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Glendenning, N.K.

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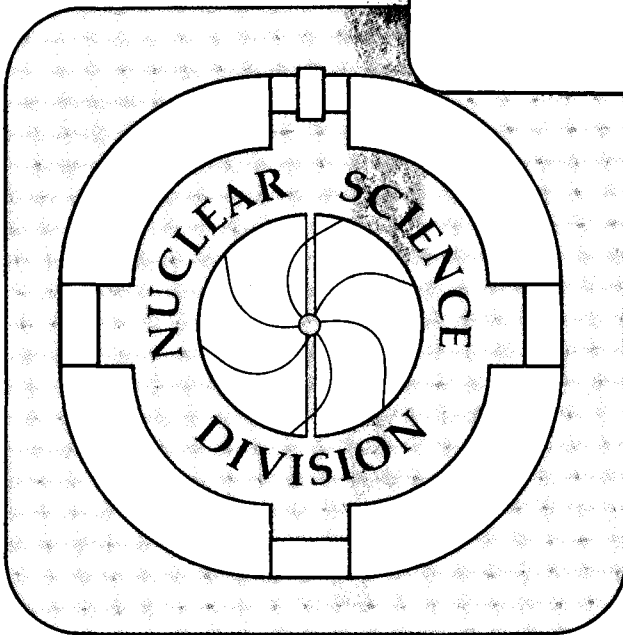
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N.K. Glendenning

July 1989

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Fast Pulsar in SN1987A:
Candidate for Strange Quark Matter[†]

Norman K. Glendenning

*Nuclear Science Division
Lawrence Berkeley Laboratory
One Cyclotron Road
Berkeley, California 94720*

July 7, 1989

[†]This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

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*Nuclear Science Division
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Abstract

We observe that all known pulsar frequencies and masses can be accounted for by plausible neutron star models with the exception of the new fast pulsar. The only neutron star models found to sustain its fast rotation do so at such high central densities that the constituents cannot plausibly be hadrons. The expected state of matter at high density is quark matter. We show that a star of strange quark matter is stable against mass loss at the frequency of the new pulsar, and suggest that there are two types of stable collapsed stars, neutron stars and strange quark stars, for which the new pulsar is a candidate. An essential difference between the two types of stars is the binding force, gravity for ordinary stars, and confinement and gravity in the case of quark stars if strange quark matter is the true ground state.

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Pulsars, of which some 400 are known, are thought to be neutron stars. Only about a half dozen masses are measured. The maximum possible mass places a constraint on the equation of state of the matter of which the star is composed, since for a given equation of state there is a maximum stable star configuration. Theories can be ruled out whose equation of state has a limiting mass below the maximum observed mass. The half millisecond pulses recently discovered [1] in the remnant of SN1987A, if attributable to rotation, imply the highest angular velocity of any known star and impose a stringent additional constraint [2,3]. The collapsed star must be highly compact so that the centrifugal force does not expel matter. In this paper we shall assume that the signals from the new pulsar are indeed due to rotation. We present arguments that it cannot be an ordinary neutron star, show that a strange quark matter star can support the high rotation if such matter is the true ground state, and infer that the new pulsar is a strange quark matter star.

Of all the equations of state employed in the recent study [2] of rapidly rotating neutron stars, only several can support both the observed masses of slowly rotating collapsed stars and the high angular velocity of the new pulsar. But all equations of state in the study are based on theories in which hadrons are the constituents, and we observe that the central energy densities of those that can support the high rotation exceed nuclear density ($\epsilon_0 = 2.48 \times 10^{14}$ g/cm³) by a large factor, 15 or so, as shown in Table 1. So the underlying hadronic structure of matter assumed in these theories cannot be the correct description at such high densities! Why is this so?

A number of authors have studied the question of whether a phase transition from neutron star matter to quark matter is likely to occur in collapsed stars, and the conclusions are that the transition takes place at a density that exceeds that expected in the center of a neutron star (usually thought to be of the order $10\rho_0$, where ρ_0 is nuclear saturation density.) [4]. However these studies are based on the notion of Gibbs phase equilibrium, in which a transition occurs when the temperature, pressure and chemical potentials are equal in the two phases. The theories of hadronic matter actually assume point nucleons. The Gibbs condition is

reasonable when the physical volume occupied by the constituents is small compared to the available volume or at least does not exceed it. Otherwise the criterion must be replaced by another that takes into account the physical size of the nucleons. The RMS nucleon radius is known from electron scattering experiments to be about 0.8 fm. If we assume an inviolable volume for nucleons corresponding to an even smaller radius, say 0.5 fm, the density of nuclear matter consisting of classical nucleons at closest packing for this radius is $6.5\rho_0$, where $\rho_0 \approx 0.15 \text{ fm}^{-3}$. Therefore none of the theories studied so far, all of which are based on hadrons as constituents, provides a plausible description of a gravitating object of such high angular velocity. Since the window in which the equation of state must fall is reasonably well delineated by the study referenced above, it seems to us unlikely that an exception can be found.

Is there a state of matter that can withstand the fast rotation at densities that do not invalidate it? Collins and Perry [5] suggested that quark matter is the state of very dense matter. The question has been much studied both as concerns the possibility of making quark matter in the laboratory [6] as well as its possible existence in astrophysical objects [4,7,8]. Witten [9] has argued for the absolute stability of strange quark matter having approximately equal mixture of u,d,s quarks. Bethe et al. [10] argue to the contrary, and earlier than these authors, Chin and Kerman [11] suggested that strange quark matter might be metastable. All arguments are schematic since only perturbative models with unsatisfactory convergence are currently practicable. Perhaps the fast pulsar suggests the answer! We have proposed [12] that it is a candidate for such a new type of star, a quark matter star, and here elaborate. We shall explore below the assumption of *strong* confinement, that strange quark matter is the true ground state of the strong interaction [9]. In that case the macroscopic structure of a neutron star and that of a quark matter star are different because they are bound by different forces, gravity in the case of the neutron star, confinement in the case of the quark star. This can be seen in the different behavior of radius as a function of mass of the star (first noted in refs. [8,13]) shown in Fig.1 where several neutron stars are compared with several quark matter stars [12]. This difference, due to confinement, is a key difference in the macroscopic properties of neutron stars and quark matter stars. In that case we do not need an exact solution of QCD, but only a model of confinement to elucidate, at least qualitatively, the properties of such stars. For this purpose we adopt the MIT

Table 1: Central energy density, ϵ_c , and angular velocity, Ω_K , of several neutron star models that sustain fast rotation. (Data adapted from ref. [2], and key to models cited therein.)

	G	B	F	A	π
ϵ/ϵ_0	20	21	17	13	18
$\Omega_K(10^4 \text{ s}^{-1})$	1.54	1.57	1.24	1.28	1.74

Table 2: Strange quark star properties at the limit; gravitational mass, radius and central density for non-rotating, and angular velocity of rotating star.

$B^{1/4}$ MeV	M/M_{\odot}	R km	ϵ_c/ϵ_0	Ω_K 10^4s^{-1}
200	1.08	5.91	27.3	1.74
170	1.50	8.17	14.3	1.26
145	2.00	10.9	7.74	0.943

bag model [14] and assume for simplicity massless quarks. At the edge of the star the fermi momentum of the quarks is $k_f = (4\pi^2 B/3)^{1/4}$ and therefore the density of the interior in the star is so high that the strange quark mass will make only a small correction. (For massless quarks, an equal admixture of the three flavors is charge neutral. For massive s quarks, the equilibrium composition will consist of a small deficit of strange quarks and a small electron population. This is important for surface properties but will have small effect on the stability conditions of the quark star.) We assume therefore massless u,d,s quarks and a bag constant $B^{1/4} = 170$ MeV, which lies between the MIT value of 145 MeV that best fits baryon resonances, and values (cf. [15,16]) that yield a phase transition in hot baryonless matter at the temperature favored by lattice QCD simulations ($T = 200 \pm 50$ MeV). It is trivial to calculate the equation of state in the above model. The solution to the Oppenheimer-Volkoff equations then provide the macroscopic properties of non-rotating (or slowly rotating) stars. The mass-radius behavior for several values of $B^{1/4}$ are shown in Fig.1. and properties of the star at the termination of each sequence are listed in Table 2. The properties of rapidly rotating stars can be obtained only from a substantially more complex system than the O-V equations [17] and have been solved for a wide sample of *nuclear* equations of state by Friedman, Ipser and Parker [2] as noted above. For the *quark matter* equation of state with $B^{1/4} = 170$ MeV, the strange quark star at the limit of stability to mass loss has a maximum (Keplerian) angular velocity, $\Omega_K = 1.254 \times 10^4 \text{ s}^{-1}$, gravitational mass $M = 1.94M_{\odot}$ and central density $\epsilon_c = 2.945 \times 10^{15} \text{ g/cm}^3$ [18]. The observed angular velocity of the new pulsar is $\Omega_{SN} = 1.237 \times 10^4 \text{ s}^{-1}$. The above termination point and also those of the hadron based models of ref. [2] are very well approximated by

$$\omega = 2.4 \times 10^5 \sqrt{\frac{M/M_{\odot}}{(R/\text{km})^3}} \text{ s}^{-1} \quad (1)$$

where M and R are the mass and radius of the non-rotating star. The limiting angular velocity so calculated is listed in Table 2. It is seen that the quark stars with larger bag pressure can withstand higher rotation. At the same time the star is more dense and the limiting mass is smaller. The curve marked R_{ω} in Fig.1 represents the trajectory defined by the above equation at the observed frequency of

the new pulsar. For equations of state for which the mass-radius relation lies below the curve, or those parts that do, the fast rotation can be supported. In a range of values of $B^{1/4}$, the window in baryon number ($A \sim M/m$) for which quark stars can sustain fast rotation is very broad, whereas for neutron stars (albeit at unrealistic densities) the window is very narrow because of the mass-radius relation (Fig.1). Of course these results should not be over interpreted in terms of particular values of $B^{1/4}$, inasmuch as the essential physics is confinement and not the particular model for its implementation.

Assuming that strange quark matter is the true ground state of the strong interaction (strong confinement), it was shown above that a strange quark star can sustain high rotation. We have not established whether *strong* confinement is essential or whether a weaker assumption leading to a hybrid star with a quark core surrounded by neutron star matter, can rotate with high frequency. In the hybrid star the quark core would be in chemical equilibrium at its interface with a neutron star exterior. Unlike the consequences that flow from strong confinement, the question whether the hybrid type of star can sustain high rotation depends much more on the particular confinement model, its parameters and the nuclear equation of state. In any case the qualitative difference in the mass-radius relation noted above is a consequence of strong confinement, so the hybrid star will have a mass-radius relationship qualitatively like neutron stars.

It is intriguing to contemplate the possibility that although the fast pulsar, according to our conjecture, reveals itself as being a quark star because of its unusually fast rotation, *conversely* it may have an extraordinary rotation *because* it is a quark star. This follows from the observation that quark stars are more compact than neutron stars (see figure), and that for given angular momentum they will spin up to higher angular frequency when the proto-neutron star converts to quark matter. For example, a neutron star of mass $M = M_{\odot}$ will spin up in angular velocity by about a factor 3 to 4 if it transforms to a quark star, assuming $B^{1/4} = 200$ MeV. Notice that another millisecond pulsar, PSR1937+214, has angular velocity $\Omega = 0.4033 \times 10^4 \text{ s}^{-1}$, which is about a third that of the new fast pulsar. All the equations of state studied in ref. [2] will sustain this lower frequency. It can be sustained in at least some hadron based models at plausible central densities. For example the $M = 1.5M_{\odot}$ star in the sequence of Fig. 1 with $K = 300$ MeV has central density $3.9\epsilon_0$ and can rotate at $\Omega_K = 0.63 \times 10^4 \text{ s}^{-1}$ without mass loss. All known pulsar masses and angular velocities can be accounted for by plausible hadron based models, with the exception of the new pulsar! The factor three separating the frequency of the new pulsar from that of the next fastest both distinguishes between them and could have been the consequence of conversion of a fast neutron star to an even faster quark matter star.

There remain a number of other interesting areas of investigation: stability with respect to non-axisymmetric deformations; creation scenario from a proto-neutron star, including the role of hyperonization [19,20,21] or of a seed of strange quark matter [22] in converting hadron matter; consequences of contraction and spin up

following conversion; possible spinoff of hadron matter, or expulsion by a secondary shock.

In summary, we infer that the pulsar in SN1987A is a strange quark matter star because so far all models that have been found to sustain the high angular velocity imputed to the new pulsar do so at such high densities that the underlying constituents cannot plausibly be hadrons. And it appears that this will be true of any model whose equation of state is based on hadrons as constituents. In contrast, the strange quark matter star can sustain the fast rotation observed, even higher, depending on the confinement parameter $B^{1/4}$. The essential difference is confinement, and not its particular implementation. It appears that there may be two types of gravitationally collapsed stars, neutron stars, of which most of the observed slowly-rotating pulsars are presumably examples, whose equation of state must obey the mass constraint discussed earlier, and strange quark stars whose equation of state we believe can withstand the high angular velocity imputed to the new pulsar.

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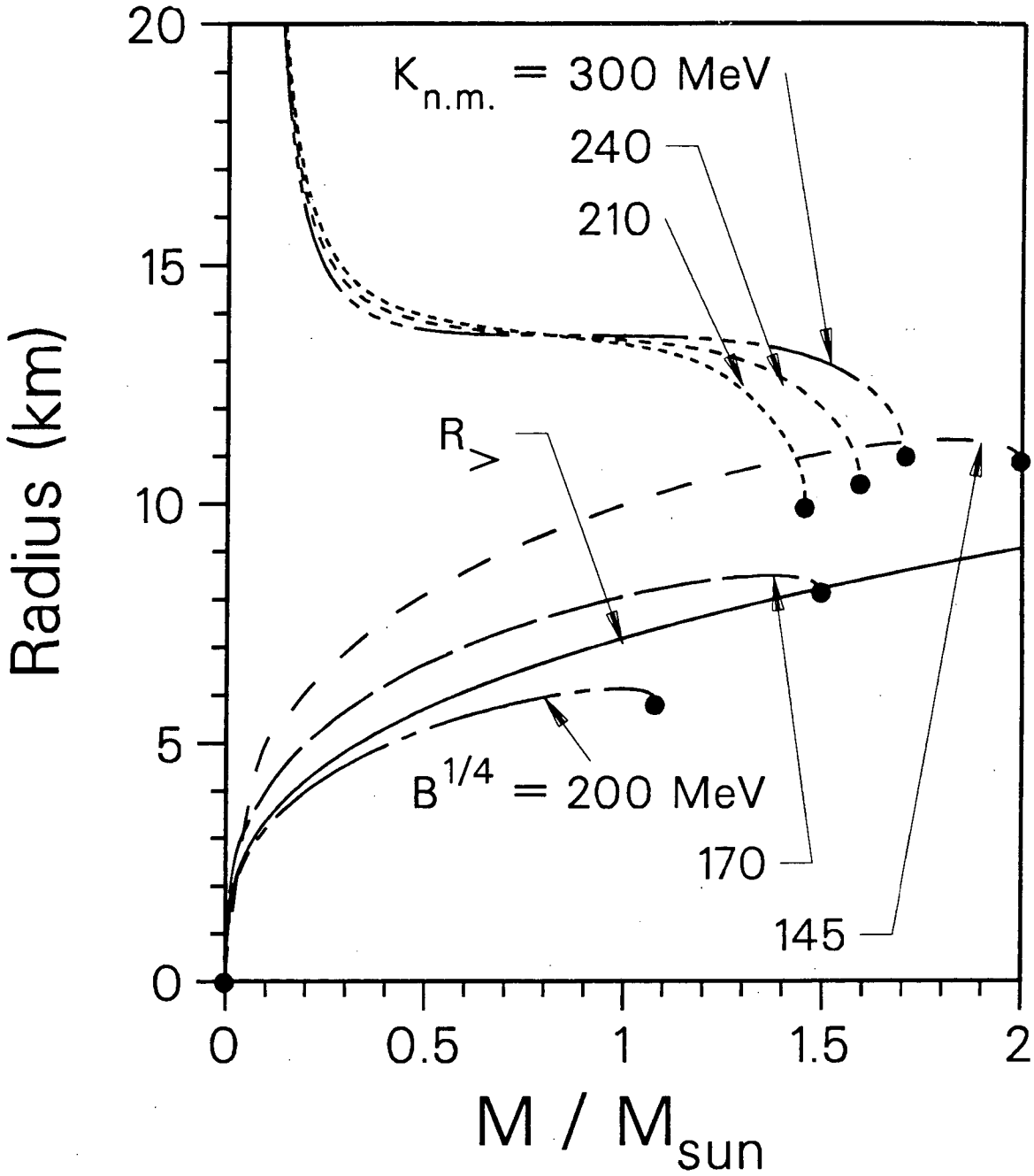


FIG. 1 Radius vs. mass for neutron stars (top three) and strange-quark matter stars labeled by compression, K , of the equation of state and bag constant, $B^{1/4}$, respectively [12]. Solid line is the upper limit on radius of stars that can sustain the high angular velocity of the new pulsar, ($\Omega = 1.237 \times 10^4 \text{ s}^{-1}$).

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