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Authors
Weber, F.
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Interpretation of Rapidly Rotating Pulsars[†]

F. Weber[‡] and N. K. Glendenning

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720, U.S.A.

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[‡]Institute for Theoretical Physics, University of Munich, Theresienstrasse 37/III, W-8000 Munich 2, Federal Republic of Germany.

Interpretation of Rapidly Rotating Pulsars[†]

F. Weber and N. K. Glendenning

Abstract

The minimum possible rotational period of pulsars, which are interpreted as rotating neutron stars, is determined by applying a representative collection of realistic nuclear equations of state. It is found that none of the selected equations of state allows for neutron star rotation at periods below $0.8 - 0.9$ ms. Thus, this work strongly supports the suggestion that if pulsars with shorter rotational periods were found, these are likely to be strange-quark-matter stars. The conclusion that the confined hadronic phase of nucleons and nuclei is only metastable would then be almost inescapable, and the plausible ground-state in that event is the deconfined phase of (3-flavor) strange-quark-matter.

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F. Weber and N. K. Glendenning

1 Introduction

The hypothesis that strange quark matter may be the absolute ground state of the strong interaction (not ^{54}Fe) has been raised by Witten in 1984 [1]. If the hypothesis is true, then a separate class of compact stars could exist, which are called strange stars. They form a distinct and disconnected branch of compact stars and are not part of the continuum of equilibrium configurations that include white dwarfs and neutron stars. In principle both strange and neutron stars could exist. However if strange stars exist, the galaxy is likely to be contaminated by strange quark nuggets which would convert all neutron stars that they come into contact with to strange stars [2, 3, 4]. This in turn means that the objects known to astronomers as pulsars are probably rotating *strange matter* stars, not neutron matter stars as is usually assumed. Unfortunately the bulk properties of models of neutron and strange stars of masses that are typical for neutron stars, $1.1 \lesssim M/M_{\odot} \lesssim 1.8$, are relatively similar and therefore do not allow the distiction between the two possible pictures. The situation changes however as regards the possibility of fast rotation of strange stars. This has its origin in the completely different mass-radius relations of neutron and strange stars [5]. As a consequence of this the entire familiy of strange stars can rotate rapidly, not just those near the limit of gravitational collapse to a black hole as is the case for neutron stars. It is the concern of this paper to determine the minimum rotational period of a neutron star possessing a mass of 1.45 $M_{\odot}$, below which stable rotation is not possible, based on a number of models of dense matter. Knowledge of that period is of decisive importance for the interpretation of the possible future detection of extremely rapidly rotating pulsars [2]. For this purpose general relativistic, rotating neutron star models are constructed by applying a representative collection of seventeen nuclear equations of state (Sec. 2), which serve as an input for solving the Einstein equations for a rotating object. For more details we refer to [6].

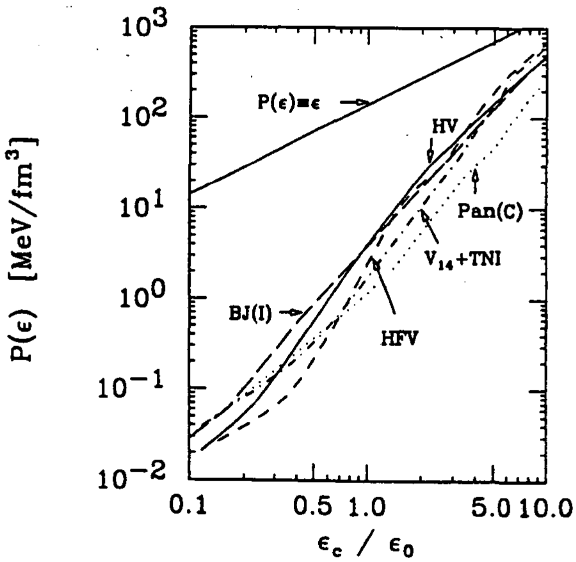

Figure 1: Graphical illustration of the equations of state BJ(I), Pan(C), FP(V_{14} + TNI), HV, and HFV.

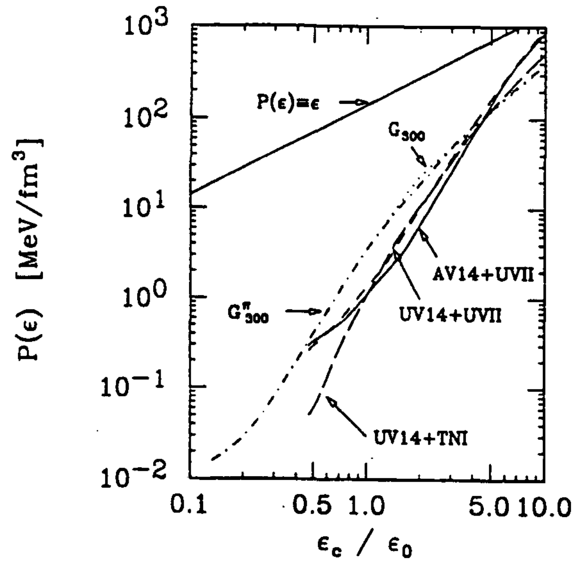

Figure 2: Same as Fig. 1, but for the equations of state WFF(AV_{14} + UVII), WFF(UV_{14} + UVII), WFF(UV_{14} + TNI), G_{300}, and G_{300}^{π}.

2 Collection of selected nuclear equations of state

The collection of nuclear equations of state applied for the construction of models of general relativistic rotating neutron stars is listed in Table 1. The equations of state are divided into two categories: (1) relativistic equations of state which are determined in the framework of relativistic nuclear field theory (i.e., relativistic Hartree (entries 1 through 6, 8, 9), Hartree-Fock (entry 10), and T-matrix (entries 7, 11) approximations). An inherent feature of these models is that they do not violate causality, i.e. the velocity of sound is smaller than the velocity of light at all densities, which is not the case for the potential models. (2) non-relativisitic potential model equations of state. Among these only the WFF(UV_{14} + TNI) equation of state does not violate causality up to densities relevant for the construction of models of neutron stars form it. The equations of state denoted $G_{225}^{\rm DCM1}$, $G_{265}^{\rm DCM2}$, $G_{\rm B180}^{\rm DCM1}$, and $G_{\rm B180}^{\rm DCM2}$ have only recently been calculated [7] for electrically charge neutral neutron star matter in β-equilibrium for the derivative coupling Lagrangian of Zimanyi and Moszkowski [8]. The possibility of a phase transition of the dense core to 3-flavor quark matter is taken into account in equations of state $G_{\rm B180}^{\rm DCM1}$ and $G_{\rm B180}^{\rm DCM2}$. Here a bag constant of $B^{1/4} = 180$ MeV has been used for the determination of the phase transition of baryon matter into quark matter, which places the energy per baryon of strange matter at 1100 MeV, well above the energy per nucleon in ^{56}Fe ($\approx$ 930 MeV). Not all equations of state of our collection account for neutron

Table 1: Nuclear equations of state applied for the construction of models of general relativistic rotating neutron star models.

Label	EOS	Description†	Reference
Relativistic field theoretical equations of state			
1	G_{300}	H, K=300	[9]
2	HV	H, K=285	[10, 11]
3	G^{DCM2}_{B180}	Q, K=265, $B^{1/4} = 180$	[7]
4	G^{DCM2}_{265}	H, K=265	[7]
5	G^{π}_{300}	H, π, K=300	[9]
6	G^{π}_{200}	H, π, K=200	[12]
7	Λ^{00}_{Bonn} + HV	H, K=186	[13]
8	G^{DCM1}_{225}	H, K=225	[7]
9	G^{DCM1}_{B180}	Q, K=225, $B^{1/4} = 180$	[7]
10	HFV	H, Δ, K=376	[11]
11	Λ^{00}_{HEA} + HFV	H, Δ, K=115	[13]
Non-relativistic potential model equations of state			
12	BJ(I)	H, Δ	[14]
13	WFF(UV_{14}+TNI)	NP, K=261	[15]
14	FP(V_{14}+TNI)	N, K=240	[16]
15	WFF(UV_{14}+UVII)	NP, K=202	[15]
16	WFF(AV_{14}+UVII)	NP, K=209	[15]
17	Pan(C)	H, Δ, K=60	[17]

† The following abbreviations are used: N = pure neutron; NP = n, p, leptons; π = pion condensation; H = composed of n, p, hyperons ($\Sigma^{\pm,0}$, Λ, $\Xi^{0,-}$), leptons; Δ = Δ_{1232}-resonance; Q = quark hybrid composition, i.e. n, p, hyperons, u, d, s-quarks, leptons; K = incompressibility in MeV; $B^{1/4}$ = bag constant in MeV.

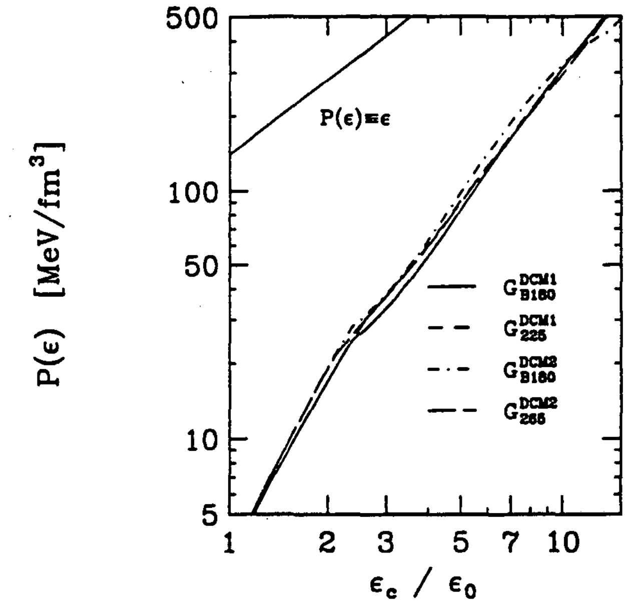

Figure 3: Same as Fig. 1, but for the equations of state G_{B180}^{DCM1}, G_{225}^{DCM1}, G_{B180}^{DCM2}, G_{265}^{DCM2}.

matter in β-equilibrium (entries 13 through 16 do not). These models treat neutron star matter as being composed of only neutrons (entry 14), or neutrons and protons in equilibrium with leptons (entries 13, 15, 16), which is however *not the true ground-state of neutron star matter predicted by theory* [10, 14, 17].

The equations of state, i.e. pressure P as a function of energy density ϵ (in units of normal nuclear matter density, $\epsilon_0 = 140$ MeV/fm^3), are graphically exhibited in Figs. 1 - 3. From Fig. 1 one sees the extremely soft behavior of the non-relativistic Pan(C) equation of state. Specifically, it is considerably softer than the other two non-relativistic equations of state shown in this figure, i.e. BJ(I) and FP(V_{14}+TNI). The BJ(I) and Pan(C) models account for baryon population in neutron star matter which leads to a slight flattening of the pressure curves at densities larger than respectively two and four times normal nuclear matter density. Two relativistic equations of state, HV and HFV, are shown too for the purpose of comparison. For $\epsilon \gtrsim 3\epsilon_0$, the Hartree-Fock HFV equation of state behaves more stiffly than the Hartree HV equation of state. The reason for this lies in the exchange contribution that is contained in the former equation of state. The kinks contained in the $P(\epsilon)$ curves of HFV and HV at densities of respectively $\epsilon \approx 1.6\,\epsilon_0$ and $\epsilon \approx 2\epsilon_0$ are caused by the onset of hyperon population. Figure 2 compares the non-relativistic equations of state of Wiringa, Fiks, and Fabrocini (WFF) with two relativistic ones. We recall that only the latter two describe neutron star matter composed of baryons in β-equilibrium with leptons (Table 1). Equation of state G_{300}^{π} additionally to baryon population also accounts for pion condensation in neutron star matter. According to this equation of state, condensation is predicted to set in at $\epsilon \approx 1.5\,\epsilon_0$ (dashdotted curve in Fig. 2). At densities $\epsilon \gtrsim 4\,\epsilon_0$ the WFF equations of state behave stiffer than the relativistic ones, violating causality at densities that are smaller than twice that value. The WFF(AV_{14} + UVII) and WFF(UV_{14} + UVII) equations of state are rather similar at sub-nuclear densities, which is not the case for the third WFF model (WFF(UV_{14} + TNI)) because of the different three-body-force model (TNI) in the latter case. The equations of state G_{225}^{DCM1}, G_{265}^{DCM2}, G_{B180}^{DCM1}, and G_{B180}^{DCM2} are graphically depicted in Fig. 3. The transition of confined hadronic matter into quark matter, which is taken into account in G_{B180}^{DCM1} and G_{B180}^{DCM2}, sets in at densities $\epsilon \gtrsim 2.3\,\epsilon_0$. It lowers the matter's pressure relative to the confined phase. The mixed phase of hadrons and quarks ends (and the pure quark phase begins) at $\epsilon \approx 15\,\epsilon_0$, which is larger than the maximum density encountered in the cores of star models constructed from these equations of state.

3 Bounds on the properties of fast pulsars

In the following we present the results obtained for the bulk properties of a fast pulsar model that rotates at (1) its general relativistic Kepler period, and (2) that period at which the gravitational radiation reaction-driven instability sets in [13]. The latter sets a more stringent limit on stable rotation. According to Table 2, any observed, newly born pulsar created in a supernova and possessing a mass of typically $1.45\,M_\odot$ that rotates at a period below ≈ 1 ms would be in contradiction to our analysis. This can be seen from Table 2 where the minimum possible rotational periods of hot (temperature $T = 10^{10}$ K) and cold ($T = 10^6$ K) pulsars are listed. (The dependence on temperature arises due to the viscosity dependence of the gravitational radiation reaction-driven instability [13].) Consequently, newly born pulsars observed in supernova explosions are predicted to have stable rotational periods $\gtrsim 1$ ms as long as their masses are close to the above cited value, which is supported by supernova calculations [18]. As one sees, half-millisecond periods, for example, are completely excluded for pulsars made of baryon matter. Therefore, the possible future discovery of a single sub-millisecond pulsar, say 0.5 ms, would give a strong hint that such an object is a rotating strange star, not a neutron star, and that 3-flavor strange quark matter is the true ground-state of the strong interaction [2].

The upper and lower bounds on the minimum possible rotational period of an old neutron star are shifted, relative to the minimum period of a hot pulsar, toward smaller values. We find that the gravitational instability is damped by viscosity as long as the star's rotational period is larger than $0.8 \lesssim P/\mathrm{ms} \lesssim 1.1$, depending on the equation of state. Specifically an old pulsar of $T = 10^6$ K and mass $M \approx 1.45\,M_\odot$ cannot be spun up to stable rotational periods smaller than ≈ 0.8 ms. We note that

Table 2: For the broad sample of equations of state, the lower and upper bounds on the properties of a pulsar of $M \approx 1.45\, M_\odot$, calculated for the collection of equations of state of Table 1 (except for Pan(C)). The listed properties are: period at which the gravitational radiation-reaction instability sets in, P (in ms) with star temperature listed in parentheses; Kepler period, $P_{\rm K}$ (in ms); central density, ϵ_c (in units of the density of normal nuclear matter); moment of inertia, I (in g cm^2); redshifts of photons emitted at the star's equator in backward ($z_{\rm B}$) and forward ($z_{\rm F}$) direction.

	$P(10^6\ K)$	$P(10^{10}\ K)$	$P_{\rm K}$	ϵ_c/ϵ_0	$\log I$	$z_{\rm B}$	$z_{\rm F}$	$z_{\rm p}$
upper bound	1.1	1.5	1	5	45.19	1.05	−0.18	0.45
lower bound	0.8	1.1	0.7	2	44.95	0.59	−0.21	0.23

the two fastest yet observed pulsars, rotating at 1.6 ms, are compatible with the periods in Table 2, provided their masses are larger than 1 $M_\odot$ [6]. The Kepler period, beyond which mass shedding at the star's equator sets in, sets an absolute lower limit on the period stable rotation. It might play a role in an old and cold pulsar whose rotation is stabilized by its large viscosity value.

4 Summary

The indication of this work is that the gravitational radiation-reaction instability sets a lower limit on stable rotation of a little more than *$P \approx 1$ ms for young and hot, and $P \approx 0.8$ ms for old and cold pulsars* having a typical mass of $M \approx 1.45\, M_\odot$. This has possibly very important implications for the nature of any pulsar that is found to have a shorter period, say below $P \lesssim 0.5$ ms. If pulsars with periods below that value were found, the conclusion that the confined hadronic phase of nucleons and nuclei is only *metastable* would be almost inescapable. The plausible ground-state state in that event is the deconfined phase of (3-flavor) strange quark matter. From the QCD energy scale this is as likely a ground-state as the confined phase. The possibility that the ground-state of baryonic matter at zero pressure is strange quark matter and that ordinary nuclei may only be metastable has important consequences for laboratory nuclear physics, the early universe, and astrophysical compact objects.

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