Consequences of Quark-Hadron Phase Transition in Dense Stars

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Abstract.   The deconfinement phase transition in a rotating compact star and its consequences on neutrino emission have been studied. It has been found that rotating twin star solutions are obtained upto $\Omega \approx 4000s^{-1}$. For faster rotating stars no twin solution is obtained. The neutrino emission shows a strong directionality.

1. Introduction

Compact stars are thought to be the best possible laboratory to study the strongly interacting matter at super nuclear densities. The matter density near the core of a compact star can be $8 - 10$ times that of normal nuclear matter. Different exotic phase transitions may take place in the strongly interacting matter [1] at such high densities. In this work we look at some of the consequences of deconfinement phase transition inside a rotating compact star.

Recently some of us have used the NLZ model for the hadronic sector and MIT Bag model for the quark sector to look at the quark-hadron phase transition in static compact stars [2]. In that work it was found that there was a solution for the third family of stars known as twin stars [3]. Here we employ the same EOS for a rapidly rotating star. The basic motivation is to study the fate of the twin stars in a rotating model and also to study the neutrino emission from theses stars as a possible signature of the phase transition. The organisation of the paper is as follows. In section 2, we discuss the properties of the rotating stars. In section 3, we study the process of neutrino emission associated with a phase transition to the quark phase. Finally, in section 4, we present our conclusion.

2. Equation of State and Star Properties

In this work we use a variant of non-linear Walecka model for the hadronic sector and the MIT bag model ($B^{\frac{1}{4}} = 180 MeV$) for the quark sector. A mixed phase has been formulated using Gibbs construction. The details of the models and the parameter sets may be obtained in ref. [2, 4]. In figure 1 we plot the Equation of State (EOS) obtained from the above mentioned model. From figure 1 one can see that the phase transition starts at around $\epsilon_c = 4 \times 10^{14} gm/cm^3$ and ends around $\epsilon_c = 1 \times 10^{15} gm/cm^3$.

The EOS obtained above is used to solve the Einstein's equations for the rotating star. The metric for a stationary rotating star can be written as [5]

$$ds^2 = -e^{\gamma+\rho}dt^2 + e^{2\alpha}\left(dr^2 + r^2d\theta^2\right) + e^{\gamma-\rho}r^2sin^2\theta\left(d\phi - \omega dt\right)^2 \qquad (1)$$

where α, γ, ρ and ω are the gravitational potentials which depend on r and θ only. The Einstein's equations for the three potentials γ, ρ and ω have been solved by Komatsu *et.al.* [6] using Green's function technique. The fourth potential α has been determined from other potentials. All the physical quantities can be calculated from these potentials [5]. Solution of the potentials, and hence the calculation of physical quantities, is numerically quite an involved process. In this work we have used the **'rns'** code [5, 6] for this purpose.
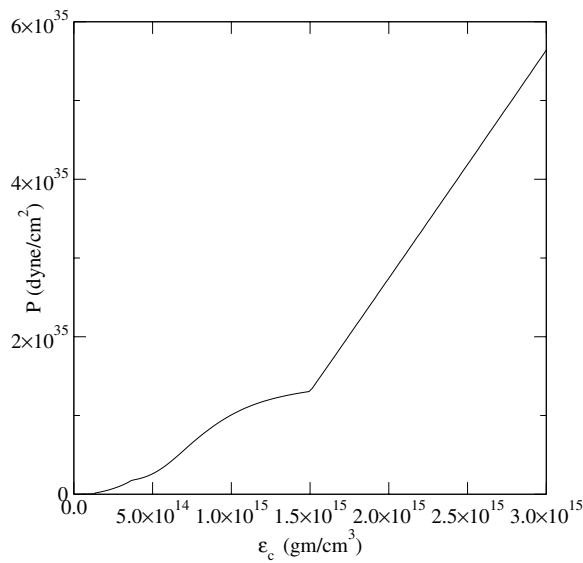

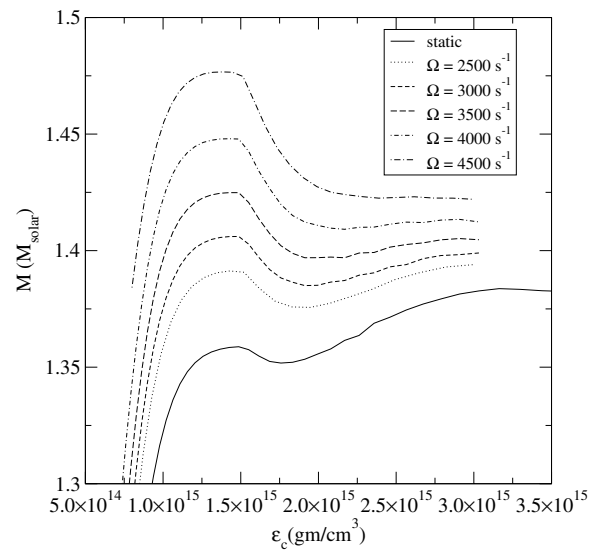**Figure 1.** Equation of state of the model considered here.

Figure 2. Mass-ϵ_c plots for different Ω.

In figure 2, we have plotted the mass - ϵ_c curves for different angular frequency Ω. Normally, the mass - ϵ_c curve for neutron stars shows a maximum beyond which no stable configuration is supposed to exist. Harrison *et al.* [7] showed that for a smooth equation of state no stable stellar configuration exists for central densities above that corresponding to the maximum mass limit. Recently Glendenning *et al.* [8] have found that if there is a first order phase transition inside the neutron star, this inference may not be valid. As a result a stable configuration for a third family of stars, with higher central densities, may arise. In the present work also, we have found the existence of stars which belong to the third family, known as twin stars. These results may be seen in figure 2. However, as we increase Ω, the third family solution becomes less probable, as can be seen from the plots, and it vanishes just after $\Omega = 4000s^{-1}$. This is natural as with increasing angular velocity, the phase boundary moves outward, matter gets redistributed to larger equatorial radii and the twin star solution vanishes.

The appearance of the twin star solution has other interesting consequences as well. In figure 3 we have plotted the moment of inertia (I) as a function of Ω for different rest masses, *i.e.*, for both normal and supermassive sequences. For the normal sequence, the moment of inertia increases with the angular velocity monotonically. However, for a supermassive sequence, there are two different branches; for one branch of the curve the moment of inertia increases with Ω, whereas, for the other, the moment of inertia decreases with increase in Ω. This anomalous behaviour

of moment of inertia is known as backbending and can be attributed to the phase transition from incompressible nuclear matter to highly compressible quark matter [9]. As pointed out by several authors, this feature could be a possible signature of the quark-hadron phase transition. Here we would like to emphasize that even for supermassive sequence, the backbending is only observed for the cases where density in the core is such that it facilitates a large quark phase region inside the star. For example, though the range of rest mass $1.35M_\odot < M_0 < 1.48M_\odot$ lies in the supermassive domain, no backbending has been found for masses within this range. Higher mass ($1.6M_\odot$ and $1.7M_\odot$) sequences correspond to larger I and Ω. Due to the redistribution of matter, as mentioned earlier, the $dI/d\Omega > 0$ part, corresponding to the quark core (as seen for masses $1.48M_\odot - 1.5M_\odot$), does not appear.
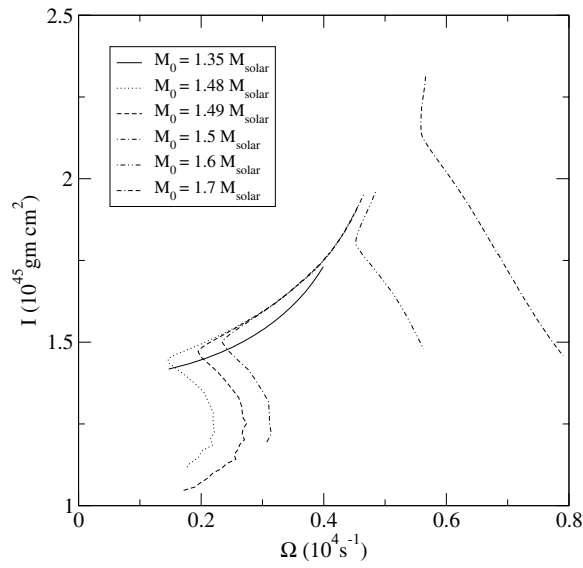

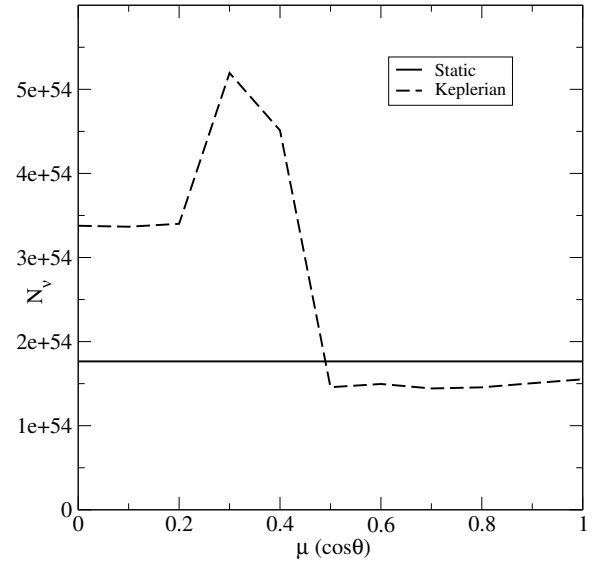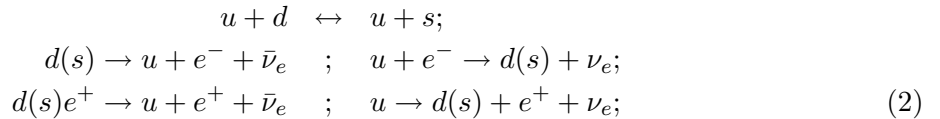**Figure 3.** I as a function of Ω for different rest masses.

Figure 4. Neutrino emissivity as a function of μ.

3. Neutrino Emission

In this section we look at the neutrino emission from a rotating compact star due to the phase transition *only*. The neutrino emission from the equilibrated matter is much smaller in magnitude and has been neglected [10].

The reactions that we consider here are

$$
\begin{aligned}
u + d &\leftrightarrow u + s; \\
d(s) \to u + e^- + \bar{\nu}_e &\quad ; \quad u + e^- \to d(s) + \nu_e; \\
d(s)e^+ \to u + e^+ + \bar{\nu}_e &\quad ; \quad u \to d(s) + e^+ + \nu_e;
\end{aligned}
\tag{2}
$$

We solve the rate equations for these reactions self consistently. The rate of change of the u quark density is given by

$$
\begin{aligned}
\frac{dn_u(t)}{dt} &= R_{d\to u}(e^-) + R_{s\to u}(e^-) - R_{u\to d}(e^-) - R_{u\to s}(e^-) \\
&+ R_{d\to u}(e^+) + R_{s\to u}(e^+) - R_{u\to d}(e^+) - R_{u\to s}(e^+)
\end{aligned}
\tag{3}
$$

Similarly, one can obtain the other rate equations. Solving the above equations one can obtain the neutrino emission rate as a function of density. The emission rate thus obtained can be folded with the baryon density profile of the star as a function of θ to get the number of neutrinos emitted as a function of θ. In figure 4, we have plotted the number of neutrinos emitted as a function μ (= $cos\theta$, $\mu = 0$ corresponds to the equator and $\mu = 1$ corresponds to the pole). From the figure one can see that as one moves from the static limit to the keplerian limit the uniformity of the neutrino emission is lost. The neutrino emission is dominated over a small angle. This happens because of the redistribution of matter due to rotation. In this particular case the neutrino emission is constrained mostly within the range 60^0 and 80^0.

4. Conclusion

To summarise, we have studied the effect of deconfinement transition in a rotating compact star. The third family of star *i.e.* the twin star solution is expected to occur due to the substantial change in the sound speed across the phase boundary. In the present model, the twin star solution is obtained for the static as well as for the rotating case. However, with the increase in angular velocity Ω, the mass as well as ϵ_c of the star increases, which implies that the twin star solutions for higher central densities vanishes beyond a certain Ω. At this point, most of the star, in the present study is found to be made up of quark matter. So the faster rotating stars have larger domain of mixed phase and do not exhibit the third family of stars.

The emission of neutrinos are also modified due to the rotation. For a compact star rotating fast enough the emission of neutrinos are constrained within a very small angle. One should also study other models and look into the angular distribution of the emitted neutrinos. Work in these directions are in progress.

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