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Hybrid stars

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Abstract. Recently there have been important developments in the determination of neutron star masses which put severe constraints on the composition and equation of state (EOS) of the neutron star matter. Here we study the effect of quark and nuclear matter mixed phase on mass radius relationship of neutron stars employing recent models from two classes of EOS's and discuss their implications.

Keywords. Neutron stars; phase transition.

It is generally believed that the evolutionary journey of a star after it has exhausted all its fuel culminates into the formation of a compact object in the form of a white dwarf, a neutron star or a black hole depending on its mass. White dwarfs support themselves against gravitational collapse by the electron degeneracy pressure, neutron stars largely by the pressure of degenerate neutrons whereas, the black holes are completely collapsed stars. Neutron stars are the most compact and dense stars known. They typically compress a solar mass matter into a tiny radius of 10 km with densities in the core reaching several times the nuclear density. With such densities in the core, they themselves can take various forms, for example they could be composed of normal nuclear matter with hyperons and/or condensed mesons. The matter at such densities may undergo phase transition to constituent quark matter. It would then be energetically profitable for the u-d matter to convert itself into u-d-s matter through weak interactions thereby lowering its energy per baryon. If it so happens that the energy per baryon of such matter called strange matter is the true ground state of matter with energy per baryon less than that of iron, the most stable nuclei, the whole star will convert itself into a strange star with vastly different characteristics. In case strange matter is not the true ground state, the neutron star may have a quark core followed by a mixed phase and nuclear mantle at the top. Such stars are called hybrid stars. A neutron star comes into existence through a cataclysmic process at time-scale large compared to not only the strong and electromagnetic interaction time-scales but weak interaction scale as well. Further, the electrostatic repulsion being so much stronger compared to gravitational attraction, the matter is electrically neutral and typical Fermi momenta of constituents being large compared to its temperature, neutron star is composed of cold, degenerate, charge neutral matter in β-equilibrium. At densities $< 2\times 10^{-3}\rho_0$ ($\rho_0 = 0.16$ nucleons/fm^3 is the equilibrium density of charged nuclear matter in nuclei), the matter is assumed to be in the form of a Coulomb lattice (to minimize energy) of nuclei immersed in a relativistic degenerate electron gas. In the lower part of the density range $10^{-3}\rho_0 < \rho < 10\rho_0$ the neutrons leak out of the nuclei and a Fermi liquid of neutrons, protons and electrons start building up. At higher densities there are several possibilities including the occurrence of muons, condensation of negatively charged pions and kaons, appearance of hyperons and finally, the transition to quark matter.

Matter at such high densities has not been produced in the laboratory and there is no available data on nuclear matter interactions. The quantities of interest are the phases and composition of neutron star matter, its energy density and pressure which determine the equation of state (EOS). The EOS up to nuclear densities is fairly well-accounted for on the basis of measured nuclear data and nucleonic interactions. Above nuclear densities there are basically two approaches: one is to take the interaction between constituents from realistic fitting with known scattering data and then use the techniques of many-body theory to calculate correlations. The other is to take a relativistic mean field type of model with couplings treated as parameters to fit observable quantities. Both approaches suffer from lack of experimental data. Whereas many-body approach is well-understood, two nucleon interactions are fairly well-known, higher-body interactions are not well-characterised and the approach is non-relativistic. Mean field theoretical models can easily incorporate many constituents, but the complicated correlations are simplified in terms of vacuum expectation of mean fields which are fitted to insufficient data.

As discussed above, if there is a phase transition to quark matter, the entire star may convert itself into a strange star or a hybrid star depending on whether the strange matter is the true ground state of matter or not. In earlier studies the phase transition was characterised as a first-order transition with a single component, viz. baryon number and charge neutrality was strictly enforced in each phase separately. This gave rise to constant pressure (liquid–vapour) type phase transition and since in a star, the pressure increases monotonically with density as we go from the surface to the core, mixed phase was strictly prohibited. It was pointed out by Glendenning [1] that matter in neutron star has two components, namely the conserved baryon number and the electric charge. Therefore, the correct application of Gibb's phase rule is that the chemical potential corresponding to baryon number and charge conservation, i.e., μ_B and μ_Q, the temperature and the pressure in two phases are equal, i.e.

$$\mu_B(h) = \mu_B(q); \quad \mu_Q(h) = \mu_Q(q)$$

$$p_h(\mu_B, \mu_Q, T) = p_q(\mu_B, \mu_Q, T)$$

and charge neutrality only demands global conservation

$$\chi Q_q(\mu_B, \mu_Q, T) + (1-\chi) Q_h(\mu_B, \mu_Q, T) = 0,$$

where χ is the fraction of the volume occupied by the quark phase. The freedom available to the system to rearrange concentration of charges for a given fraction of phases χ, results in variation of the pressure through the mixed phase. The structure of the star in hydrostatic equilibrium is determined by solving the Tolman–Openheimer–Volkoff equations and the only information required is the knowledge of the EOS. For the EOS we use a RFT model taken from Glendenning and a potential model incorporating relativistic corrections and three-body interactions given

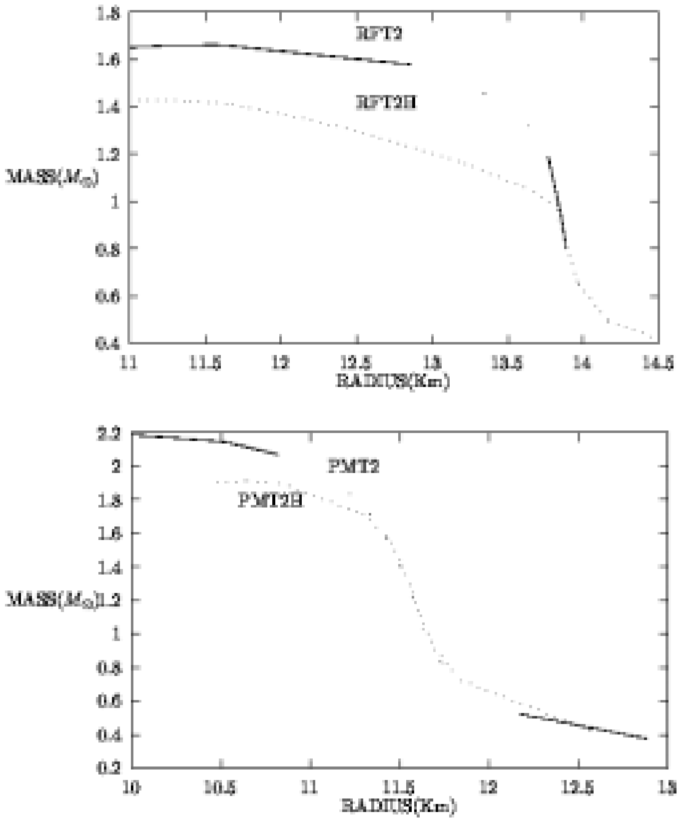

Figure 1. Plot of mass in solar mass unit vs. radius in km.

by Akaml *et al* [2]. Both classes of models admit mixed quark–nucleon phase in the core [3]. In figure 1 we see that the effect of the existence of mixed quark–nuclear matter phase in the core of neutron stars is to reduce the maximum mass. The effect is more pronounced for the relativistic mean field theory model than for the potential model. In contrast, a strange star mass varies as $\sim R^3$ for $M \sim 0.5M_0$ and gravity plays a minimal role, bag pressure provides the confinement and the star is self-bound. As mass increases, gravity becomes important and the star reaches a maximum mass and the strange star radii decrease with decrease in mass and there is no minimum mass.

During the last thirty years since the discovery of first pulsar in 1968 by Hewish *et al*, using radio telescope and X-ray probes in space, close to two thousand pulsars have been discovered in a variety of circumstances: (i) as isolated radio sources at times in binary orbits with other stars, (ii) as X-ray pulsars and X-ray bursters in X-ray binary system and (iii) most recently by Rossi XTE X-ray satellite as KHz quasi-periodic oscillations and burst oscillations in low mass X-ray binaries. This has led not only to their identification as neutron stars but has provided physical laboratory with unprecedented potentialities to perform tests of GTR and to obtain information on the EOS of high density matter, its composition and phase transition. Masses of ten neutron stars have been measured by observing relativistic effects in binary orbits and all of them have masses in the range $1.35 + 0.04 M_0$ [4] with exceptions of PSR J1012 of mass $2.1 + 0.4 M_0$. Masses of X-ray pulsars are measured less accurately and recent observations for Vela X-1 and Cygnus X-2 give $1.9 + 0.2 M_0$ and $1.8 + 0.4 M_0$ respectively [5]. The QPO observations correspond to masses $\sim 2 M_0$ [6]. Thus if large masses of neutron stars are confirmed and complemented by other neutron star masses $\sim 2M_0$, (i) EOS is severely restricted and only stiff EOS's without any significant phase transition below $5n_0$ are allowed. (ii) On the other hand if heavy neutron stars prove erroneous by more detailed observations and masses like those of binary pulsars ($\sim 1.4 M_0$), this will indicate that accretion does not produce heavier stars which will mean either a soft EOS or significant phase transition at few times the nuclear saturation density. (iii) Observation of a star of mass $\leq M_0$ and radius ≤ 10 km or a submilli-second pulsar would be a good strange star candidate.

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