Understanding the behaviour of finite entropy Neutron Stars with antikaon condensates in their cores

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Introduction

Neutron stars (NS) are superdense. Their core density may reach many times that of nuclear matter density. Observations have put very tight constraints on NS mass but there exists huge ambiguity about their radii. As a result, the equation of State (EoS) governing their behaviour and hence their properties is not known to sufficient accuracy. Matter just below nuclear density consists of neutrons, protons and leptons. Lack of experiments at higher density matter means we are not sure what its constituents are and how they interact with one another. Many theoretical studies have hinted at the presence of exotic matter (such as kaon/pion condensates) inside a NS core. Appearance of exotic matter in highly dense matter results in the softening of EoS, which lowers the maximum mass reached in a NS sequence.

Most NS are born in a core-collapse supernovae (CCSN) explosion, which is believed to be an adiabatic event. Also, many NS have very high magnetic fields and are known as magnetars. Such NS can also be formed during merger of binary NS. Owing to their extreme density, NS are extremely relativistic objects and can emit gravitational waves (GW) via different mechanisms. For example, when the rotation axis of NS is not aligned with its magnetic axis, it causes non-axisymmetric deformation in NS structure thereby which resulting in GW emission.

In this work, we study the NS with antikaon condensates and which are at finite entropy per baryon (s), as a result of being born in adiabatic event of CCSN and wherein the temperatures have not yet cooled down below the Fermi level. We study their structural evolution with rotation. We also calculate the GW amplitude emitted by a NS whose magnetic axis is not aligned with its rotation axis.

Compact Star model

For NS core model, we consider nuclear and antikaon (K^-) condensed matter in its dense interior. The relevant physical variables for the EoS such as, number density, energy density, pressure are calculated starting from a model Lagrangian. We calculate the EoS within the framework of relativistic mean-field model with density dependent coefficients. The details can be found in [1]. Further, we adopt the finite temperature treatment of K^- condensates as given in [2]. In addition to nucleons and K^- mesons, we also have leptons in the system. They are treated as non-interacting particles. However, in our model, energetically favourable K^- condensates replace the leptons as soon as they are formed. Further, we consider NS to be at constant s while deriving its EoS.

For nucleons-only matter, we use Hempel-Schaffner-Bielich constructed HS(DD2) EoS for dense matter consisting of protons, neutrons and leptons [3]. The low density, inhomogeneous part of this EoS is calculated in extended Nuclear statistical equilibrium model, and we use that for our crust EoS. As the K- condensates appear at high densities only, the nuclei and exotic matter are never found to coexist. Therefore we simply use the non uniform part of above EoS following the standard prescription of minimization of free energy. This procedure allows for a smooth transition between different parts of EoS at around nuclear saturation density.

To compute and compare the hydrostatic equilibrium configurations of rotating NS with above-mentioned EoS, we use the *nrotstar* code of numerical library *LORENE*, which implements multidomain spectral method for calculating accurate models of rotating NS in full general relativity. We compute stable NS configurations for different EoS as described earlier.

Results

We generate a number of isentropic EoS profiles and compute the properties of rotating NS [4]. The EoS for NS with K^- and thermal kaons is denoted as 'npK' and that for n and p only is denoted as 'np'. We compute many npK profiles for different entropies and different strength of antikaon optical potential (U_K) and compare the same with np EoS profiles. Fig 1 shows this comparison. We see, that npK EoS is softer than np EoS, An increase in s further softens the EoS.

We then calculate the constant total entropy (S) mass sequences for EoS with a medium U_K. The sequences are compared for different values of S. We see that mass sequences follow the EoS profiles, as expected. We also study the fraction of different particles in a NS core at different entropies and potentials. The temperature profile in NS interior was also studied.

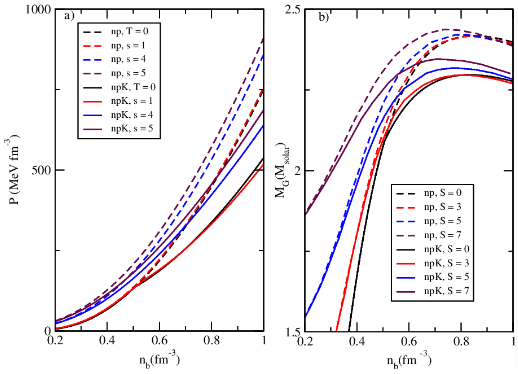

Fig. 1: The left panel shows various EoS for K^- condensed matter in NS, the right panel shows the NS Mass sequences for different EoS.

We also study the effect of rotation on NS configuration. We notice that mass of a NS increases with increase in its angular momentum (J). Further, we also see evolution in its structure with J. We notice an increased axisymmetric deformation as the NS spins faster. In Fig 2, we plot the energy density contours in its equatorial slice for low and high J. Faster rotating NS is deformed much more from spherical shape than a slow rotating star.

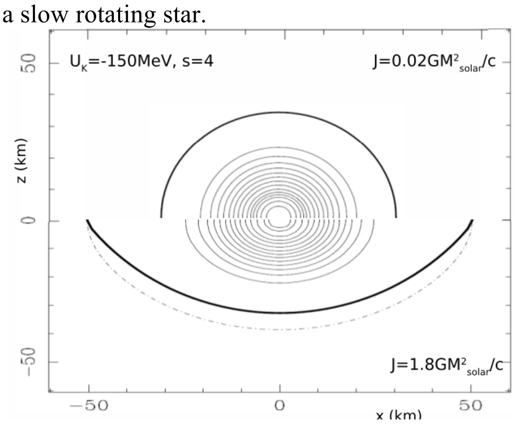

Fig. 2 Contours of energy density inside a NS for low J (top half), and high J value (bottom half).

Finally,we estimate the strength of GW that may be emitted from a highly magnetized NS, having B ~10^{12} T and frequency ~200 Hz; and which obeys the aforementioned EoS. We consider that its magnetic axis and rotation axis are not aligned. We used the prescription given in [5] for the calculation. GW amplitude for a hot NS with high s was found to be considerably larger than that for a cold NS. Still its strength is not large enough to come in the range of the present day detectors, but might just come within the grasp of next generation of GW observatories.

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