equation of state (EoS) table of dense matter relevant to neutron star and supernova with Λ hyperons. We use this EoS to investigate the role of strange hyperons in the dynamical collapse of a non-rotating massive star to a black hole(BH) using 1D General relativistic simulation *GR1D*. We follow the dynamical formation and collapse of the protoneutron star (PNS) from the gravitational collapse of a massive progenitor, adopting this EoS table.

1 Introduction

Neutron stars are born in the aftermath of massive stars ($> 8M_\odot$) through the core-collapse supernova (CCSN) explosions in the penultimate stage of their evolution. The fate of the compact object depends on the EoS and the amount of infalling material. In addition to the nucleons and nuclear matter, several novel phases with large strangeness fraction such as, hyperon matter, and quark phase, and Bose-Einstein condensates of antikaons are theoretically predicted in the early post-bounce phase of a core-collapse supernova. There are several exotic EoS, including quark and hyperons, for supernova simulations. However, none of them are within the observational constraints of $2M_\odot$ neutron stars [1, 2].

The Banik, Hempel and Bandyopadhyay (BHB) EoS is the first realistic EoS table involving hyperons [3] that is compatible with the recent observations. It is based on the density-dependent relativistic mean field model (DD2). The model is exploited to describe the uniform and non-uniform matter in a consistent manner. Further, light and heavy nuclei along with interacting nucleons are treated in the nuclear statistical equilibrium (NSE) model of Hempel and Schaffner-Bielich (HS) which includes excluded volume effects and DD relativistic interactions [4]. We considered only Λ hyperons and exclude other hyperons such as Σ and Ξ, due to scarcity of experimental data about their potential depth values in nuclear matter.

The presence of exotic particles may have considerable effect on the core collapse supernova explosions. It was earlier reported that hyperons appear just after the core bounce. And they trigger the BH formation, but fail to generate the second shock because the EoS is softened too much with their appearance [5]. These studies were carried out with the hyperonic EoS of Shen et. al. [6], which do not conform to the the observational mass limit of neutron star.

In this paper, we follow the dynamical formation and evolution of a PNS beginning from the onset of core collapse adopting our BHB EoS table[3]. We report the effect of hyperons on the black hole formation using the spherically-symmetric general relativistic hydrodynamic code, $GR1D$[7]. We use both the variants of BHB hyperonic EoS tables. In one case the repulsive hyperon-hyperon interaction is mediated by the strange ϕ mesons [BHB$\Lambda\phi$] and in the second case ϕ mesons are not considered [BHBΛ]. We also compare these results with nucleon-only EoS, that we denote by HS(DD2).

2 The equation of state and the numerical simulations

The BHB EoS table is based on a density dependent (DD2) relativistic hadron field theory [8, 9], where baryon-baryon interaction is mediated by σ, ω, ρ mesons. The additional ϕ mesons take care of the hyperon-hyperon couplings. The density-dependence of the couplings gives rise to a rearrangement term in baryon chemical potential that on the other hand, changes the pressure. Thus the EoS is significantly changed at higher densities. Nuclear symmetry energy is another important parameter that controls the stiffness of the EoS. The symmetry energy and its density dependence near the saturation density n_0 are denoted by $S_\nu = E_{sym}(n_0)$ and slope parameter $L = 3n_0 dE_{sym}/dn|_{n=n_0,T=0}$. The DD2 model, with $S_\nu = 31.67$ MeV and $L = 55.04$ MeV, are fully consistent with the experimental and observational constraints [8]. The BHB$\Lambda(\phi)$ EoS table covers a broad range of density ($\sim 10^{3.22} - 10^{15.22(15.3)}$ g/cm^3), temperature($T = 0.01 \quad \text{to} \quad 158.48$ MeV) and charge-to-baryon number ratio ($Y_p = 0 \quad \text{to} \quad 0.60$) [3].

The matter consists of nuclei, (anti)neutrons , (anti)protons, (anti) Λ hyperons, and photons at different regions. Electrons and positrons form a uniform background; contribution of neutrinos and muons are not taken into account in the calculations. In the DD2 parameter set, the nuclear matter saturation density is 0.149065fm^{-3}, binding energy 16.02MeV, incompressibility of matter 242.7MeV and symmetry energy 31.67MeV. The effective Dirac mass (m*/m) of neutron and proton are 0.5628 and 0.5622 respectively. For the Λ, the experimental mass value is 1115.7MeV, and the potential depth in nuclear matter is -30MeV.

We use the open source code $GR1D$ [7] 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 for different zero age main sequence(ZAMS) progenitors.

3 Result & Discussions

We report our simulation results for a $40M_\odot$ progenitor model of Woosley et. al [10] using GR1D [7] for BHB EoS. We solved the Tolman-Oppenheimer-Volkov equation for zero temperature (T=0) β-equilibrated matter. The maximum mass of the neutron star for nucleon-only HS(DD2) EoS is $2.42M_\odot$, whereas for BHB$\Lambda(\phi)$ EoS, the maximum mass reduces to $1.95(2.1)M_\odot$. The corresponding radii are 11.9 km and 11.7(11.6) km respectively [9, 3].

Fig. 1 shows the plot of 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, a BH is formed. The spike in the gravitational mass correspond to a blow-up and the BH formation. For the HS(DD2) EoS(solid line), this happens for a $2.47M_\odot$ star at 0.94 sec after bounce, whereas for BHB$\Lambda(\phi)$ EoS (the dashed line, colour online) this happens much earlier at 0.55 sec after bounce for a $2.25M_\odot$ star.

Figs. 2 and 3 show the evolution of central density (ρ_c) and temperature (T) for the nucleon-only HS(DD2) (solid lines) and BHB$\Lambda(\phi)$ EoS (dashed lines) respectively. The bounce

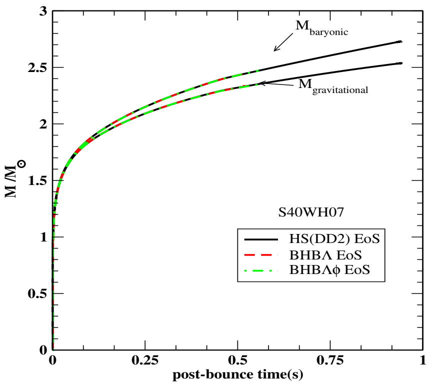

Figure 1: Post-bounce evolution of baryonic mass and gravitational mass.

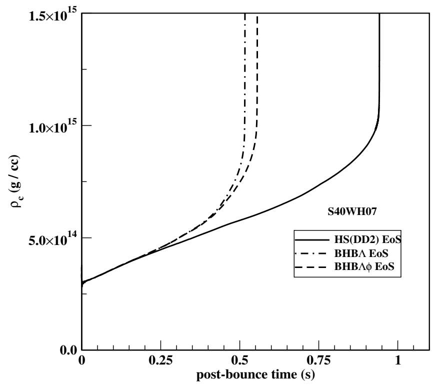

Figure 2: Central density as a function of post-bounce time.

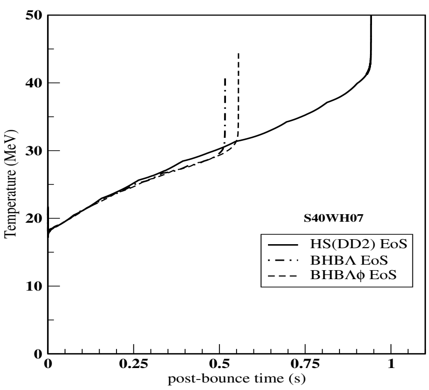

Figure 3: Temperature as a function of post-bounce time.

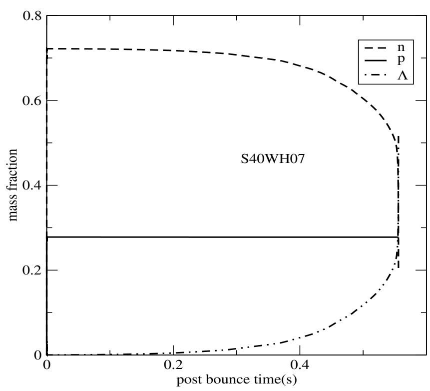

Figure 4: Mass fractions of various species are plotted as a function of post-bounce time.

corresponds to the spikes at real timeline $t_{bounce} = 0.321$sec, which we take as t=0 in the figure. The value of t_{bounce} is same for the HS(DD2) and BHB$\Lambda(\phi)$ cases; the hyperons do not appear at that density as evident from the mass fraction graph (Fig. 3). The onset of BH formation is marked by a sharp rise in the value of central density as well as the temperature profile. 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.

In Fig. 4, we show the compositions of PNS. Initially at core bounce the system consists of neutron and protons only, hyperons appears first at 0.16 sec after core bounce. As soon as the Λ hyperons populate, they replace the neutrons. And the central density that was just above normal nuclear matter density at bounce rises to $\sim 4 \times 10^{14} gm/cm^{-3}$ and the temperature rises to $\sim$ 23MeV.

4 Summary

We studied the effect of hadron-hyperon phase transition in core-collapse supernova using general relativistic hydrodynamic simulation GR1D [7]. By following the dynamical collapse of a new-born proto-neutron star from the gravitational collapse of a $40M_{\odot}$ star adopting the BHB hyperonic EoS table [3], we noticed 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. Also the presence of hyperons triggers the early BH formation, compared to nucleon-only case.

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