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Compact Star Properties revised with Color Superconducting Phases of Quark Matter: Implications on Rotation and Emission

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There has been much recent progress in our understanding of quark matter, culminating in the discovery that if such matter exists in the cores of neutron stars it ought to be in a Color Superconducting state. This paper presents a detailed study of the consequences of superconducting quark matter on the properties of Compact Stars such as Masses, Radii, Surface gravity and Photon Emission patterns. Special emphasis is put on the Rotational properties of such stars and their temporal evolution.

1. Introduction

Understanding the composition of matter inside compact stars is one of the toughest theoretical challenges of relativistic astrophysics [1, 2]. Despite some progress that has been made over the years, the physics of the ultra-dense core of such objects is still only vaguely known. Recently it has been theorized that the core may be made of color superconducting quark matter [3, 4], rather than just ordinary nucleons. If true, this would change our traditional understanding of *neutron* stars dramatically. This paper studies the implications of color superconducting quark matter on the global properties of neutron stars. The study is based on three different models for the Equation Of State (EoS). The first model is the Hartree V EoS [5] which treats the core matter as made of conventional hadronic particles (nucleons and hyperons) in chemical equilibrium with leptons (electrons and muons). The second EoS is known as $\mathrm{G}_{300}^{\mathrm{B}180}$ [2] and describes the matter in the star in two phases, one being regular hadronic matter (in the outer layers of the star), the other being deconfined quark matter described by the MIT Bag Model (with a nuclear compressibility of 300 MeV and a value for the bag constant of 180 MeV). The third model for the EoS treats quark matter in the color flavor locked (CFL) superconducting phase [4]. Figure 1 shows the Pressure-Energy relations for the three EoS used in the paper.

2. Results and Conclusions

In this section we present various plots which illustrate the differences between conventional neutron stars (Hartree V), and neutron stars with color superconducting quark matter cores (CFL) and non-superconducting quark matter cores ($\mathrm{G}_{300}^{\mathrm{B}180}$). In figure 2 we present the calculations for the Mass-Radius relations of different stars according to the EoS that rule their interior composition. Because of the extreme softness of the CFL EoS, these stars are much more compressed than the other two stars of our collection. The mass peak of the CFL sequence is at around 1.36 $\mathrm{M}_{\odot}$and the corresponding radius of 9 km. In contrast to this, the conventional neutron stars (Hartree V) can have masses up to around 2 $\mathrm{M}_{\odot}$and radii of $\sim$ 11 km. This differences in size and mass can also be seen in figure 3 where we also plot the evolutionary (constant stellar baryon number, A) paths that isolated rotating neutron stars would follow during their stellar spin-down caused by the emission of magnetic dipole radiation and a wind on e^{+}–e^{-} pairs. Figure 3 reveals that CFL stars may spend considerably more time in the spin-down phase than their competitors of the same mass. Figure 4 shows the general relativistic effect of frame dragging [1] which is tremendously pronounced for the CFL stars, from the center of the star ($\bar{\omega}/\Omega$=0.48) all the way up to about two times the size of the star. This may be of great importance

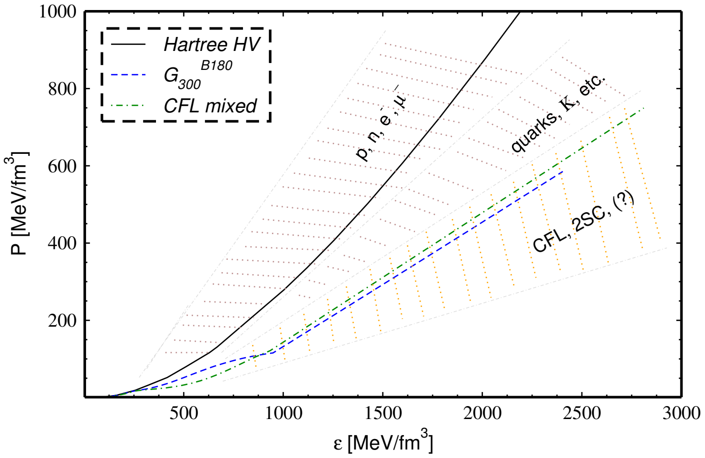

Figure 1. Equations of State used in this study. The shaded areas indicate competing stellar compositions in the P–ϵ plane.

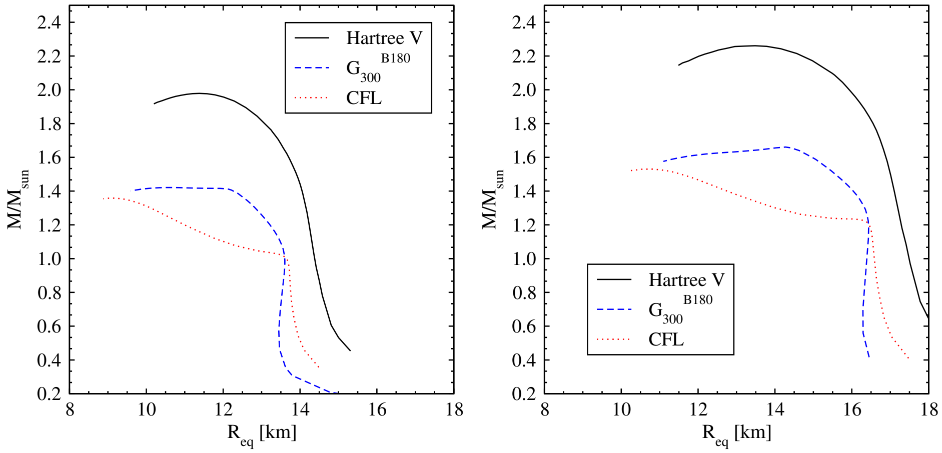

Figure 2. Mass–Radius Relations of static (left panel: $\Omega = 0$) and rotating (right panel: $\Omega = \Omega_K$) neutron stars computed for the EoS of this work. Ω_K denotes the general relativistic Kepler (mass shedding) frequency.

for binary millisecond neutron stars in their final accretion stages, where the accretion disk approaches the star very closely. As seen in Table 1, if quark matter is indeed in a color superconducting state inside the cores of neutron stars, this fact can be checked for a number of properties. In the mentioned table we show for the static (three left columns) and the rotating (three right columns) solutions of Einstein's field equation the central energy density (ϵ_c), which can be up to 20 times higher than nuclear density, the Moments of Inertia, Masses and Radii which all account for the superdense form of CFL stars. We also show the surface redshifts (from the pole and from the equator with and against the direction of rotation of the star) which have a strong impact on the observational temperature determination since $T_\infty/T_{\text{eff}} = 1/1+z$ and CFL stars can present redshifts 50% higher than their regular hadronic matter counterparts. Finally we also show in Table 1 the surface gravity (in units of 10^{14} cm/s^2) which again is up to 50% higher for the CFL stars than for the other stars, the Rotational Kinetic Energy in units of the total Energy of the star (T/W) [1], the Binding Energy (BE) and

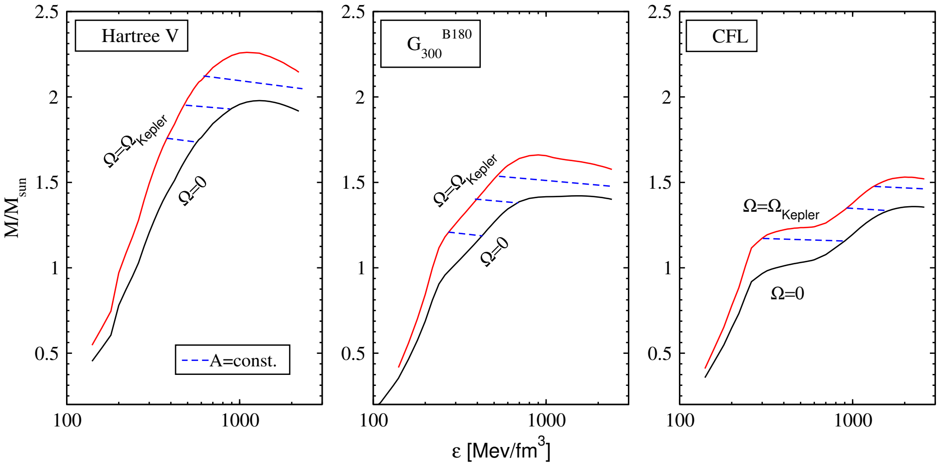

Figure 3. Mass–Central Energy Relations of the three model stars of this study (for details, see text.)

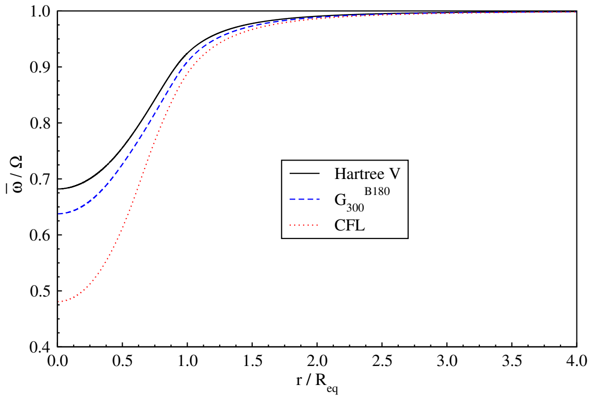

Figure 4. Dragging of local inertial frames (Lense-Thirring effect) caused by 1.3 $M_\odot$ stars rotating at a period of 2 ms.

the velocity at the equator in units of *c*. The plots in figure 5 show the evolution of the particle populations (nucleons, hyperons, quarks) inside our three sample stars with changing stellar frequency of rotation. In each panel, from right to left, the two most outer-lying curves indicate the surface of the star and the end of the outer crust, followed by lines which mark the transitions to more exotic phases, as indicated in the figure. Increasing rotation rates decrease the interior stellar density drastically [1], which could constrain the existence of quark matter to neutron stars rotating below moderate frequencies only.

3. Acknowledgements

We would like to thank Mark Alford for providing us with an EoS that accounts for Color Superconducting Quark Matter. We would also like to thank the NSF (USA) and the Science and Technology Department of Spain for financial support.

Table 1. Key differences between standard stars and quark matter stars of this study. (See text for more details.)

	Hartree V $\Omega = 0$	G^{B180}_{300} $\Omega = 0$	CFL $\Omega = 0$	Hartree V $\Omega_K = 5360\text{s}^{-1}$	G^{B180}_{300} $\Omega_K = 5900\text{s}^{-1}$	CFL $\Omega_K = 8800\text{s}^{-1}$
ϵ_c	361.0	814.3	2300.0	280.0	400.0	1100.0
$\mathrm{I(km^3)}$	0	0	0	223.6	217.1	131.8
$\mathrm{M\ (M_\odot)}$	1.39	1.40	1.36	1.39	1.40	1.41
R (km)	14.1	12.2	9.0	17.1	16.0	12.6
$\mathrm{Z_{pole}}$	0.1889	0.2322	0.3356	0.2374	0.2646	0.3618
$\mathrm{Z_{fw}}$	0.1889	0.2322	0.3356	-0.1788	-0.1817	-0.2184
$\mathrm{Z_{bw}}$	0.1889	0.2322	0.3356	0.6046	0.6502	0.9190
$\mathrm{g_{s,14}(cm/s^2)}$	1.1086	1.5447	3.0146	0.7278	0.8487	1.4493
T/W	0	0	0	0.0894	0.0941	0.0787
$\mathrm{BE/M_\odot}$	0.0937	0.1470	0.1534	0.0524	0.1097	0.1203
$\mathrm{v_{eq}/c}$	0	0	0	0.336	0.353	0.424

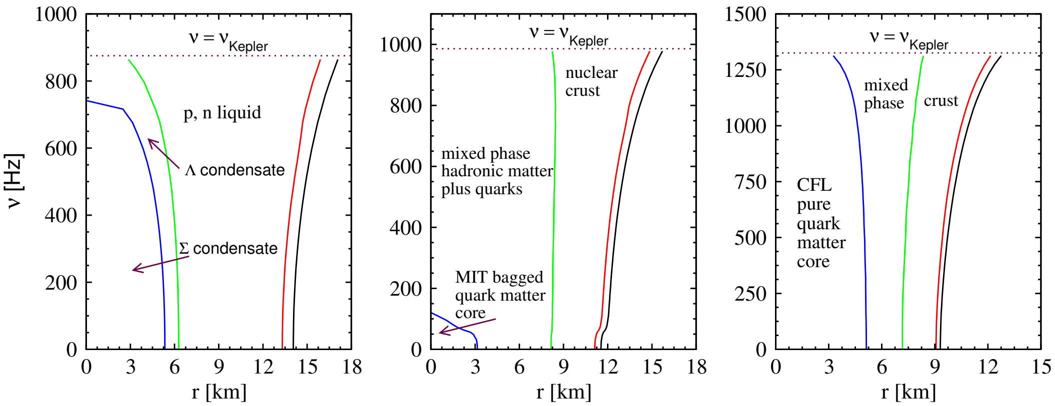

Figure 5. Particle profiles of the neutron stars of our collection, showing the various depths at which the different phases of matter are found inside the stars. (The non-rotating stellar mass in each case is 1.4 $M_\odot$.)

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