Probing the metastability of protoneutron star using DD2 hyperon equation of state in core-collapse supernova

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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 supernova SN1987A, since its discovery, has become the most studied star remnant in history and has provided great insights into supernovae and their remnants. Observation of a burst of neutrino signal for at least 12s after the explosion strongly supports to the scenario that a proto neutron star (PNS) was initially present in the core which cooled via neutrino emission and collapsed later. The fading light curve also lends support to this picture. During deleptonisation, the hot and neutrino-trapped PNS may end up either to form a cold neutron star (CNS) or a black hole (BH). Till date astronomers were not able to find a neutron star in the remnant of this type II supernova. However, the existence of a metastable PNS at least 12s after the explosion indicates to some deep physical implications[1, 2].

The fate of the compact object depends on the equation of state (EoS) and the amount of infalling material. We study the metastability of PNS in the presence of Λ hyperon in the long-time evolution of the progenitors, relevant to supernova SN1987A using one dimensional general relativistic code $GR1D$[3]. We follow the dynamical formation and evolution of a PNS to a BH using various progenitor models, adopting our recent hyperonic EoS(DD2) table[4]. Our EoS table is based on a density dependent (DD2) relativistic hadron field theory [5, 6] where baryon-baryon interaction is mediated by mesons. Also, this is the first supernova EoS table involving exotic matter which is compatible with the recently measured $2M_{\odot}$ neutron star. The maximum gravitational mass of the β-equilibrated PNS exceeds that of the NS. The PNS cools via neutrinos and once sufficient thermal support is lost, no stable configuration exists and the PNS might collapse to a BH. Since one-dimensional supernova simulations is unlikely to produce a successful explosion, we artificially adjust the amount of neutrino heating via a scale factor f_{heat} to achieve explosions. We investigate if the hadron to hyperon phase transition delays the collapse of the PNS into BH. Neutrinos may be a useful probe to core collapse. We comment on the neutrino signal that might be observed as a result of phase transition from nucleonic to hyperonic matter. Finally, we compare these results with our previous one[7, 8], that was done for hyperonic EoS of Shen et. al.[9].

Result

We choose a $40M_{solar}$ progenitor of Woosely et. al [10] using GR1D [3] and follow the dynamical formation of a protoneutron star and its subsequent collapse to a black hole. We use our DD2 EoS [4] and Shen EoS- nucleon (np) as well as and hyperon (npY) [9, 11]. In Figs. 1 & 2 the time evolution of central density and temperature are plotted respectively. The bounce corresponds to the spikes at real timeline, 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 ρ_c. Similar trend

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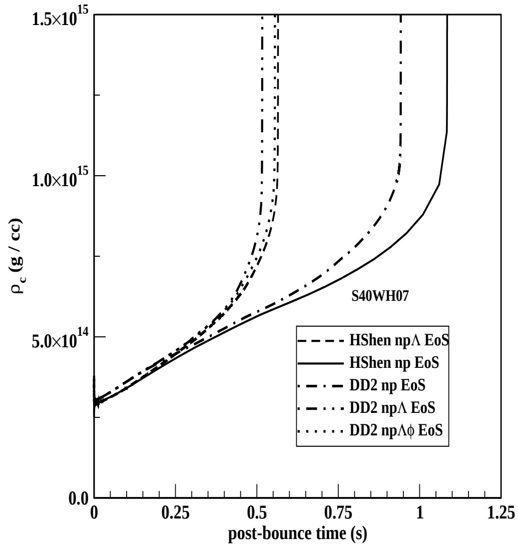

FIG. 1: Density profiles for DD2 & Shen EoS

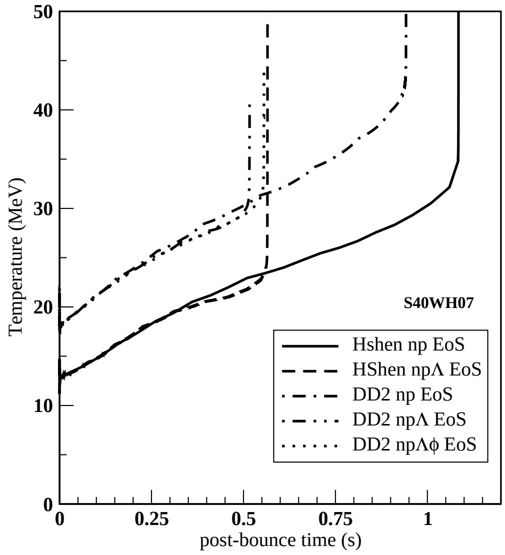

FIG. 2: Temperature profiles for DD2 & Shen EoS

is noticed in 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. Both the EoS sets, DD2 and Shen, shows similar trend. However for DD2 EoS, the black hole formation occurs a little earlier.

Summary

We have studied the effect of hadron-hyperon phase transition in core-collapse supernova using general relativistic hydrodynamic simulation GR1D [3]. By following the dynamical collapse of a new-born proto-neutron star from the gravitational collapse of a $40M_{solar}$ star adopting our DD2 [4] EoS and Shen EoS table[9], 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.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. No second neutrino burst is observed.

References

[1] S. Banik and D. Bandyopadhyay, Phys. Rev. **C63** 035802 (2001).

[2] G.E. Brown and H.A. Bethe, Astrophys. J. **423** 659 (1994).

[3] C. D. Ott and E. O'Connor, Class. Quant. Grav.**27** 114103 (2010).

[4] S. Banik, M. Hempel, D. Bandyopadhyay, Astrophy. Suppl. J, **214** 22 (2014).

[5] S. Typel, G. Röpke, T. Klähn, D. Blaschke and H.H. Wolter, Phys. Rev.**C 81** 015803 (2010).

[6] P. Char, S. Banik, Phy Rev **C90** 015801 (2014).

[7] S. Banik, J Phys, Conf. Series, **426** 012004 (2013).

[8] S. Banik, Phy. Rev. **C 89** 035807 (2014).

[9] H. Shen, H. Toki, K. Oyamatsu, K. Sumiyoshi, Astrophy. J. Suppl, **197**, Issue 2, 14 pp. (2011).

[10] S. E. Woosley, A. Heger, and T. A. Weaver, Rev. Mod. Phys. **74** 1015 (2002).

[11] H. Shen, H. Toki, K. Oyamatsu, K. Sumiyoshi, Nucl.Phys. **A637** 435 (1998).