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Neutron star interiors and the equation of state of ultra-dense matter

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Abstract. 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 explores the impact of superconducting quark matter on the properties (e.g., masses, radii, surface gravity, photon emission) of compact stars.

Keywords: stars, equation of state, quarks, color superconductivity, phase transition
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Exploring the composition of matter inside compact stars has become a forefront area of modern physics [1, 2]. Despite the progress that was made over the years, the physical properties of the matter in the ultra-dense core of compact stars is only poorly known. Recently it has been theorized that, if quark matter exists in the core, it ought to be a color superconductor [3, 4]. This paper reviews the consequences of color superconducting quark matter cores on the properties of neutron stars. The study is based on three sample

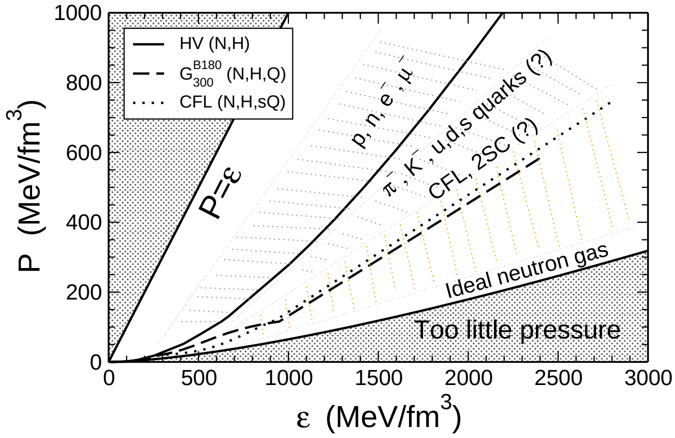

FIGURE 1. Eos considered in this study. The shaded areas reflect the uncertainties in the eos originating from different many-body treatments and competing assumption about the particle composition.

models for the nuclear equation of state (eos). The first model, HV[5], treats the core matter as made of conventional hadronic particles (nucleons and hyperons) in chemical equilibrium with leptons (electrons and muons). The second eos, G^{B180}_{300} [1], additionally accounts for non-superconducting quark matter. Finally, the third model accounts for quark matter in the superconducting color-flavor locked (CFL) phase [6]. Figure 1 shows these eos graphically.

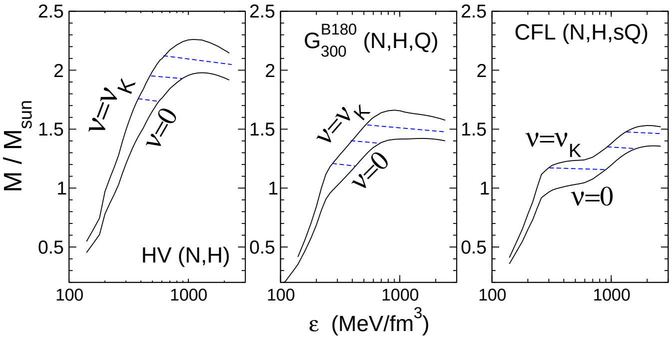

FIGURE 2. Mass–central energy density relations for the three model stars of this study.

Figure 2 shows 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 2 reveals that CFL stars may spend considerably more time in the spin-down phase than their competitors of the same mass. Figure 3 shows the general relativistic effect of frame dragging [1, 2, 7],

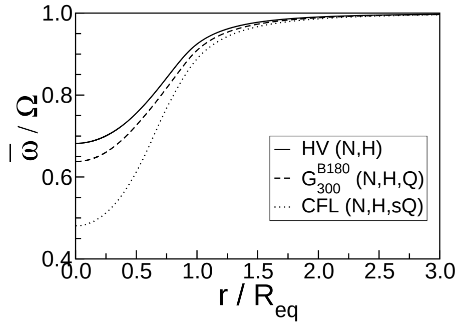

FIGURE 3. Lense–Thirring effect caused by $\sim 1.4\ M_{\odot}$stars rotating at 2 ms.

which is considerably more pronounced for the CFL stars because of their much greater densities. This may be of great importance for binary millisecond neutron stars in their final accretion stages, when the accretion disk is closest to the neutron star. Table 1 summarizes the impact of strangeness on several intriguing properties of non-rotating as well as rotating neutron stars. The latter spin at their respective Kepler frequencies. One sees that the central energy density, $\varepsilon_{\rm c}$, spans a very wide range, depending on particle composition. The surface redshift is of importance since it is connected to observed neutron star temperatures through the relation $T^{\infty}/T_{\rm eff} = 1/(1+Z)$. CFL quark stars may have redshifts that are up to 50% higher than those of conventional stars. Finally, we also show in Table 1 the surface gravity of stars, $g_{s,14}$ [8], which again may be up to 50% higher for CFL stars. The other quantities listed are the rotational kinetic energy in units of the total energy of the star, T/W, the stellar binding energy, BE, and the rotational velocity of a particle at the star's equator [2].

TABLE 1. Properties of neutron stars composed of nucleons and hyperons (HV), nucleons, hyperons, normal quarks (G^{B180}_{300}), and nucleons, hyperons, superconducting quarks (CFL) [2].

	HV $\nu = 0$	G^{B180}_{300} $\nu = 0$	CFL $\nu_K = 0$	HV ν_K = 850 Hz	G^{B180}_{300} ν_K = 940 Hz	CFL ν_K = 1400 Hz
ε_c (MeV/fm^3)	361.0	814.3	2300.0	280.0	400.0	1100.0
I (km^3)	0	0	0	223.6	217.1	131.8
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
Z_p	0.1889	0.2322	0.3356	0.2374	0.2646	0.3618
Z_F	0.1889	0.2322	0.3356	−0.1788	−0.1817	−0.2184
Z_B	0.1889	0.2322	0.3356	0.6046	0.6502	0.9190
$g_{s,14}$ (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
BE ($M_\odot$)	0.0937	0.1470	0.1534	0.0524	0.1097	0.1203
V_{eq}/c	0	0	0	0.336	0.353	0.424

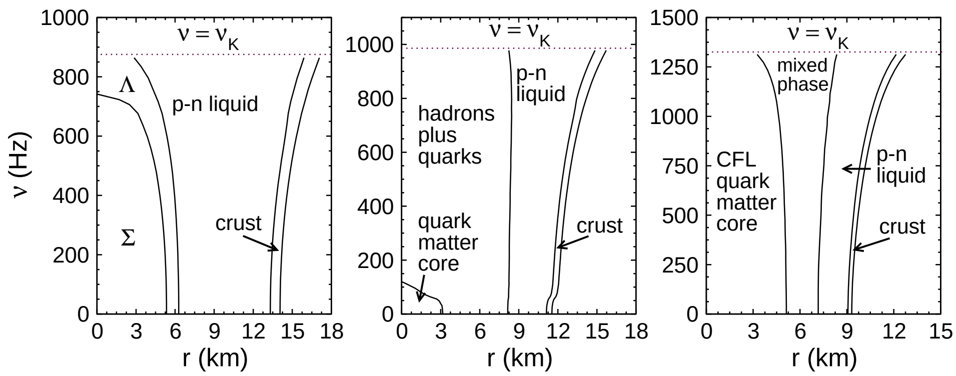

FIGURE 4. Particle profiles of the neutron stars of our collection.

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REFERENCES

1. N. K. Glendenning, *Compact Stars, Nuclear Physics, Particle Physics, and General Relativity*, 2nd ed. (Springer-Verlag, New York, 2000).
2. F. Weber, *Pulsars as Astrophysical Laboratories for Nuclear and Particle Physics*, High Energy Physics, Cosmology and Gravitation Series (IOP Publishing, Bristol, Great Britain, 1999).
3. K. Rajagopal and F. Wilczek, *The Condensed Matter Physics of QCD*, At the Frontier of Particle Physics / Handbook of QCD, ed. M. Shifman, (World Scientific) (2001).
4. M. Alford, Ann. Rev. Nucl. Part. Sci. **51** (2001) 131.
5. N. K. Glendenning, Astrophys. J. **293** (1985) 470.
6. M. Alford and S. Reddy, Phys. Rev. D **67** (2003) 074024.
7. F. Weber, Prog. Part. Nucl. Phys. **54** (2005) 193, (astro-ph/0407155).
8. M. Bejger and P. Haensel, Astron. & Astrophys. **420** (2004) 987.