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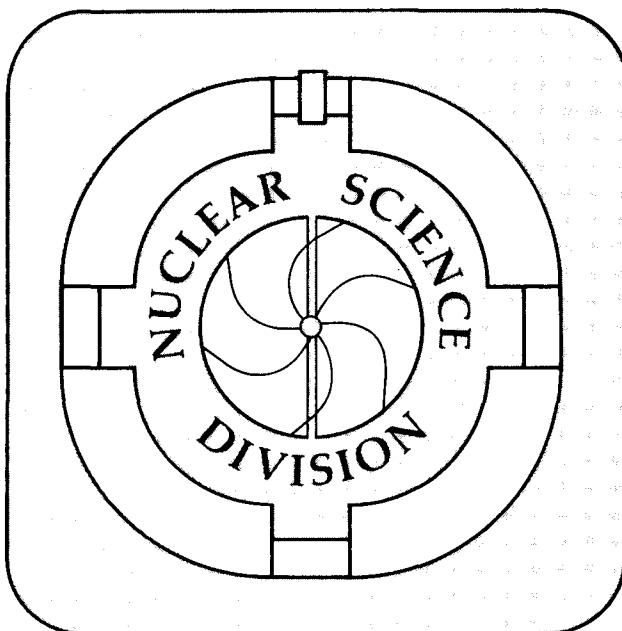
## Strange-Quark-Matter Stars

N.K. Glendenning

November 1989

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# Strange-Quark-Matter Stars<sup>†</sup>

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**Invited Paper**

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# Strange-Quark-Matter Stars

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## ABSTRACT

We investigate the implications of rapid rotation corresponding to the frequency of the new pulsar reported in the supernovae remnant SN1987A. It places very stringent conditions on the equation of state if the star is assumed to be bound by gravity alone. We find that the central energy density of the star must be greater than 13 times that of nuclear density to be stable against the most optimistic estimate of general relativistic instabilities. This is too high for the matter to consist of individual hadrons. We conclude that it is implausible that the newly discovered pulsar, if its half-millisecond signals are attributable to rotation, is a neutron star. We show that it can be a strange quark star, and that the entire family of strange stars can sustain high rotation if strange matter is stable at an energy density exceeding about 5.4 times that of nuclear matter. We discuss the conversion of a neutron star to strange star, the possible existence of a crust of heavy ions held in suspension by centrifugal and electric forces, the cooling and other features.

## 1 Introduction

Our understanding of collapsed stars, the remnant stars produced in type II supernovae is in a state of ferment. They have been thought of as neutron stars since shortly after the discovery of the first pulsar in 1967. If the observational evidence is accepted, the discovery of a new pulsar [1], the fastest of all, in the remnant of SN1987A, suggests remarkable conclusions about the state of dense matter and collapsed stars. I shall discuss why I believe that this pulsar cannot be a neutron star, a star bound only by gravity, as would have to be the case since nuclear matter is otherwise unbound beyond  $A \sim 200$ ; I shall present the evidence that it is a type of compact star not previously identified, a self-bound star made of strange quark matter. It may be that all collapsed stars are strange stars. It is possible however that there are two distinct families of stable collapsed stars, neutron stars and strange stars.

If the interpretation [2, 3, 4] is upheld by further study, then the discovery of this pulsar will be the most significant discovery in nuclear astrophysics of our decade.

## 2 The Sub-millisecond Pulsar

First I make a few remarks on the most obvious of the unusual features of the new pulsar discovered in the remnant of the recent supernova, SN1987A [1] before going into its interpretation. Although pulsars (neutron stars) are believed to be born in supernova, this is the first time that such a close association in time has been observed. In fact of 85 supernova remnants in the galaxy and the Magellanic clouds there are only five positive pulsar associations, and they are made long after the explosion. The new pulsar is the fastest, and its period lies far from the mean by a factor of about a thousand, as shown in Fig.1. Assuming, as is believed to be the

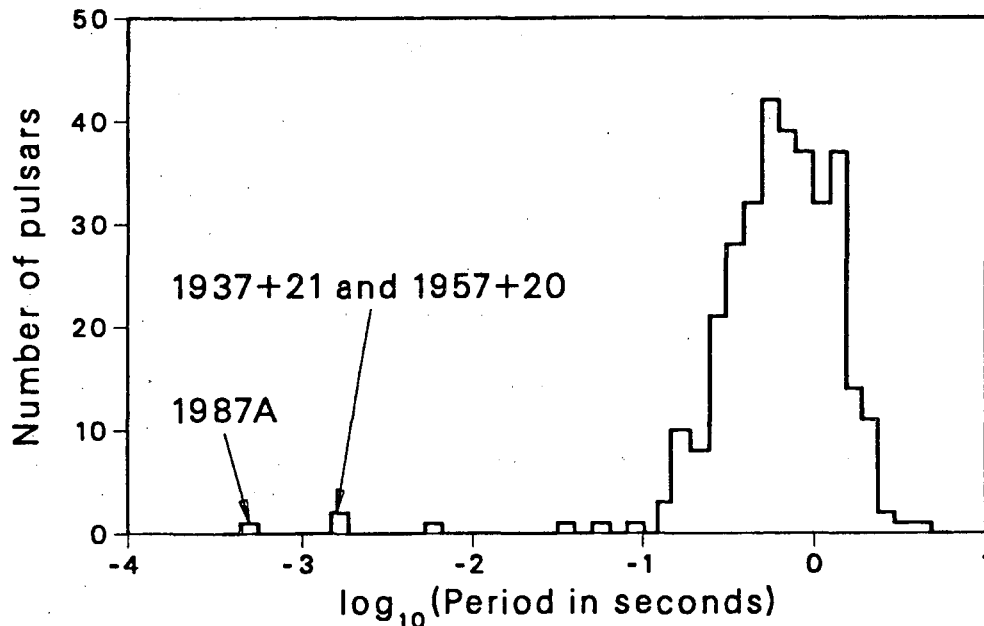


Figure 1: Distribution of pulsar periods. The mean is  $\sim 0.6$  sec. The new pulsar has period 0.508 ms and the next fastest 1.6 ms.

case with all others, that its pulsed radiation is caused by rotation. Then with a period  $P \sim 1/2$  ms it rotates 1969 times per second, three times faster than the next fastest. This factor of three is significant in two important respects and sets it in a class by itself. All other pulsar frequencies, including the next fastest, can be easily accounted for by conventional neutron star models. The new one cannot! I will show you this in several steps. The second remarkable significance of the factor three is that this is about the amount that a neutron star would spin up if it converted to a strange-quark-matter star, as I will discuss later. In other words, if a pulsar, rotating at what now appears to be the limit of a neutron star, about 1.6

ms, were to convert to a strange star, it would spin up to the frequency of the new pulsar.

The pulses were observed over an eight-hour interval one night in January. At the observed frequency, 60 million pulses were recorded in that session. The team, headed by Carl Pennypacker, that made the discovery, did not have a turn at a telescope until two weeks later. It was not seen then, nor has it been seen since. There are two trivial reason why this may be so, and several non-trivial and interesting reasons as well [5, 6, 7]. First it may not have been a signal from space, but rather a spurious instrumental signal. This is almost ruled out by the following facts. The 1/2 ms pulses were frequency modulated with a period of seven hours. In Fig.2 the modulation is shown in the laboratory frame. The laboratory is an

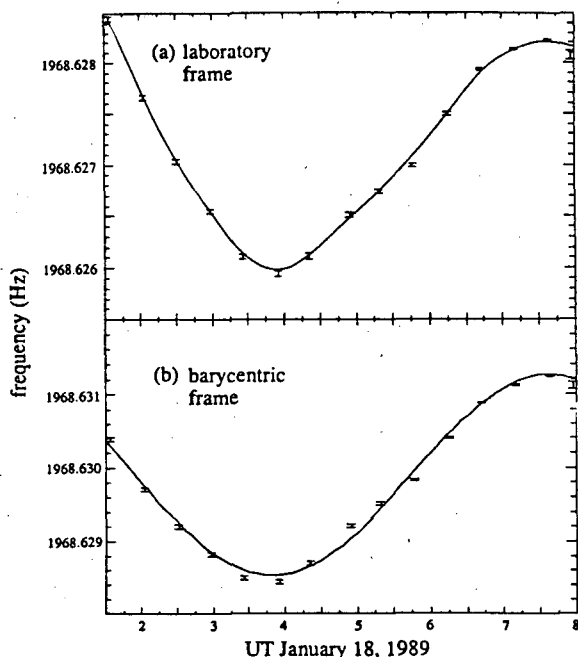


Figure 2: Frequency modulation of the 0.5 ms pulses of PSR1987A as seen in the laboratory frame, and in a frame corrected for the earth's motion (barycentric). [1]

observatory located on earth, which rotates about its axis, and is in orbit around the sun. Taking account of these motions, the frequency modulation, which in the lab frame is definitely not sinusoidal, becomes so in the barycentric frame. Such a modulation would be produced if the emitting pulsar is in orbit with a companion. There is another example known where a 1.6 ms pulsar, PSR1957+20, is frequency modulated with a nine hour period by a companion, whose orbital motion periodically eclipses the pulsar for about 50 minutes, thus revealing its existence in two ways. The famous PSR1913+16, a 59 ms pulsar is in binary orbit with an eight hour period. So there are precedents for binary modulation of the frequency of millisecond pulsars. If the frequency modulated 1/2 ms pulses were of instrumental or terrestrial origin, what an enormous coincidence that a barycentric transformation would turn it into a sine wave! There are other more technical reasons to believe that the observation is sound [8].

Why then has it not been seen again? The trivial reason could be simply that it



has been obscured again by debris which is rotating as it expands out into space. If this is so, then since with time the debris becomes thinner, we should see it again. There are other non-trivial reasons why the pulsar has disappeared, and I have discussed them elsewhere [5, 6, 7].

One may also ask why no other group saw it at the time the discovery group did? One other group headed by Manchester made a search six hours later (from Australia), but used a blue filter which according to calculations of Woosley and Pinto[9] would have extinguished a signal in the particular frequency range of the optical at which the discovery team made their observation, by a factor  $> e^{-1000}$ .

### 3 Stars Bound Only by the Gravitational Force

#### 3.1 Outline of the problem.

Pulsars are believed to be rotating neutron stars [10, 11]. The new pulsar reported to be found [1] in the remnant of the supernova SN1987A in the Large Magellanic Cloud has the highest frequency of all known pulsars, with a period of  $P = 0.508$  *milliseconds*. Its frequency is about three times faster than the next fastest. If attributable to rotation, the factor three sets the new pulsar in a class by itself because the next fastest pulsar can be easily accounted for by conventional neutron star models, whereas the new one places very stringent conditions on the equation of state of the matter of which *this* star is made. The mass, radius *and* distribution of energy density, of non-rotating or slowly rotating stars in the sequence corresponding to a given equation of state,  $p = p(\epsilon)$ , is uniquely prescribed by Einstein's general theory, nothing more. The known masses provide one constraint on the equation of state because corresponding to it there is a maximum mass which must equal or exceed the largest known one. Similarly, under the assumption of uniform rotation which seems justified because of viscosity, the structure of rotating stars is uniquely specified for chosen angular velocity. Stability to rapid rotation provides another constraint since the star must remain stable and not fly apart. Roughly, this can be stated in terms of the classical balance of gravity and centrifuge. In recent general relativistic studies by Friedman, Ipser and Parker [12] and by Sato and Suzuki [13], it has been shown that of a collection of a dozen equations of state only several could satisfy the double constraint. We have observed elsewhere [2, 3] that for those models in the above cited study that can withstand the fast rotation without mass loss, the central energy densities are very large, from 13 to 21 times that of nuclear matter at saturation,  $\epsilon_0 \approx 2.48 \times 10^{14}$  gm/cm<sup>3</sup>. If this is not merely a coincidence of the limited number of models studied, but is a physical requirement on the compactness of the star imposed by stability to such a rapid rotation as attributed to the new pulsar, it has profound implications. *For it is implausible that matter at 13 times nuclear energy density can consist of individual hadrons!* From geometrical considerations alone, the baryon density for cubic close packing of classical spheres of radius equal to the charge radius of protons is  $1.6\rho_0$ .

If packed to the ‘hard core radius’ say 0.5 fm, the factor is 6.7. And this does not reflect the effects of the uncertainty principle which would give nucleons enormous momenta with which to destroy each other’s structure if packed to such densities.

In this section we make a general study of the question: *What attributes must the equation of state have so that stars bound only by gravity can account for the observed masses of slowly rotating pulsars and is such that a rapidly rotating one is stable at the frequency of the new pulsar with least possible central energy density?* Since the arrangement of energy density <sup>1</sup> in the star is prescribed by Einstein’s equations and the equation of state, we can answer the question by employing a very general parameterization of the latter.

### 3.2 Stars bound only by gravity.

It is important to understand the restriction implied by the assumption that the star is bound only by gravity, as is the case for all stars that we know. For collapsed stars it is equivalent to the restriction that ordinary hadronic matter is the absolute ground state. As far as we know this is the case. Hadronic matter is not bound beyond  $A \sim 200$  and therefore gravity is the binding force for star-like quantities of nuclear matter. However nothing is known which contradicts a different hypothesis, that of Witten [14], that strange quark matter, with an approximately equal number of u,d,s quarks, is the absolute ground state. Very small systems (eg. the lambda baryon) are known not to be the lowest state, but beyond a critical  $A$  where finite number and surface effects become negligible, it is assumed by hypothesis that such matter is self-bound and of lower energy per baryon charge than  $\text{Fe}^{56}$ . Since an object with  $A$  beyond the critical value is bound *without* gravity, a star made of such matter would have a very different macroscopic structure than a neutron star [14, 15, 16].

### 3.3 Limits on rotation.

An absolute upper limit on the angular velocity is imposed by stability to mass loss at the equator, which corresponds to an equatorial surface velocity that is equal to the Keplerian velocity. This is the velocity of a particle in circular orbit at the equator, whose angular velocity is denoted by  $\Omega_K$ . It is the criterion applied by Friedman, Ipser and Parker [12], although they note that instabilities at lower frequency may occur. These have to do with pulsation modes which would convert rotational energy into gravitational radiation. In a recent general relativistic study, Ipser and Lindbolm [17] find that, assuming conventional scenarios for the cooling rate of the new pulsar in the two year period between the supernova and the observation of the half-millisecond signals, the maximum angular velocity is 10 to 15

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<sup>1</sup>Frequently the equation of state is expressed in terms of the baryon number density,  $\rho$  as  $p = p(\rho), \epsilon = \epsilon(\rho)$ . Since the parametric dependance on  $\rho$  could be scaled, and since it does not appear in Einstein’s equations which depend only on  $p = p(\epsilon)$ , it is important to express the results in terms of  $\epsilon$  and not  $\rho$ .

percent less than the maximum imposed by stability to mass loss.

$$\Omega < \Omega_{G.R.} \approx (0.86 - 0.91)\Omega_K \quad (1)$$

The limiting (Keplerian) angular velocity for a star can be calculated only as the solution of the general relativistic problem which has been done by the authors of ref.[12, 13, 18]. Fortunately it can be approximated to within a few percent by a simple modification of the numerical constant in the classical expression for the balance of gravity and centrifuge,

$$\frac{GMm}{R^2} > m\Omega^2 R \quad (2)$$

The modified expression is,

$$\Omega_K = 24 \sqrt{\frac{M/M_\odot}{(R/\text{km})^3}} \quad (10^4 \text{s}^{-1}) \quad (3)$$

where  $M$  and  $R$  are the mass and radius of the spherical (non-rotating) star, and 24 is an empirical factor which would otherwise be 37.

### 3.4 Variation of the equation of state.

For the equation of state we construct a very general form. We use a modification of the BCK equation of state [19]. To this we add the flexibility of introducing local softening or stiffening, *and* first- or second-order phase transitions. Of course the contributions of electrons is included and the star properties are computed corresponding to an equilibrium admixture, found by minimizing the energy at each density with respect to the lepton fraction. The binding energy and saturation density of symmetric matter are fixed at their empirical values,  $B = 16$  MeV and  $\rho_0 = 0.15 \text{ fm}^{-3}$ . There remain 6 parameters. These are the compression modulus of neutron star matter,  $K$ , the adiabatic index,  $\gamma$ , that defines the high density behavior, and the symmetry energy coefficient,  $a_{sym}$ , and three parameters that define the local modification, which we shall refer to as a condensate energy, since it can introduce a local softening, as of a second-order phase transition, as well as a more severe softening with a form as of a first-order phase transition. Its parameters define its central location in density,  $\rho_c$ , its width in density,  $\Delta$ , and its strength,  $f$ , which is defined below.

In terms of the variables,

$$u = \rho/\rho_0, \quad x = \rho_e/\rho = Z/A \quad (4)$$

where  $\rho_e$  denotes the electron number density, the nuclear contribution to the pressure and energy density are

$$\begin{aligned}
p_n &= \frac{K\rho_0}{9\gamma}u^\gamma \\
\epsilon_n &= \rho \left\{ \frac{K}{9\gamma(\gamma-1)}(u^{\gamma-1}-1) + m_px + m_n(1-x) - B + a_{sym}(1-2x)^2 \right\} \quad (5)
\end{aligned}$$

The contribution of the leptons is,

$$p_e = \frac{1}{4}(3\pi^2)^{1/3}(x\rho)^{4/3}, \quad \epsilon_e = 3p_e \quad (6)$$

and the condensate contribution is,

$$p_c = -2E_0(\rho/\Delta)^2(\rho - \rho_c)e^{-w}, \quad \epsilon_c = \rho E_0 e^{-w}, \quad w = \left(\frac{\rho - \rho_c}{\Delta}\right)^2 \quad (7)$$

where

$$E_0 = f \left\{ \frac{\epsilon_n(\rho_c)}{\rho_c} - \frac{\epsilon_n(\rho_c - 2\Delta)}{\rho_c - 2\Delta} \right\} \equiv f\Delta\epsilon \quad (8)$$

So the energy parameter of the condensate is taken as a fraction,  $f$ , of the nuclear energy change over the interval  $\rho_c - 2\Delta$  to  $\rho_c$ .

For phenomenological parameterizations of the equation of state, as with all Schroedinger based theories of matter, the equation of state may violate the causality condition,  $v_s^2 \equiv \partial p/\partial\epsilon \leq 1$ . Let  $\rho_s$  denote the lowest density at which this happens. Then the equation of state is replaced thereafter by the causality limit, which is the stiffest the equation of state can be from that point. The conditions,

$$\frac{\partial p}{\partial\epsilon} = 1, \quad p_s \equiv p(\rho_s), \quad \epsilon_s \equiv \epsilon(\rho_s), \quad p = \rho^2 \frac{\partial(\epsilon/\rho)}{\partial\rho} \quad (9)$$

yield for the region above  $\rho_s$ ,

$$p = \frac{1}{2} \left\{ p_s - \epsilon_s + (p_s + \epsilon_s) \left(\frac{\rho}{\rho_s}\right)^2 \right\}, \quad \epsilon = \epsilon_s + p - p_s \quad (10)$$

The above formulae (4-10) describe a very flexible parameterization of the equation of state in the range from about 1/10 nuclear density to supernuclear density. Below this range we employ the equation of state of Negele and Vautherin [20] for the region of the crystalline lattice of heavy metals, and below this, that of Harrison and Wheeler [21] for the range of the crystalline lattice of light metals

and electron gas, as described in ref.[22]. It should be noted that  $\rho$  is really only a parameter in the above equation of state, and plays no role whatsoever in the structure of the star, since Einstein's equations for star structure depend only on  $p$  and  $\epsilon$  through the relation  $p = p(\epsilon)$ . This relationship is invariant to any scale change in  $\rho$ , so the central conditions of a star can be stated unambiguously in terms of the value of  $\epsilon$  or  $p$  but not  $\rho$ .

First we assessed the role of  $a_{sym}$  within the bounds of 25-35 MeV in which it is determined to lie, and found it to have minimal effect on the angular velocity that a star can withstand. Next we carried out an extensive survey of 1440 models whose parameters were all the combinations of the following values:

$$\begin{aligned}
K &= 50, 80, 100, 150, 200, 300 \text{ MeV} \\
\gamma &= 2, 2.5, 3, 3.5, 4 \\
f &= 0, -.2, -.5, -1, -1.5, -2, -2.5, -3 \\
\rho_c/\rho_0 &= 3, \quad \Delta/\rho_0 = 1 \\
\rho_c/\rho_0 &= 4, \quad \Delta/\rho_0 = 1, 1.5 \\
\rho_c/\rho_0 &= 5, \quad \Delta/\rho_0 = 1, 1.5, 2
\end{aligned} \tag{11}$$

For each we solved the equations of star structure. Of these we show in Table 1 a severely truncated set of results for those cases that can support a non-rotating neutron star mass of  $1.44M_\odot$ , that are rotationally stable at the least restrictive of the conditions of eq.(1), and for which the central energy density has the least value in each category of equation of state. The star at the termination of the sequence corresponding to a given equation of state has the highest mass and limiting angular velocity so we list the radius, mass, Kepler angular velocity and central energy density,  $R, M, \Omega_K, \epsilon_c$ , for the star at the limit. In addition we list the energy density  $\epsilon_1$  corresponding to the least restrictive condition in eq.(1), and when the conservative condition in eq.(1) can be met, the corresponding value  $\epsilon_2$ . Otherwise this position is marked by a dash. If the parameters of the equation of state describe a  $p$  vs  $\epsilon$  relation (see Fig. 1) that corresponds to a first-order phase transition, this is indicated by a 'y' in the column labeled 't'. The baryon density at which the causality limit is reached is denoted by  $\rho_s$ .

### 3.5 Attributes of the equation of state.

Now we discuss these results. First note that in all of the categories  $(K, \gamma)$  a softening in the equation of state is required at intermediate density to obtain relatively low values of the central energy density under the constraints discussed at the end of subsection 3.1. This situation is signaled by a negative value for the parameter,  $f$ , of the condensate energy, eq.(6,7). In many cases the softening is severe, corresponding to a first-order phase transition. In Fig. 3 we show the equation of state for the three cases that  $K = 100$  MeV,  $\gamma = 3$  that are listed in Table 1. In one case the softening corresponds to a first-order phase transition.

Table 1: For various equation of state , limiting star properties,  $R, M, \Omega_K, \epsilon_c$ . Central densities for the stars with  $\Omega_K/(10^4/\text{s}) = 1.36$  and  $1.44$ , the two frequencies of eq.(1) for the new pulsar with  $\Omega/(10^4/\text{s}) = 1.2369$ , are labeled  $\epsilon_1, \epsilon_2$ . Notation ‘y’ means the equation of state has first-order phase transition.  $\rho_s$  denotes density where causal limit is reached. For all cases  $a_{sym} = 30$  MeV.

$K$ MeV	$\gamma$	$f$	$\rho_c$ $\rho_0$	$\Delta$ $\rho_0$	$t$	$\rho_s$ $\rho_0$	$R$ km	$M$ $M_\odot$	$\Omega_K$ $10^4/\text{s}$	$\epsilon_c$ $\epsilon_0$	$\epsilon_1$ $\epsilon_0$	$\epsilon_2$ $\epsilon_0$
50	2.5	-3.0	5.0	1.0	y	4.87	8.24	1.93	1.41	14.7	12.0	-
50	3.0	-2.0	5.0	1.5	y	5.21	8.28	1.94	1.40	14.5	11.9	-
50	3.5	-0.5	5.0	2.0		9.72	7.67	1.70	1.47	18.0	13.2	16.4
		-1.0	5.0	2.0	y	9.81	7.81	1.74	1.45	16.5	12.8	16.0
		-1.5	5.0	1.5	y	4.81	8.39	1.97	1.38	14.1	12.6	-
80	2.0	-3.0	5.0	1.0	y	4.94	8.28	1.92	1.40	14.8	12.6	-
80	2.5	-2.5	5.0	2.0	y	5.16	8.28	1.95	1.41	14.4	11.8	-
80	3.0	-0.5	5.0	2.0		14.6	7.10	1.48	1.54	22.0	15.0	17.6
		-2.0	5.0	2.0	y	4.97	8.41	1.99	1.39	13.8	12.1	-
100	2.0	-3.0	5.0	1.5	y	5.12	8.33	1.94	1.39	14.6	12.9	-
100	2.5	-2.0	5.0	2.0	y	5.16	8.33	1.95	1.40	14.3	12.1	-
100	3.0	0.0	-	-		13.1	7.40	1.54	1.48	21.0	16.1	19.1
		-0.5	5.0	2.0		13.1	7.57	1.58	1.45	19.0	15.5	18.6
		-2.0	5.0	2.0	y	4.84	8.51	2.01	1.37	13.5	12.9	-
150	2.0	-2.0	5.0	2.0	y	5.10	8.37	1.95	1.38	14.4	12.9	-
150	2.5	-1.5	5.0	2.0	y	5.03	8.44	1.98	1.37	14.0	13.1	-
200	2.0	-1.5	5.0	2.0	y	5.10	8.44	1.95	1.37	14.3	13.8	-
200	2.5	-1.0	5.0	2.0	y	5.13	8.50	1.98	1.36	13.9	13.8	-

This is the case which has a constant pressure region, which is the mixed phase (of unspecified nature), and which extends from below to about 6 times nuclear density. In another case the softening is less severe, as for a second-order transition. These are compared with a smooth equation of state , a polytrope. The distinction between those cases having a first-order phase transition which *extends from below to a few times nuclear density* and others is a crucial one, as can be seen in Fig. 4, where the density profile of the limiting star is shown in both cases. The profile corresponding to the first-order phase transition actually simulates a situation corresponding to a self-bound system; the density falls precipitously at a well defined radius from a value which in this case is a multiple of a few times nuclear density, as for a system for which the pressure is zero at the energy density at which the drop occurs (self-bound at that density). The multiple is about 6. At a density considerably below  $\epsilon_0$  there is a thin crust, which is of little consequence for the radius and mass, and therefore for the Kepler velocity. Self-bound strange-quark-matter stars can also have a crust [15]. *In other words, the search for a description of the fast pulsar as a star that is bound by gravity alone and which has the least possible central energy*

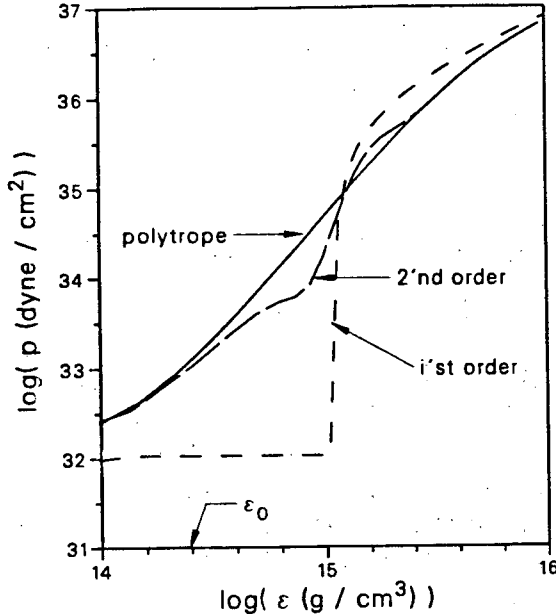


Figure 3: Equations of state for the three cases listed in Table 1 with (neutron star)  $K = 100$  MeV and  $\gamma = 3$ . The slight softening above nuclear density simulates a second-order phase transition, and the case with a constant pressure over a region of  $\epsilon$  is first-order. The smooth curve is the polytrope.

density, leads instead to a structure that simulates a self-bound system, one that would be bound without gravity at a density that is a few times nuclear.

In view of this, the only candidates that remain as a description of stars that are bound *only* by gravity have a minimum central energy density of 13.2 if the least stringent condition on stability is applied, and a minimum of 16 for the conservative condition of eq.(1). The corresponding equations of state are all soft at low density, having both  $K \leq 100$  MeV and a second-order softening of the equation of state. In addition all are stiff at high density, having  $\gamma \geq 3$ . This adiabatic index can be compared with a value 2 that would hold for the repulsive interaction due to vector meson exchange, and which is the asymptotic causal limit.

At this point we can note that such equations of state as those just described seem unphysical in the sense that physical systems exploit processes that lower the energy [22, 23] ie. which soften the equation of state, such as would be achieved in this context by conversion of nucleons to hyperons at high density, or a phase transition to quark matter, both of which lower the energy by an increase in the number of degrees of freedom. Yet we are forced to equations of state that stiffen rather than soften, by our insistence that the star is bound only by gravity, and then looking for a central density that is low enough to make a description in terms of hadrons seem plausible.

We have established in this section that if the new pulsar is rotating *and* it is bound only by gravity, as with all stars that we know of, its central energy density must be at least 13 times nuclear density. At this density it is implausible that matter is composed of individual hadrons. I conclude that it is implausible that the

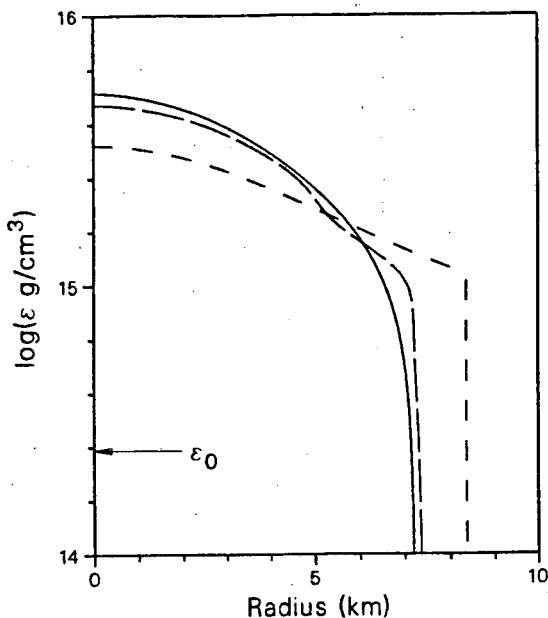


Figure 4: Star profiles for the three equations of state shown in Fig. 3. The sharp-edged profile corresponds to the first-order phase transition with mixed phase extending from below to  $\sim 6$  times nuclear density. It simulates therefore a self-bound system, bound at the multiple of nuclear density.

sub-millisecond pulsar is a neutron star.

### 3.6 Generic relations for neutron stars

Let us pause now to examine generic relationships for neutron stars, which like all others we know of are bound only by gravity. This we do for several models computed in relativistic nuclear field theory, which includes both nucleons and hyperons [22]. In Fig.5 we show the mass-radius relationship that is typical of a neutron star, whose only binding force is gravity. Recall that the densities are high in collapsed stars, and the net effect of nuclear forces is repulsive. This is in fact what resists gravities pull, and succeeds up to a critical point. Beyond a critical central density or total mass, depending on the particular equation of state, gravity will overwhelm the repulsion, and no stable solution to Einstein's equations exists. The star will become a black hole. Near this termination point the radius is rapidly decreasing with increasing mass, reaching a minimum value at the maximum mass. This is why the star at the termination point can have the maximum Keplerian frequency. It is the most massive and compact in the sequence. At the other extreme, as the mass becomes small, gravitational attraction is becoming small, and the size of the star grows as mass decreases. This, as I said, is the typical and inevitable relationship when gravity alone binds the star. In addition to familiarizing you with this, so as to contrast it shortly with another situation, I point out that the "phase space" in mass for which a star can have very high rotation is very small. *If* the new pulsar belonged to this class of stars *two* coincidences would have had to occur. The pre-supernova star must have had unusually high angular velocity (which further spins



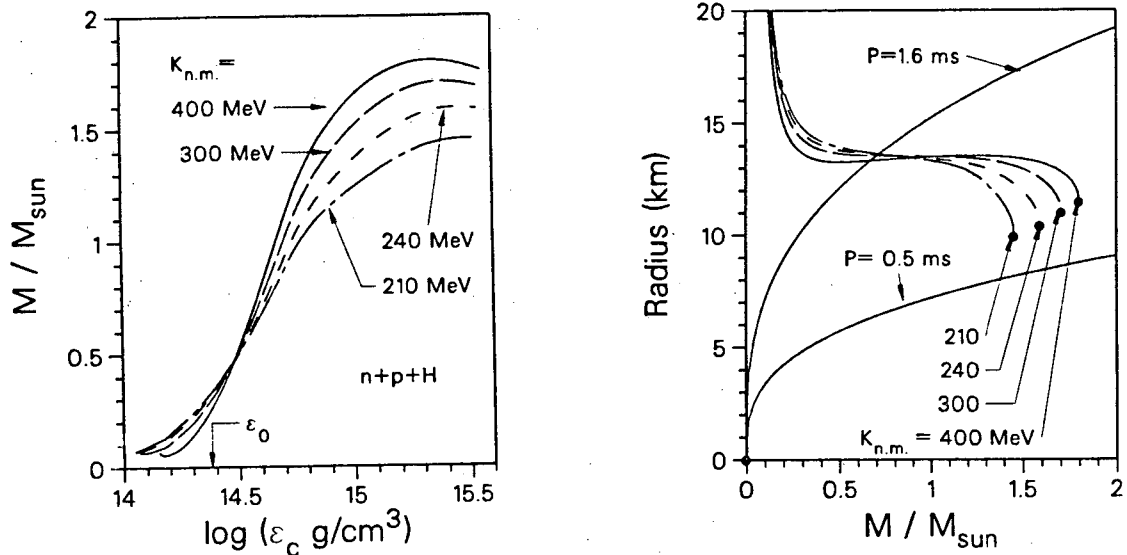


Figure 5: Generic relations for neutron stars for several equations of state as labeled according to compression of *nuclear matter*. For the R-M plot the limits imposed by a 1.6 ms and 0.5 ms pulsar are shown. Stars below these curves are stable for still shorter periods.

up on collapse of the star) *and* the mass of the neutron star, or in other words its baryon number,  $A \sim M/m$ , must have been very precisely tuned else the matter would have spun apart and never have formed a stable rotating star having a high frequency.

Now one of the above mentioned coincidences was in fact fulfilled, the high spin. But two for the same star?

### 3.7 Hybrid stars

We have learned that to account for fast rotation and the mass of known pulsars, the central density of the star, if bound only by gravity, must be very high. The plausible state of matter at high density is quark matter. Could the star be a neutron star with a quark matter interior, the two states of matter being in equilibrium at their interface?

Usually it is (tacitly) assumed that hadronic matter, in which quarks are confined in nucleons as in the nuclei of which the world around us is made, is the absolute ground state of the strong interactions. In this case such hadronic matter can coexist with quark matter at sufficient pressure, but if the pressure is released, that matter will return to the hadronic state. If the pressure due to gravity is sufficiently high in the core of a compact star we expect that it will convert to quark matter so that the star has a quark core and a neutron star exterior, and the whole

would be bound by gravity.

However, the equation of state of quark matter, because of asymptotic freedom, is expected to be soft. For example, in the bag model,  $\epsilon \approx 3p+4B$ ,  $v_s^2 = 1/3$ . In contrast, to satisfy the double constraint of sufficient mass to account for PSR1913+16, and stability to rotation at the frequency of the new pulsar, the models in my study were stiff at high density; many had reached the causal limit,  $v_s^2 = 1$ , in the star.

Such stars, which I call hybrid<sup>2</sup> stars, ones with a neutron star exterior and a quark matter core, the two phases being in equilibrium at their interface, seem to be incompatible with the findings of this study. It should be noted that again the binding of the star is provided by gravity alone, so the mass-radius relation has the generic form discussed before, with only the new twist arising from the region of mixed phase of hadronic and quark matter. (See Fig.6) As with neutron stars, the

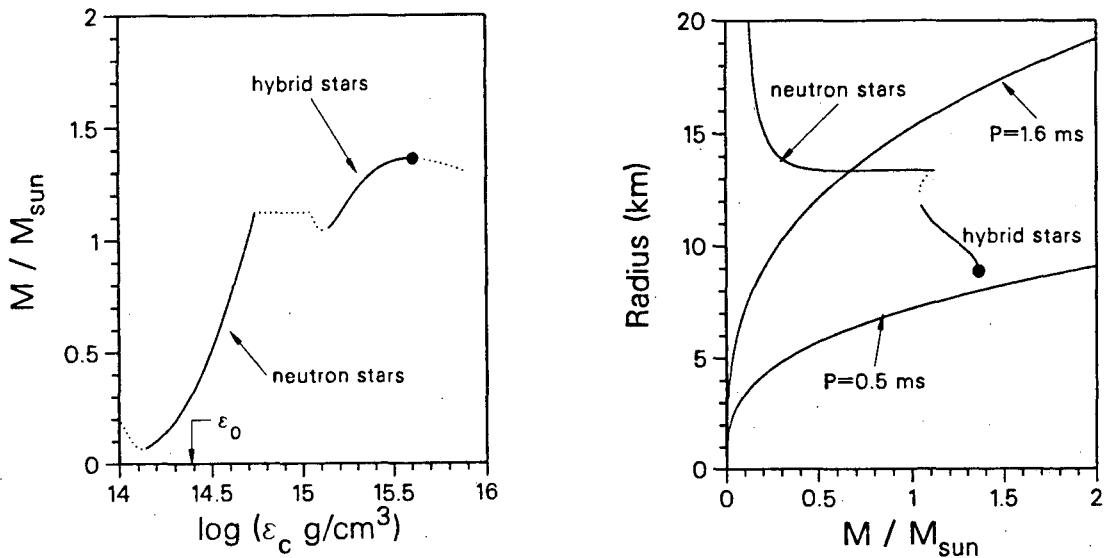


Figure 6: Same as Fig. 5 but for hybrid stars with a first order phase transition between hadron and quark phases (the region of constant  $M \approx 1.1M_{\odot}$ ). Dotted regions are unstable. Stable regions marked by solid lines.

window in  $M$ , and hence in  $A \sim M/m$ , for which fast rotation can be sustained is very narrow, the second of the coincidences mentioned before.

### 3.8 Conclusions

Within the context of pulsar models that are *bound only by gravity*, to satisfy the double constraint of sufficient limiting mass and stability to fast rotation we are led

<sup>2</sup>Possibly the first calculation of the structure of a star for which a first order phase transition occurs was made by C. K. Chung and T. Kodama, Rev. Bras. Fis. **8** (1978) 404.

to conclude that;

1. The equation of state must be soft at low density and stiff at high.
2. This requirement seems to be incompatible with hybrid stars, those with a quark matter core and neutron star exterior.
3. The central energy density must be very high,  $> 13\epsilon_0$ , for those models for which the star profile is like that of a star bound by gravity alone under the least stringent assessment of relativistic instabilities, and still higher,  $> 16\epsilon_0$ , under the conservative assessment.
4. Only stars in a very narrow window in mass, or equivalently in baryon number,  $A \sim M/m$ , those on the verge of collapse to a black hole, can withstand fast rotation.
5. The star profiles that are obtained by minimizing the central energy density are not those of neutron stars, but rather of self-bound systems, which are bound at zero pressure with density  $\sim 5\epsilon_0$  or more.

In attempting to understand the new pulsar as a collapsed star that is bound only by gravity we arrive at an impasse. The conditions imposed on the equation of state by the 1/2 ms period seem unphysical for the reason discussed in section 3.5. Moreover the central density of the star must be very high if bound by gravity alone as for a neutron star, so high that it appears to invalidate the notion that the constituents are hadrons. On the other hand, the equation of state must be stiff at high density, which seems incompatible with the notion of asymptotic freedom in the quark matter phase. In either case, there is a very narrow window in baryon number for which a star bound by gravity alone can withstand fast rotation. For the new pulsar to be a neutron or hybrid star we require the coincidence, or a very delicate creation mechanism, that supplies neither too many baryons, nor too few to the final collapsed star, else it will subside into a black hole, or be unstable to fast rotation respectively.

Perhaps the assumption that *this* star is bound only by gravity leads us into all these difficulties!

## 4 Self-Bound Stars

### 4.1 Strange-quark-matter stars

As already remarked, since nuclear matter is unbound beyond  $A \sim 200$ , and neutron matter probably not at all, neutron stars and hybrids are bound only by gravity. Usually we assume that strange quark matter (u,d,s quarks), which is a lower energy state of quark matter (u,d), is also unbound. On the contrary, Witten has suggested [14] that strange matter may actually be bound and also be the absolute ground

state. In this case strange matter, from nuggets with sufficiently large  $A$  to overcome finite number and surface effects, all the way to strange stars are stable. All other states of matter would be only metastable. Since ordinary matter would have an expected lifetime exceeding the age of the universe by far, Witten's hypothesis does not violate our experience nor any other physical facts.

It is not possible to decide on theoretical grounds whether ordinary matter or strange matter is stable. Lattice QCD, which in principle could answer the question, cannot be solved with sufficient accuracy now, and not in the foreseeable future. For example, to decide whether the energy per baryon in strange matter is less than it is in  $\text{Fe}^{56}$  (930.4 MeV) or greater than the proton mass (938.3 MeV) requires an accuracy of less than one percent. At best the bag model can give us guidance at the ten percent level (100 MeV)! Neither assumption contradicts any known fact, so we must look to experiment and astrophysical observation for the answer, and it appears that the new pulsar tells us that strange matter is self-bound, if not the absolute ground state.

The structure of strange stars, if strange matter is stable, is entirely different from that of neutron stars. This shows up most dramatically in the mass-radius relationship [15, 16]. Because strange matter is self-bound, say at energy density  $\epsilon_b$ , the mass of a small spherical strangelet is  $M = (4\pi/3)R^3\epsilon_b$  and, just as for a nucleus, the radius scales as  $M^{1/3}$ , in contrast to neutron stars, where for small masses, the radius is very large because of the weak gravitational field. The generic form of the mass-radius relation for a self-bound star is *independent* of any particular model of binding. If such a self-bound state exists, then there are two distinct families of collapsed stars, neutron stars and stars made of the self-bound phase, most plausibly strange matter. The two cases are contrasted in Fig.7.

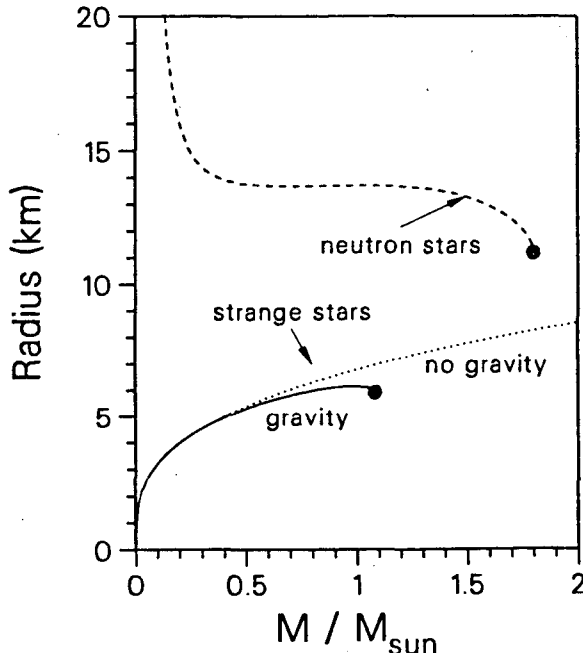


Figure 7: The generic form of the mass-radius relation for a neutron star and self-bound strange star are illustrated.

Under the Witten's hypothesis, strange stars can have only a very thin neutron

star skin whose maximum density is the neutron drip density ( $\sim \epsilon_0/500$ ), which is suspended out of contact with the quark matter by the electric force [15].

In Fig.8 I show the density profile for all three types of compact stars of the same mass, neutron star, hybrid star and strange star. It is easy to imagine which of these stars can be spun to the highest angular velocity without shedding mass at the equator.

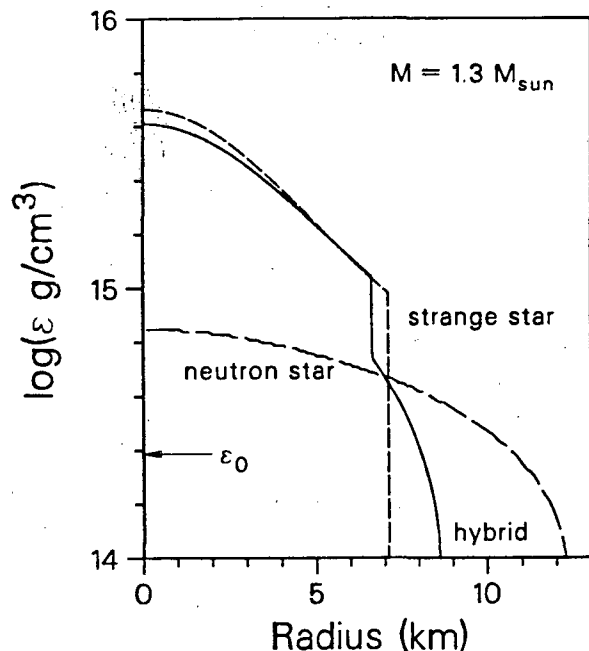


Figure 8: Density profiles of strange, hybrid and neutron star all of mass  $1.3 M_{\odot}$ . Clearly the strange star can rotate most rapidly. (The vertical region of the hybrid star is the mixed phase.)

## 4.2 Limit on the normal density of self-bound matter

If the energy density at which the matter is self-bound, which is its normal density, is sufficiently high, the whole family of stars can withstand fast rotation, not just the few in a narrow window near the termination of the sequence, as for neutron stars. We can easily derive a lower bound on the energy density for which self-binding must occur for this to be the case, independent of any model of the stable state. In classical mechanics stability of a star to rotation is expressed as the balance of gravity and centrifuge,

$$\Omega < \Omega_K = \alpha \sqrt{\frac{M}{R^3}} \quad (12)$$

where the factor  $\alpha$  is unity. The general relativistic calculations of Friedman, Ipser and Parker [12] can be approximated very well at the maximum mass by  $\alpha = 24/37$  and  $M$  and  $R$  are the mass and radius of the non-rotating star. So we can think of  $\alpha$  as an empirical factor that is near unity for very light stars and near the above quoted value near the termination of a sequence of stars. The above relation can

be expressed as a constraint on the average density, and the following inequalities can be written,

$$\bar{\epsilon} > \frac{3}{4\pi} \left( \frac{\Omega}{\alpha} \right)^2 > \frac{3}{4\pi} \Omega^2 \quad (13)$$

Since  $\bar{\epsilon} > \epsilon_b$ , a lower bound on the  $\epsilon_b$  that will ensure that the entire family of strange stars can withstand rotation up to frequency  $\Omega$  is provided by,

$$\epsilon_b \geq \frac{3}{4\pi} \left( \frac{\Omega}{\alpha} \right)^2 = 1.3\epsilon_0 \left( \frac{\text{ms}}{P} \right)^2 \quad (14)$$

where  $\epsilon_0$  is normal nuclear density and  $P$  is the period in milliseconds. For  $P = \frac{1}{2}$  ms, we find  $\epsilon_b > 5.4\epsilon_0$  ensures that the whole family of stars can withstand the half-millisecond rotation. In the presence of gravity, the density at the edge of the star is  $\epsilon_b$ , whereas it is larger in the interior because of the compression of gravity. So the actual limit is somewhat smaller than that derived above. We show in this way that the question of whether a self-bound star made of stable matter can withstand the fast rotation attributed to the new pulsar can be divorced from any particular model of the binding mechanism.

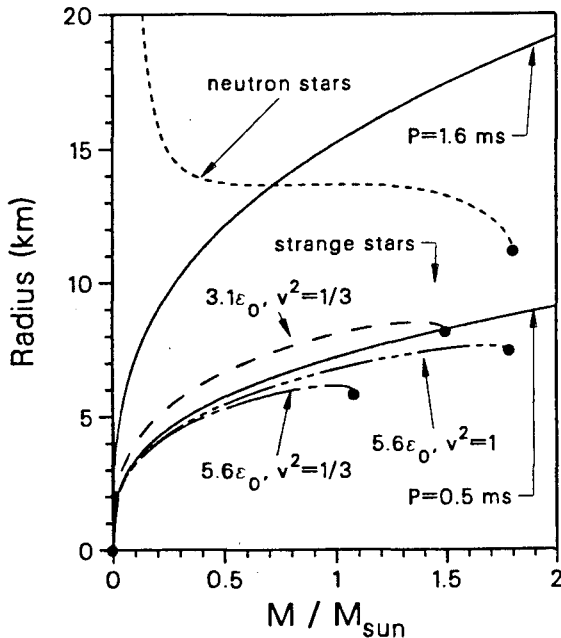


Figure 9: The mass-radius relation for a typical neutron star equation of state and for strange quark matter cases. The solid lines denote limits for the 1.6 and 0.5 ms pulsars, computed from eq. (3). Stars below these lines respectively are stable for shorter periods of rotation. [7, 3]

We show three strange star sequences obtained by solving the Oppenheimer-Volkoff equations in Fig.9, marked according to the value of the self-binding energy density  $\epsilon_b$ , measured as a multiple of normal nuclear density,  $\epsilon_0$ , one above and two below the limit derived above. In addition to this energy we need to postulate an equation of state for strange quark matter which has a self-bound state. This we

take, for illustration, as  $\epsilon = p/v^2 + \epsilon_b$ . A value  $v^2 = 1/3$  corresponds to a soft quark-matter equation of state, and  $v^2 = 1$  to a stiff one. The choice  $v^2 = 1/3$  and  $\epsilon_b = 4B$  corresponds to the bag model. Nothing forbids that we depart from such a crude model however. We see that it is quite possible to account both for compact stars of masses greater than any so far observed and also for sub-millisecond rotation.

The *qualitatively* different behavior compared to neutron stars does not depend on any particular model of strange matter, but only on the postulate that it is the absolute ground state. Strictly speaking the self-bound state could be other than strange matter. If a more plausible ground state with normal density obeying the above obtained limit can be found, then it is also a candidate for describing this star.

Absolute stability of strange matter ensures a mass-radius relation of the form discussed above. It does not necessarily ensure that a small nugget will not break up into smaller pieces of the same material. The surface energy mitigates against this of course. But for stellar objects, gravity will prevent breakup, except if there is a large input of energy, as in a collision of two compact stars. So gravity plays an important role in the structure of strange stars. But it shares the spotlight with whatever mechanism it is that produces the self-bound state. In the case of strange-quark-matter stars, this is QCD confinement.

### 4.3 Discussion of Strange Stars

We now discuss the above results. From the structure of the mass-radius relation for neutron stars shown in Fig.9, notice that if a neutron star model can sustain fast rotation it will be near its termination point, for which the window in mass is extremely small. This contrasts with strange-quark stars, where, depending on the 'normal' density of strange matter, the energy density at which it is self-bound, the whole sequence can sustain very high rotation. A neutron star will generally spin up to conserve angular momentum if it converts to a quark star, because the latter is more compact for the same baryon number ( $A \sim M/m$ ) as seen in Fig.9. A mass  $M = M_\odot$  neutron star in Fig.9 has stability against mass loss up to  $P \sim 1.3$  ms (ie. shorter than the period, 1.6 ms, of PSR1937+21). From the moments of inertia, we calculate that such a star will spin up by a factor about 3.9 in converting to a quark star on the most compact of the sequences of Fig.9. Therefore the angular velocity of the new pulsar may be the result of the conversion of a fast neutron star with angular velocity about equal to that of PSR1937+21. High angular velocity like that of the new pulsar appears to be the most conspicuous way in which a quark star can differ in observable properties from a neutron star. It could be that some other pulsars are also quark stars, but at frequencies that do not distinguish them from neutron stars (see Fig.1). However, if a pulsar were observed to spin up by a significant amount, especially a factor two or more on the time scale for conversion, it would be a candidate for a strange quark star. (Pulsar glitches are small spin ups of the order of  $\sim 10^{-4}$  %, thought to be caused by crust readjustments.)

Conditions under which a neutron star might convert to a quark star have been

discussed in the literature [15, 24]. It is of course particularly advantageous if the hyperon population is already high, which is likely to be the case for the heavier neutron stars where we calculate a preponderance of hyperons in the core [22].

It appears from all the foregoing that there may be two types of collapsed stars, neutron stars and quark matter stars, most of which are indistinguishable. So far as we know, rapid rotation, the factor three in frequency that separates the new pulsar from the next fastest, is what distinguishes it from the others. So all or some of the others could also be strange stars, since we otherwise have no way of telling them apart. The equation of state of one or the other, neutron stars or strange stars would have to obey the mass constraint and that of strange quark matter stars would have to satisfy the angular velocity constraint of the new pulsar, if both exist. In Fig.10 we show one possible family of each which satisfy the

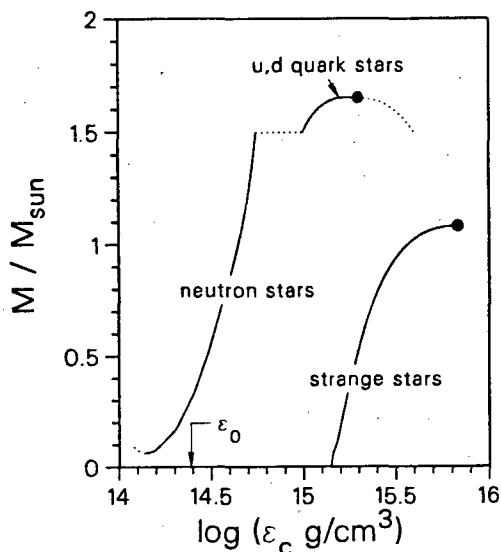
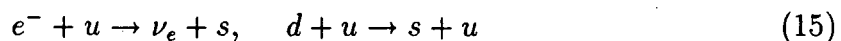


Figure 10: Two families of compact stars. Adapted from ref [3].

above constraints, respectively. The neutron star branch is metastable but will live indefinitely unless an interstellar nugget of strange matter falls onto it as discussed below, or unless one was present already in the pre-supernova star. In either case the nugget will grow in the dense neutron environment, eventually converting all hadrons except possibly for a thin skin. If the core pressure or density in the most massive members of the neutron star family is high enough, hadronic matter will convert to (u,d) quark matter (with an admixture of strange quarks, because of the presence of hyperons in high density neutron star matter). This branch is highly unstable if strange matter is the absolute ground state, because sufficient conversion of u,d quarks by weak interactions



will occur to form three flavor strange quark matter, which will then commence to convert the neutron star matter in contact with it. Conversion will likely be accompanied by neutrino production. However for several reasons it may not be



prodigious. First, because of the hyperonization that may have already taken place in the core, the admixture of strange quarks may already be close to equilibrium. Second, neutrinos, produced in the neutronization of the hadronic matter during collapse, diffuse out of the core on a long time-scale, seconds, and their presence will tend to Pauli block the first of the two processes in eq.(15). Third, depending on the time scale for conversion, which is rather uncertain [24], the neutrino production may be spread over a long time period.

There is another way in which conversion of neutron star to strange star could occur. If strange matter is the ground state, the universe is likely to be contaminated by strangelets, not primordial as first envisioned by Witten, for these would have evaporated into nucleons before the universe had cooled to a few MeV in temperature, when strange matter was hot and of higher energy per baryon than the nucleon. However strangelets could be created in subsequent generations of collapsed stars which had subsequently collided with a partner. After all there are no stable orbits; they are all damped by gravitational radiation, and close compact binaries damp especially rapidly (but still on astronomical time scales)[26]. If one of the partners is a strange star, strangelets will be dispersed in the explosion of the collision. Such strangelets that fall onto a star will gravitate to the center and remain dormant until the star collapses. As the density reaches the neutron drip point of neutron rich nuclei ( $\approx 4 \times 10^{11}$  gm/cm<sup>3</sup>  $\approx \epsilon_0/500$ ), the strangelet will begin to accrete neutrons, since they are not repulsed by the Coulomb barrier and will grow, eventually converting all matter in contact with it. Since the neutron drip point is reached in the early stage of a type II supernova, the conversion to a strange star by this path will be contemporaneous with the early stages of the supernova collapse. Some neutrinos will be produced as the hadronic matter is converted to strange quark matter, since the elementary processes are those of eq.(15). However, once the density reaches about  $10^{12}$  g/cm<sup>3</sup> the prodigious number of neutrinos produced by the neutronization of hadronic matter in the process  $e^- + p \rightarrow \nu_e + n$  and the analogous one on nuclei will be trapped and inhibit the first of the processes of eq.(15). I expect therefore that the neutrino signal of conversion by this path will be weak and hidden by that of the collapse. (See however [27].)

The spin-up of a neutron star that accompanies a conversion to a strange quark star has interesting ramifications. Using Fig.10 as an illustration, we see that more massive neutron stars may have to spin off considerable material, else the quark matter star will exceed its mass limit and subside into a black hole. Depending on the time scale, a secondary shock may accompany the collapse during conversion, which may eject mass, mostly hadronic matter but possibly some quark matter "strangelets". Such a shock can be a very weak one and still succeed in ejecting mass for several reasons. First, the shock is propagating in quark and hadronic matter, and so does not suffer the large energy losses associated with nuclear dissociation as for the first shock that followed the initial collapse from presupernova. Second, the excess matter is at or near the Kepler velocity so it needs only a slight push, and third there is not much of it, say a half solar mass, as compared to the tens of solar

mass that have to be ejected in the primary supernova event. Ejected hadronic material, if below the neutron star mass limit ( $\approx 0.05M_{\odot}$ ) will explode. Otherwise it will be disbursed into dust by the strong tidal forces of the quark star and create a very dirty environment about it. But the high density of the strangelets may allow them to survive and serve as seeds for the conversion of other stars, or possibly as companions of PSR1987A, in this instance. Such a mini strange-quark star may be the small mass object ( $M \sim \frac{1}{20}M_{Jupiter}$ ) that we have conjectured in a recent paper [7, 5] and for which some evidence appears in the the reanalysis of the data on the new pulsar [8].

We do not expect that the entire neutron star will convert to strange quark matter. As the core converts, and contracts, the supporting pressure on the neutron star matter is withdrawn. In such a rotating star as the new pulsar, the neutron star matter will then spiral inward, increasing in angular velocity as it does so. This matter will initially fall into the quark core and be converted. However the situation may be reached where the infalling hadronic matter approaches Kepler velocity. This together with the strong outwardly directed electric field [15] that is expected to exist in a thin exterior region outside the strange quark core can hold a layer of hadronic matter in suspension and out of contact with the core. At the poles, the thickness of this layer, and the upper limit on the density (neutron drip) are exactly as discussed by Alcock et al [15]. However because of the rotation at other locations and especially at the equator, the layer can be thicker and the total mass of the crust greater than that which can be supported by a non-rotating star. The angular velocity of quark star and nuclear halo can be and probably are different at early times. Accretion is expected. The drop in temperature from interior to exterior of the star will be similar to that of a neutron star because it occurs at densities below neutron drip [28]. The cooling characteristics of a quark star with crust should therefore be similar to those of a neutron star, modulo the possible differences in neutrino emissivity and the fact that the strange star will cool on conversion because of the greater number of degrees of freedom in quark than in hadron matter.

## 5 Summary

We have come to some remarkable conclusions. Let me state briefly the ones concerning the nature of the new pulsar and its implications for the ground state of matter.

1. All known pulsar masses and periods, with the exception of the new sub-millisecond pulsar can be understood in terms of plausible neutron star models in which neutron stars of masses up to  $\sim 1.5M_{\odot}$  and rotational periods as short as 1 ms are achieved at central densities of 3-4  $\epsilon_0$  (see fig.5).
2. It is implausible that the new sub-millisecond pulsar is a neutron star if (as all others) it is rotating, since its central energy density would have to exceed

$13\epsilon_0$  under the optimum stability condition, and  $16\epsilon_0$  under the conservative condition.

3. It is unlikely that it is a hybrid star consisting of a quark core *in equilibrium* at the interface with a neutron star exterior.
4. Fastest rotation in a family of neutron or hybrid stars can be achieved only in a small window of mass (or  $A$ ) near the verge of collapse to a black hole.
5. The hypothesis that most comfortably fits this star is that it is made of matter in a phase that is absolutely stable at somewhat more than five times nuclear energy density. The likely candidate for such matter is strange-quark-matter. If another plausible state of matter which fits the above description can be found and for which the lifetime of hadronic matter is greater than the age of the universe with respect to decay to such a state, then it is also a candidate for describing the fast pulsar.
  - (a) A strange star does not have to be fine tuned in  $A$ , to be *the* one at or very near the end of the sequence that can spin fast.
  - (b) Possibly the whole family of stars can spin fast, not just those near the limit. This depends on whether the energy density of strange matter in its ground state is greater than about  $5.4\epsilon_0$ .

How strange are strange stars? Perhaps not very strange. We have no evidence one way or the other which is the absolute ground state, ordinary matter or strange matter. Atomic nuclei would have lifetimes exceeding by far the age of the universe; indeed because of finite number effects[29], stable strange matter may exist only for nuggets with atomic number much greater than nuclei, in which case the barrier for conversion of nuclei would be effectively infinite. Only in the cores of the most massive neutron stars is the density so high that spontaneous conversion might take place unaided by a seed of preexisting strange matter. No matter which is the ground state, it is expected that the universe would consist mostly of ordinary matter. This is because, although Witten's hypothesis was motivated to suggest that the dark matter in the universe may consist of unobtrusive stable strange nuggets created in the very early universe, it has since been shown that they would have evaporated into nucleons before the universe had cooled to a few MeV in temperature. [30, 31]. Therefore primordial strange matter probably does not exist, and if so, only in a few planetary-mass objects. Although, as we pointed out earlier, models of confinement cannot arbitrate which is the ground state, on a grosser energy scale for which it is appropriate to take some guidance, bag model calculations suggest that the energy per nucleon in strange matter can be close to that of  $\text{Fe}^{56}$  or the proton, either above or below depending on the bag parameter. For all these reasons it is perhaps only egocentricity that causes us to regard the world as we see it, the hadronic world, as the ground state. Evidently the universe

would be imperceptibly different in the the two cases. If our interpretation is correct, the new pulsar may be the first evidence on this question.

There remain many fascinating aspects of fast pulsars that need to be worked out in detail, many of them alluded to above. Certainly we eagerly await another sighting both to confirm the first and to provide additional data on the pulsar in SN1987A, whose presence was first signaled by the neutrino burst preceding the first visual sighting of the supernova. Of course the interpretation that I have given, that this pulsar is evidence that matter has a high density stable or metastable state, is one that will be carefully scrutinized for compatibility with whatever relevant observations can be brought to bear.

Let me look for a moment to the future. Referring to fig.1 we see that about one in a hundred pulsars have millisecond periods, and one in four hundred have sub-millisecond periods, if you permit me to play loose with statistics. Twenty years ago we did not even know that pulsars existed. Given the high technology that is being brought to bear in astronomical observation, satellite searches in the infrared, computer driven telescopes that rapidly scan the sky according to a programmed plan, digital storage of images with very sensitive detectors (the new pulsar was observed in the optical) it is not far fetched to suggest that within a few years we will have additional data on fast pulsars.

The outlook for laboratory and terrestrial searches for quark matter, that are underway by many groups working at CERN and Brookhaven [32], could be much improved if strange quark matter is the ground state because a very promising signature would be strangelet production [33, 34]. However, one problem for laboratory production of strangelets is that they are presumably created at high temperature and may suffer the same fate as the primordial strangelets, evaporation.

**Acknowledgements:** I am indebted to J. L. Friedman for many stimulating electronic mail conversations as well as for performing one general relativistic calculation for a rapidly rotating strange star which confirmed the accuracy of eq.(3) for strange stars. 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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