

PROPERTIES OF MAGNETIZED QUARK-HYBRID STARS

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The structure of a magnetized quark-hybrid stars (QHS) is modeled using a standard relativistic mean-field equation of state (EoS) for the description of hadronic matter. For quark matter we consider a bag model EoS which is modified perturbatively to account for the presence of a uniform magnetic field. The mass-radius (M-R) relationship, gravitational redshift and rotational Kepler periods of such stars are compared with those of standard neutron stars (NS).

Keywords: Quark-hybrid star; kepler periods; gravitational redshift.

1. Introduction

It is known that compact objects such as NS or hybrid stars possess enormous magnetic fields. Anomalous X-ray pulsars (AXPs) and soft γ -repeaters (SGRs), may contain NS with magnetic fields greater than 10^{15} G at the NS surface (magnetars). Some authors^{1,2} claim that magnetized QHS or magnetized quark stars (QS) might be the real sources of such objects.

In a recent paper³ we modeled QS as high-density quark bags with magnetic fields of $B \sim 4-6 \times 10^{17}$ G. Although such magnetic fields are typical for magnetars, it was shown that the magnetic field is still low enough so that it can be treated perturbatively (*i.e.*, $B \gg \mu^2$, with μ being the baryon chemical potential).

In this paper we analyze the structure of a QHS, consisting of a strange quark matter (SQM) core enveloped in a thin hadron matter crust. We neglect the narrow gap that exists between the SQM core and the crust, and use an EoS for such stars which describes confined hadronic matter in terms of nucleons and hyperons (HV of Ref. 4) and deconfined quark matter in terms of a relativistic gas of up, down and strange quarks, as described by the modified MIT bag model of Ref. 3.

2. High Density Magnetized SQM EoS

For the quark matter in the core of a QHS we consider massless quarks, which implies that the electrons are not present and the quark chemical potentials are, as a consequence of chemical equilibrium, all equal, $\mu_u = \mu_d = \mu_s \equiv \mu$. Considering the limit of weak magnetic fields, $\mu^2 \gg B$, after some analytic approximations the EoS of magnetized SQM within the framework of the MIT Bag model becomes³

$$\rho \simeq 3P + 4B_{\text{eff}} - \frac{B^2}{3\pi^2} \left(2 - \text{Log} \frac{B}{2^{1/3} 3 \mu^2} \right), \quad (1)$$

with $B_{\text{eff}} = \frac{B^2}{8\pi} + B_{\text{bag}}$, where B_{bag} denotes the bag constant. Bag values in the range of $57 \text{ MeV fm}^{-3} < B_{\text{bag}} < 90 \text{ MeV fm}^{-3}$ correspond to SQM which is absolutely stable with respect to nuclear matter,^{4,5} even when the magnetic field $B \neq 0$.³ For QHS, which are made of meta-stable SQM, we consider $B_{\text{bag}} = 120 \text{ MeV fm}^{-3}$. For such a value of the bag constant the threshold for the magnetic field is $B_{\text{max}} = 6.4 \times 10^{17} \text{ G}$.

3. Redshift and Kepler Period

Several EoS for NS, QHS and QS have been proposed but none of them is conclusive.⁶ Each EoS produces a different mass-radius (M-R) relationship which can be contrasted with the available observational data in order to test its range of validity and/or set bounds on some parameters. The gravitational surface redshift is of particular interest for distinguishing between QHS and NS because it is an observable quantity. The surface redshift, z , depends on the mass M and radius R of the star and is given by

$$z = (1 - 2GM/Rc^2)^{-1/2} - 1. \quad (2)$$

We also consider the effect of rotation and calculate the maximum possible rotational periods of these stars. It is known that the absolute upper limit on stable stellar rotation is given by the Kepler frequency, Ω_K , which is the maximum frequency a star can have before mass loss at the equator sets in.⁷ Knowing Ω_K ,^{7,8} the rotational period is given by $P_K = \Omega_K/2\pi$.

4. Results and Conclusions

In this section we show the differences between a standar NS (HV EoS) which includes neutrons, protons, hyperons, electrons, and muons, and a magnetized QHS. The left panel of Fig. 1 shows the M-R relationship for non-rotating stars. Note that for the QHS there are two mass peaks, one at $1.44 M_\odot$ and the other at $1.52 M_\odot$. The radii of these stars are $\sim 13 \text{ km}$ and $\sim 10 \text{ km}$ respectively. In contrast to this, the traditional (HV) NS has a maximum mass of around $\sim 2 M_\odot$ with an associated radius of $\simeq 11 \text{ km}$. We note that not all stars between the two QHS maxima are gravitationally stable, which is a consequence of the phase transition

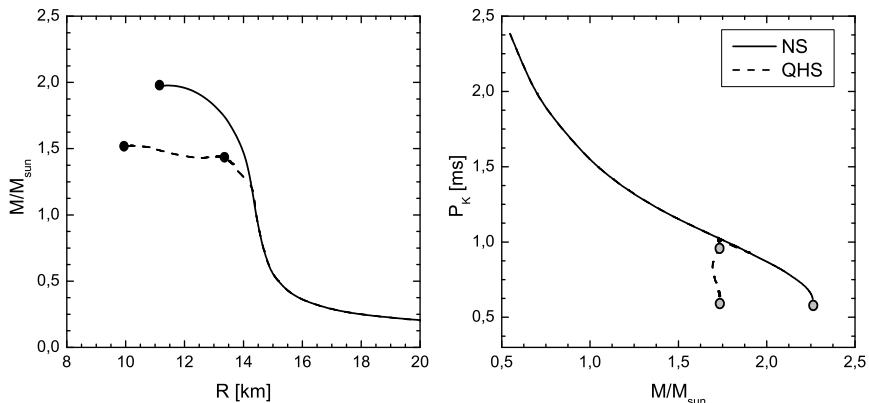


Fig. 1. Left panel shows the $M - R$ relation for non-rotating NS (solid line) and QHS (dashed line). Right panel shows the Kepler period P_K as a function of the star mass in solar masses for the NS (solid line) and the QHS (dashed line).

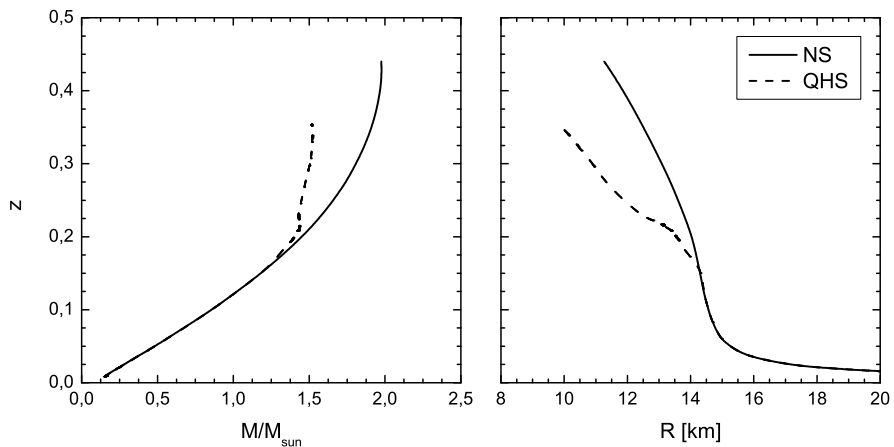


Fig. 2. Surface redshift parameter z as a function of the star mass in solar masses (left panel) and the star radius R (right panel) for the NS and the QHS (solid and dashed line respectively).

between hadronic matter and quark matter.^{9,11} The differences in the masses reflect the fact that the QHS is more compressed than the NS, since its EoS is distinctly softer. In the right panel of Fig. 1 we show the Kepler period as a function of rotating star mass. Rotation shifts the mass peaks from $\sim 1.44 M_{\odot}$ to $\sim 1.69 M_{\odot}$ and from $1.52 M_{\odot}$ to $\sim 1.73 M_{\odot}$ for the QHS, and from $\sim 2 M_{\odot}$ to $\sim 2.26 M_{\odot}$ for the NS. Since rotation stabilizes a star against gravitational collapse, the rotating stars can carry more mass than the non-rotating star. The range of observed NS masses is between about 1 and $2 M_{\odot}$ ¹⁰ and the observed rotational periods are greater than

1.38 ms, which is compatible with the P_K curves shown in Fig. 1. However, phase transition in the cores of NS may lower this value.⁷ We obtain $P_K = 0.88$ ms and $P_K = 0.64$ ms for the stellar QHS twins, and $P_K = 0.62$ ms for the maximum-mass NS configuration.

In Fig. 2 we show the gravitational surface redshift. The differences in the M-R relationships of QHS and NS leads to markedly different redshift, which opens up the possibility of distinguishing a QHS from a NS. For the maximum mass QHS we find $z = 0.22$ and $z = 0.34$. These values are $\sim 50\%$ and $\sim 20\%$ lower than the redshift of the corresponding NS, which is $z = 0.43$. The inclusion of the magnetic fields, up to $\sim 10^{17}$ G, in the SQM EoS influences the stellar properties discussed above only very little. This may be different for magnetic fields greater than $\sim 10^{17}$ G. The study of such high fields is however outside of the scope of the perturbative formalism presented in this paper.

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