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Supernovae, Compact Stars and Nuclear Physics

N.K. Glendenning

August 1989

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Supernovae, Compact Stars and Nuclear Physics[†]

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ABSTRACT

We briefly review the current understanding of supernova. 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 12 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 plausibly consist of individual hadrons. We conclude that the newly discovered pulsar, if its half-millisecond signals are attributable to rotation, cannot be 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 under appropriate conditions. 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

In a spectacular way, supernovae connect astrophysics and other branches of physics including very importantly nuclear physics. It is a dynamical process that involves such a broad category of phenomena, including networks of nuclear reactions that are involved in the star's evolution over ten million years from hydrogen to an iron core with successive layers of lighter elements in the exterior regions, convection between the layers, the iron core mass, its entropy, neutrino physics, their production, trapping, thermalization, diffusion, shock propagation, nuclear dissociation by the shock, and the equation of state, which from the beginning of collapse to core bounce is needed to describe the state of matter over six to seven orders of magnitude in density, of which only the last order lies in the nuclear and super-nuclear domain. Moreover most of the time during the explosion, matter lies at densities far below nuclear density. It is therefore difficult to isolate any particular aspect, for example the nuclear equation of state and claim that one can obtain evidence about it from a supernova event. All of the above factors are comparable in importance, interact dynamically with each other, and there remain many uncertainties as well as approximations in their handling.

The physics of neutron stars, especially those that relate to the equation of state, is by comparison simple. Even for rapidly rotating neutron stars, the structure is determined from equilibrium conditions and the connection between the large scale properties of the star, such as limiting mass and angular velocity are uniquely connected to the equation of state by Einstein's equations, nothing more.

I will first tell you briefly what the situation is with respect to our understanding of supernovae. It has changed dramatically in the last four years. You will recall that at that time it was believed that the mechanism by which stars explode was understood, and the claim was widely made that the equation of state could be constrained essentially by the fact that stars explode. The defects in those earlier scenarios are now understood, and successful explosions cannot be obtained in the way it had been thought, when the best physics known today is incorporated. However promising mechanisms are being explored, and we can hope that in the near future this long outstanding problem will be resolved.

Then I will discuss neutron stars. There also our understanding is in a state of ferment. If the observational evidence is accepted, the discovery of a new pulsar, the fastest of all, in the remnant of SN1987A, suggests remarkable conclusions about the state of dense matter. I shall discuss why I believe that this pulsar cannot be a neutron star, I shall present the evidence that it is a type of compact star not previously identified, a star made of strange quark matter, a conclusion that implies that the ground state of the strong interactions is strange quark matter, not ordinary hadronic matter.

2 Supernovae

2.1 Prompt Bounce and Ejection

Four years ago, at the level of approximation employed then, it was found that supernova explosions could be simulated if the equation of state was sufficiently soft at high density [1, 2]. This finding was then inverted and it was widely claimed that by their occurrence, supernovae inform us that the equation of state is soft. The scenario invoked at that time was that after nuclear burning had reached its end point in the pre-supernova star, having evolved about a Chandrasekhar mass of iron core, the core commenced to collapse. Upon reaching supernuclear density the inner core rebounds, sending out a shock wave that promptly expels most of the infalling material, typically 10 or more solar masses ($10M_\odot$) into a supernova explosion. In the particular case of SN1987A, about 16 $M_\odot$ has to be ejected. With the *particular* approximations made in this collapse-bounce-explode scenario, sufficient explosion energy could be generated if the nuclear equation of state was assumed to be very soft. Claims for the success of the prompt mechanism have floundered in two ways. More than two years ago, I showed that the equation of state that gave successful explosions was too soft to be consistent with the observed masses of several neutron stars [3]. The softer the equation of state the smaller the mass that can be supported against gravitational collapse, and the favored BCK equation of state cannot support the observed masses. In brief, the explosion energy was bought in those simulations at the expense of neutron star mass. Second, it was shown by Bludman [4, 5] and Bruenn [6] that the neutrino physics failed to account for important processes which reduce the chance for the explosion to occur promptly. The first generation of neutrinos are electron neutrinos produced by the neutronization of matter, $p + e \rightarrow n + \nu_e$. Because neutrino opacity goes as the square of their energy, these neutrinos would be trapped as the density approaches 10^{12} g/cm^3. However the early work failed to account for the down scattering of neutrinos to lower energy, for which the cross-sections that cause trapping are smaller. The neutrinos down-scatter because the electrons have to up-scatter on account of the Pauli blocking by occupied states. The partial deleptonization of the core during infall causes the shock to form at a deeper point inside the iron core, meaning that the shock must propagate through a greater overlaying mass of iron. It suffers severe energy losses in doing so. This loss is easily calculated. For each $1/2M_\odot$ of iron core through which the shock propagates the dissipation is

$$\Big(\frac{1}{2}A\Big)B \approx \Big(\frac{1}{2}10^{57}\Big) \times 10\text{MeV} = 5 \times 10^{57}\text{MeV} \tag{1}$$

where B is the binding energy and A is the number of nucleons in a solar mass. This dissipation energy is about five times the entire kinetic energy of the explosion. Bludman finds that even using the very soft equation of state of BCK and a small iron core, which is favorable to the prompt ejection, the explosion fails with these improvements in neutrino physics.

There is now universal agreement among those who have studied the problem, including now the authors of the original papers [7] that the prompt mechanism fails when the best physics to date is incorporated. Perhaps it fails just because it is prompt! It is vulnerable to energy losses on the one hand and on the other its time scale is too short for this energy loss to be replenished from the tremendous energy that will be released ultimately as the proto-neutron star sinks into its gravitational potential. (On the time scale of the prompt scenario, the proto-neutron star is still very hot and has a radius of $\sim$ 100 km, whereas it will finally shrink to $\sim$ 10 km, with consequent further release of binding energy.)

Typically the shock is overwhelmed by the energy loss caused by the heating and disintegration of nuclei as it propagates. As noted above, for each $1/2M_\odot$ of iron that the shock has to propagate through it looses about five times as much kinetic energy as is typically seen in supernova explosions. Yet a hundred times this energy will soon be released in binding energy of the neutron star. It will appear mostly in neutrinos because they can escape on a shorter time scale than photons.

Evidently since stars do explode, nature finds a way of converting enough of this neutrino energy into explosion energy. This brings us to the next scenario.

2.2 Neutrino Reheating Explosion

J. Wilson discovered this mechanism[8], and others [9] have contributed very importantly to recent refinements. As we just saw, the shock typically stalls and turns into an accretion shock at several hundred kilometers. Most of the material of the pre-supernova star is still falling inward toward this point. If it is not expelled, the star will collapse to a black hole. For the next several hundred milliseconds, after core bounce, the matter behind the stalled shock is heated by partial absorption of an intense neutrino flux from the evolving neutron star as it gives up binding energy. The heated material expands pushing the accretion shock front out to greater distance and leaving a hot rarefied bubble region in its place. A weak explosion may be the result of this. However, more likely this matter again stalls, but now at greater distance where the neutrino flux is smaller so that neutrino absorption is reduced. Meanwhile because of expansion the matter has cooled. Together with these factors and under the force of the infalling matter, the shock front would be pushed in again and the cycle would repeat itself since at the new closer position reheating by neutrino absorption would reoccur. But the important new realization is that for the next few hundred milliseconds there is another energizing mechanism, neutrino-antineutrino annihilation in the bubble region which raises the pressure in this region. It is only a matter of time until there is sufficient energy deposition to unbind the material at the stalled shock and with surplus energy with the resulting ejection in a supernova. It is now believed by a number of workers in the field that this is a fairly accurate description of how stars explode. It is a mechanism which unique among earlier ones, couples some of the binding energy being released by the proto neutron star to the outer layers over an *extended* time.

In this rather long term mechanism, matter spends much time at sub- nuclear density. Nuclear density plays a role in the explosion only at the time of high compression just before the bounce. It will not be surprising therefore if its effects are masked by the long evolution after the (stalled) bounce.

As it appears at present, the prompt mechanism may ultimately be found to produce supernovae in the *lightest* progenitors and the late-time neutrino reheating mechanism to be responsible for the explosion of all the others. It is hoped and expected that this long outstanding problem will be solved within the next year or two.

3 Rapidly Rotating Pulsars

The newly observed pulsar[10] in the remnant of supernova 1987A may prove to be the most significant discovery in astrophysics of our decade. In this section I will tell you why I believe this may be so. First a few remarks on the most obvious of its unusual features. 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. Assuming, as is believed to be the 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. Together with a few others, it lies far out in the trail of the distribution. This factor of three 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 is in several steps. But first a little more about the actual observations.

The pulses were observed over an eight-hour interval one night in January. At a frequency of 1969 per second, 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 [11, 12, 13]. 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.1 the modulation is shown in the laboratory frame. The laboratory is an 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.

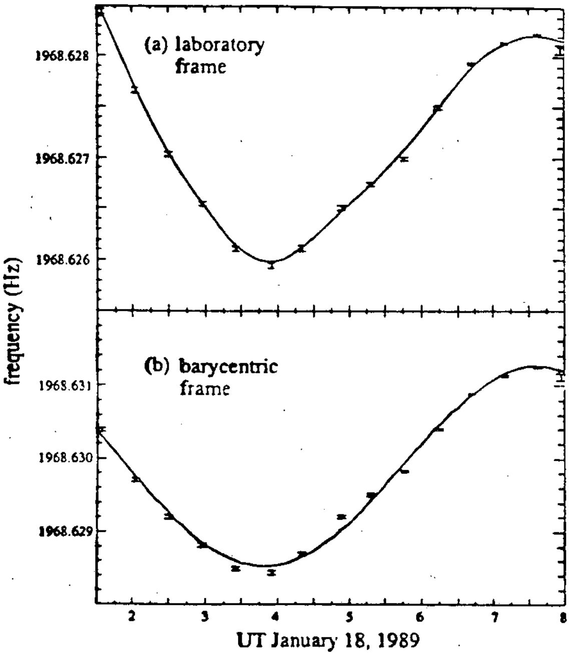

Figure 1: Frequency modulation of the 0.5 ms pulses of PSR1987A as seen in the laboratory frame, and in a frame corrected for the earth's motion (barycentric). [10]

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. But I leave that for the experts to discuss [14].

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 [11, 12, 13].

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[15] would have extinguished a signal in the particular frequency range of the optical at which the discovery team made their observation, by a factor $> e^{-1000}$.

3.1 Neutron Stars

Now I begin a discussion of the implications of this pulsar if its pulsed radiation is due to rotation. It is evident that there must be a maximum frequency at which a neutron star can rotate. Whatever the equation of state there is a maximum possible mass, the Oppenheimer-Volkoff limit and a corresponding radius. Classically we can write the condition for stability; gravity must be stronger than centrifuge acting on a mass m at the surface of the star.

$$\frac{GMm}{R^2} > m\omega^2 R \tag{2}$$

which for the mass and radius of the star places an upper limit on its rotation frequency. To calculate it convincingly one must go beyond this classical expression and solve Einstein's general theory of relativity for rapidly rotating stars. This is much harder to do than for static, or slowly rotating stars for which rotational energy is negligible compared to total energy. Friedman, Ipser, and Parker [16] and Sato and Suzuki [17] have done so for a large (but somewhat old fashioned) collection of equations of state. Equations of state which are very stiff at low density have no chance of accounting for the rapid rotation (in stars bound only by gravity). They are not shown in Fig.2. Otherwise, the maximum frequency at which stability against mass loss can be maintained is shown as a function of mass

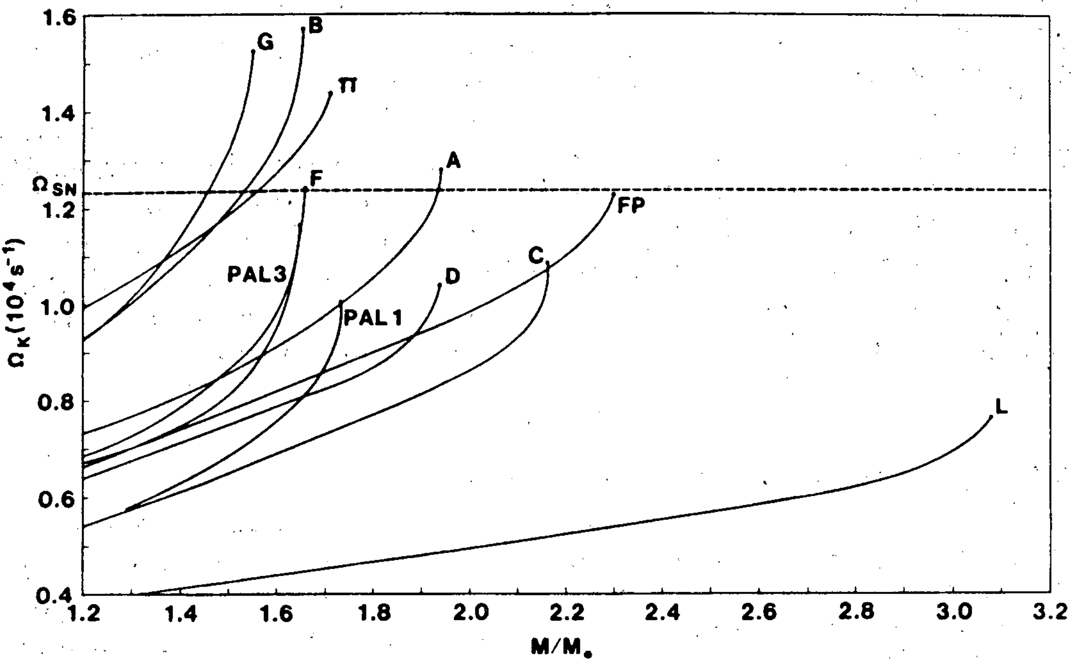

Figure 2: Maximum angular velocity, Ω_K vs M for a number of equations of state. The final dot in each case marks the maximum mass and angular velocity consistent with stability. The angular velocity of the new pulsar is marked by the horizontal line. Taken from [16]

for various equations of state which are soft and intermediate in stiffness, though as we shall soon see, this is a very imprecise specification of the restrictions imposed by fast rotation. First notice that all these equations of state can account for the frequency $\Omega \doteq 4033\ \mathrm{s}^{-1}$ of the next fastest pulsar. But only several can account for the new one at $\Omega = 12,370\ \mathrm{s}^{-1}$. Two of these (case G and B) can be ruled out because the non-rotating mass limit lies lower than the well-established mass $1.442 M_\odot$ for PSR1913+16. Be that as it may, I show you in Table 1 the central energy densities for stars at the termination point as a ratio to the energy density of symmetric nuclear matter ($\epsilon_0 = 2.48 \times 10^{-14}\mathrm{g/cm}^3$). What we observe here is

Table 1: Central energy density, ϵ_c, and limiting angular velocity, Ω_K, of the star at the termination point of several neutron star models that sustain fast rotation. (Data adapted from ref. [16]. Key to models cited therein.)

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

that they range from 13 to 21 times normal nuclear density. In the corresponding non-rotating stars, these numbers would be about 20 percent higher. Matter at such densities cannot consist of individual hadrons!

The stability discussed above is with respect to mass loss at the equator. Formally this limit is given by the Keplerian angular velocity, Ω_K, corresponding to a particle in a Kepler orbit at the equator. Other instabilities having to do with pulsations that convert rotational energy into gravitational radiation occur at lower frequency than this. These have been studied recently by Ipser and Lindholm [18]. They find that the maximum angular velocity is 10-15 percent less than the maximum imposed by stability to mass loss. So the limiting frequency is

$$\Omega < \Omega_{G.R.} = (0.86 - 0.91)\Omega_K \tag{3}$$

which is even more stringent than discussed above.

So I have remarked on two observations that I have made[19] concerning the work of Friedman et al. (1) Many conventional neutron star models can account for the next fastest pulsar. (2) None in their study can account for the new one, except for models in which the central energy density is enormous. Perhaps that is only a coincidence of the limited number of models in the study. Therefore, I have sought to answer the question, "What is the least possible value of the central energy density [1] of a star that is bound only by gravity, that will allow it to rotate at the frequency of the new pulsar and which corresponds to an equation of state that yields a limiting mass that is at least as large as the largest observed neutron star mass?" Since the arrangement of energy density in the star is uniquely prescribed by Einstein's equations and the equation of state, we can answer the question by employing a very general parameterization of the latter. I have made an exhaustive study[20] of 1470 models, belonging to a very flexible parameterization that can describe both soft and stiff equations of state, and that has in addition the possibility of describing a local softening as in a second order phase transition or a more severe softening leading to an equation of state of the characteristic form of a first order phase transition (see appendix for details). If the causal limit is reached, the equation of state is thereafter continued at that limit. In each case I solve the Oppenheimer-Volkoff equations, find the mass and radius of stars in each sequence as a function of central density, and employ the relation

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

which is good to ~ 5 percent, to compute the limiting angular velocity. From this exhaustive study I find that the central density must exceed $12\epsilon_0$ for stability at

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[1] Frequently the equation of state is expressed in terms of the baryon number density, ρ as $p = p(\rho), \epsilon = \epsilon(\rho)$. Since the parametric dependance on ρ 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 ϵ and not ρ.

$0.91\Omega_K$ and must exceed $16\epsilon_0$ for stability at $0.86\Omega_K$. This confirms my earlier observation.

We can also look to see what attributes are required of an equation of state that satisfies the double constraint of sufficient mass for slowly rotating stars and stability for rapid rotation, in the case that the star *is bound only by gravity.* All of the variational models in the above search that could satisfy the constraints are soft at low density having a first order phase transition above saturation density, and they are very stiff at high density, generally at the causal limit in the star! I want to stress here that this is a conclusion we are driven to within the constraint that the star is bound only by gravity. And the result, especially the extreme stiffness at high density is very unphysical. Nature generally finds mechanisms to lower the energy, and there are such mechanisms, for example conversion of nucleons to hyperons. Such processes as lower energy, soften the equation of state.

Let us pause now to examine generic relationships for neutron stars, which like all others we know of are bound only by gravity. In Fig.3 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, 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

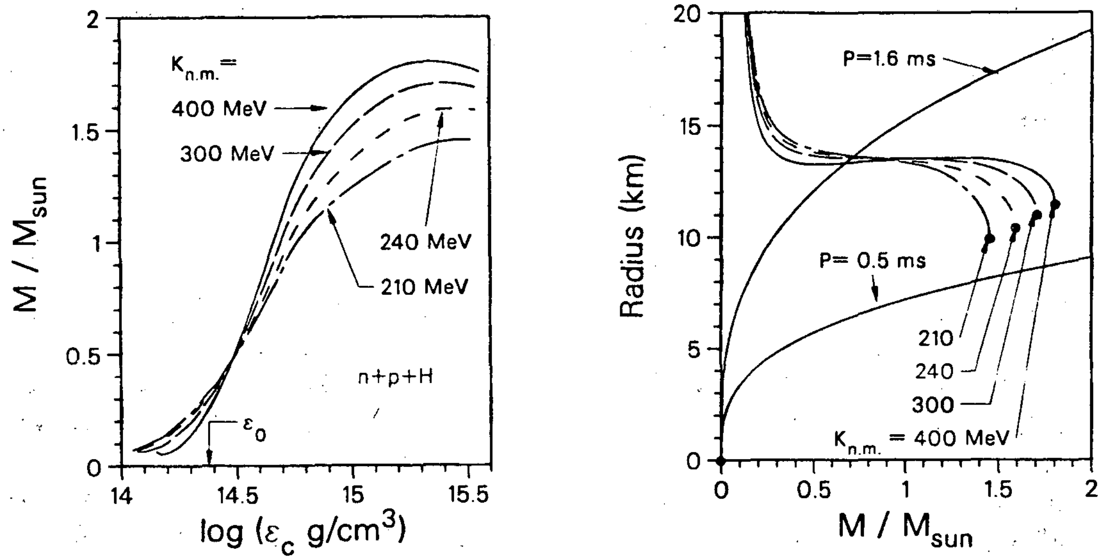

Figure 3: Generic relations for neutron stars for several equations of state as labeled according to compression. For the R-M plot the limits imposed by a 1.6 ms and 0.5 ms pulsar are shown. Stars below these curves are stable for still shorter periods.

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 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? Not likely, but not impossible.

Nonetheless, to resume the main line of argument, we have established 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 12 times nuclear density. At this density matter cannot be composed of individual hadrons. I conclude that the new pulsar cannot be a neutron star.

3.2 Hybrid Stars

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? This is expected if the density in the interior is sufficiently high, *and* if we assume, that hadronic matter is the absolute ground state, not strange quark matter. This is of course the assumption that is tacitly made with rare exception. 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; they had reached the causal limit, $v_s^2 = 1$, in the star.

Such stars, which I call hybrid[2] stars, ones with a neutron star exterior and a quark matter core, the two phases being in equilibrium at their interface, seem to be ruled out by 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.4) As with neutron stars, the window in M,

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[2] 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.

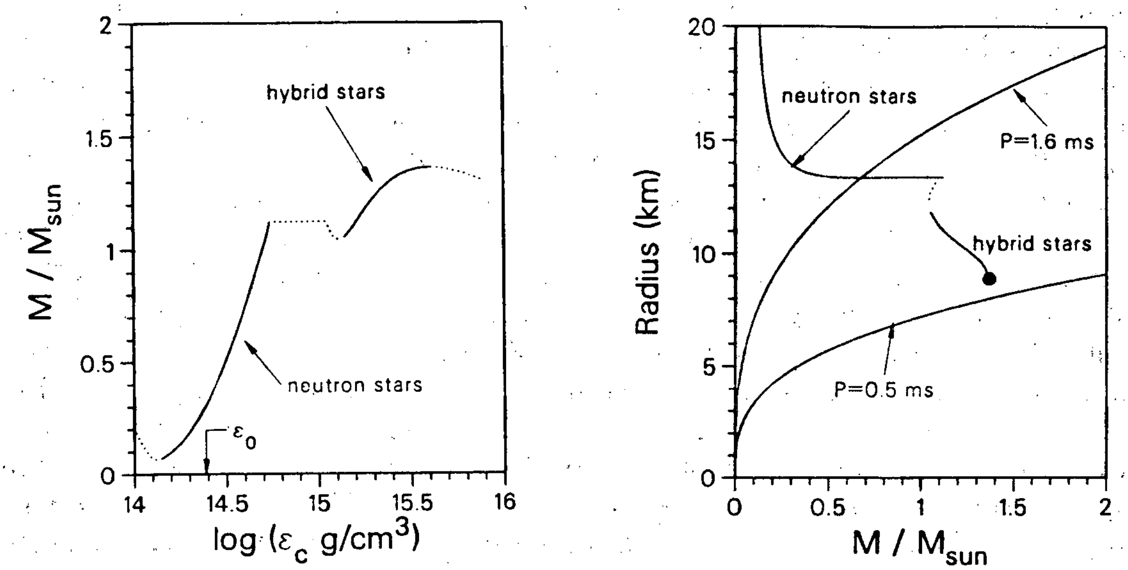

Figure 4: Same as Fig. 3 but for hybrid stars with a first order phase transition between hadron and quark phases (the region of constant $M \approx 1.1 M_{\odot}$). Dotted regions are unstable. Stable regions marked by solid lines.

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

In attempting to understand the new pulsar as a collapsed star that is bound only by gravity we arrive at an impasse. The central energy densities are too high for the constituents to be individual hadrons, while the equation of state at high density must be too stiff to describe quark matter. Since quark matter is the expected state at high density, perhaps the assumption that *this* star is bound only by gravity is at fault!

3.3 Strange Quark Matter Stars

Several times I have remarked that the stars being discussed are bound only by gravity. This is not a gratuitous remark. Two situations can be distinguished 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 inside 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. This is the hybrid star discussed above. If, on the other hand, strange quark matter is the true ground state of the strong interactions, as was suggested by Witten [21], then for baryon number sufficiently large (but very small compared to that of compact stars, $\sim 10^{57}$), objects of such composition are bound without gravity. Gravity plays a role in the larger of such objects of course, but their structure is entirely different from that of neutron stars on account of QCD confinement. These stars do not have a neutron star exterior because in the case that strange quark matter is the ground state, any neutron star exterior of appreciable mass would come into contact with the core and be absorbed and converted to strange quark matter. Matter, once in this state, if indeed it is the ground state, will not spontaneously convert back to hadronic matter (except if the baryon number is smaller than a critical value such that finite number effects are so important that hadronic matter is lower in energy as in the case of three quarks where the nucleon has lower energy than the lambda). In Fig.5 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.

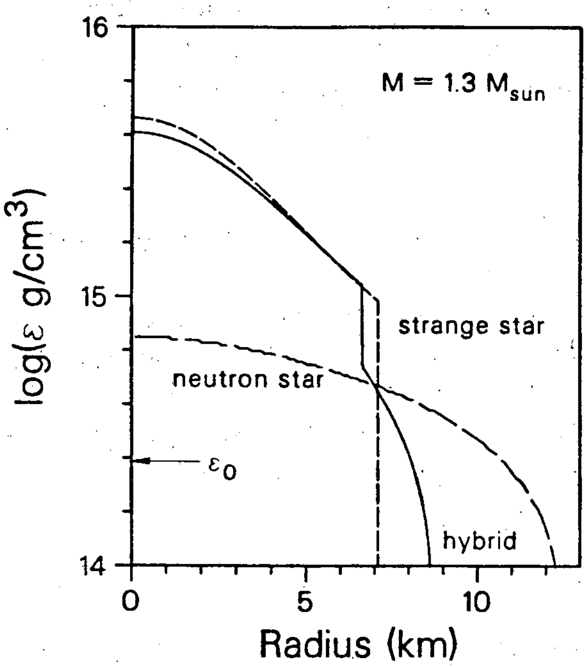

Figure 5: Density profiles of strange, hybrid and neutron star all of mass 1.3 $M_{\odot}$. Clearly the strange star can rotate most rapidly. (The vertical region of the hybrid star is the mixed phase.)

Strange quark matter, consisting of an approximately equal mixture of u, d, s quarks has lower energy than non-strange quark matter. This is so because for given baryon number the Fermi energy of the former is lower than the latter, there being an additional flavor to carry baryon charge. On any macroscopic time scale, non- strange quark matter will decay by the weak interactions, into strange matter. Witten's hypothesis is that such matter is the true ground state of the strong interactions and I refer to this as *strong* confinement. This hypothesis is controversial with opinions in favor [21, 22] and against [23]. We may note that neither assumption contradicts any known physics: that hadronic matter, the matter of which we are made, is the absolute ground state, or in contrast that strange quark matter is. The former (anthropomorphic) view is the most commonly held tacit assumption. Such a fundamental issue as to what state of matter is the absolute ground state cannot be settled by recourse to models of confinement with their unsatisfactory convergence, and the problem is so far intractable for lattice QCD. In the meantime we may look to laboratory experiments, such as those at CERN and Brookhaven, or to the stars. I believe that the new pulsar together with our other considerations may provide the answer. For if Witten's hypothesis is true, the mass-radius relation for quark stars is remarkably different than for neutron stars [24, 25] and its generic form is *independent* of any particular confinement model. The two cases are contrasted in Fig.6. Since the strange quark star is self-bound by hypothesis, even low mass objects are stable (except below a critical value where finite number effects are important, eg. the lambda) For constant energy density, valid once finite number effects are negligible, the radius will scale as $M^{1/3}$ in the absence of gravity. Because of the generic character of the results there is no point in adopting anything but the simplest of models so we adopt the MIT bag model in its simplest form, massless quarks and $\alpha_s = 0$ [26].

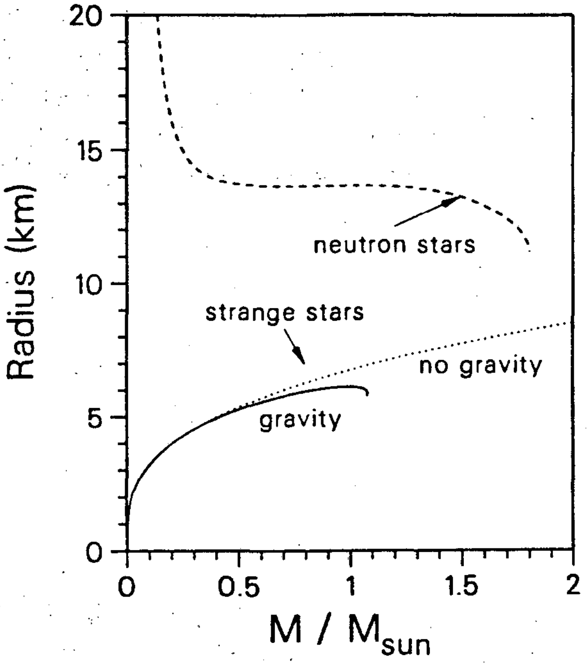

Figure 6: The generic form of the mass-radius relation for a neutron star and self-bound strange star are illustrated.

$$\rho = \frac{\mu^3}{\pi^2}, \quad p = \frac{3}{4\pi^2}\mu^4 - B, \quad \epsilon = 3p + 4B, \quad Q = 0 \qquad (5)$$

where $\rho, p, \epsilon, \mu, B$ and Q are the baryon number density, the pressure, energy density, chemical potential (fermi energy), bag pressure and electric charge density. Under the hypothesis that strange quark matter is the absolute ground state, the equilibrium configuration in the absence of gravity, and for sufficient bulk that finite size effects are no longer important, is given by $p = 0$. This gives

$$\epsilon = 4B, \quad \mu = \left(\frac{4\pi^2 B}{3}\right)^{1/4} \approx 300 \text{ MeV}, \quad M = \left(\frac{4}{3}\pi R^3\right)\epsilon \longrightarrow R \sim M^{1/3} \qquad (6)$$

In the presence of gravity the above value of the energy density and chemical potential are those at the edge of the star. The energy density will fall from this finite value to zero in a strong interaction length ~ 1 fm. Inside, because of the gravitational force, the energy density and chemical potential will be larger. Thus we see that the strange quark mass, $m_s \sim 150$ MeV can be neglected in first approximation, while the higher mass quarks, c,t,b will be absent.

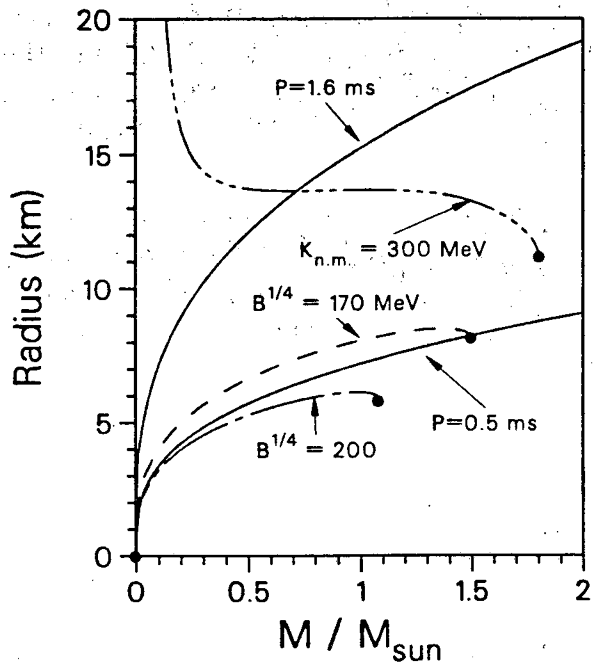

Figure 7: The mass radius relation for a typical neutron star equation of state and for two strange quark matter cases. The solid lines denote limits for the 1.6 and 0.5 ms pulsars. Stars below these lines respectively are stable for shorter periods of rotation. [13, 19]

We show two strange star sequences obtained by solving the Oppenheimer-Volkoff equations in Fig.7, marked according to the value of the bag constant, $B^{1/4}$, and list properties at the limit in Table 2 [13, 19]. The *qualitatively* different behavior compared to neutron stars is not model dependent but rather is a consequence of the postulate. Under the postulate, the quark stars are bound by confinement and gravity, whereas all other stars are bound by gravity alone. The solid lines are the trajectories of Eq.(4) at the frequency of the new pulsar and at the frequency of the next fastest one, labeled according to their periods. (Eq.(4) is good to 2 % as confirmed for us in ref. [27] for $B^{1/4} = 170$ MeV.) Stars in sequences or parts thereof that lie below the line labeled $P = 0.5$ ms are stable against mass loss above the frequency of the new pulsar. Therefore strong confinement of strange quark matter stars can account for the high frequency, depending, in this model, on $B^{1/4}$, or generally on the *degree* of confinement strength. We place no interpretation on the value of the $B^{1/4}$ however because it is a model dependant quantity, and we do not expect the bag model to be more than a caricature of confinement. Rather it is the generic form of the mass-radius relation that we rely on to show that for suitable *degree* of confinement, the fast rotation of the new pulsar can be sustained.

We now discuss the above results. From the structure of the mass-radius relation for neutron stars shown in Fig.7, 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 quark stars, where, depending on the degree of strong confinement, 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.7. A mass $M = M_\odot$ neutron star in both models of Fig.7 have stability against mass loss up to $\Omega \approx 0.48 \times 10^4$ s^{-1} (which is about the frequency of PSR1937+214). 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.7. 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+214. 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. Indeed most pulsar periods are in the 0.2 to 2 second range rather than near the millisecond range. 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 [25, 28]. 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 [29].

It appears from all the foregoing that there are two types of collapsed stars,

Table 2: Strange quark star properties at the limit; gravitational mass, M, radius, R, and central energy density, ϵ_c, for non-rotating, and angular velocity, Ω_K 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

neutron stars and quark matter stars, most of which are indistinguishable. The equation of state of neutron stars would have to obey the usual mass constraint and that of strange quark matter stars would have to satisfy the angular velocity constraint of the new pulsar. In Fig.8 we show one possible family of each which satisfy the above constraints, respectively. The neutron star branch is stable and will live indefinitely unless it contains a seed of strange quark matter that was present already in the pre-supernova star, or unless it is subsequently struck by a strangelet from interstellar space. The most massive members of this family will, if the core pressure or density is high enough, 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

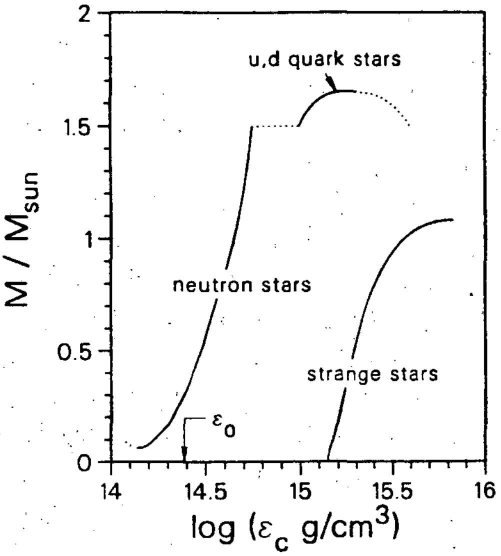

Figure 8: Two families of compact stars. Adapted from ref [19].

$$e^- + u \rightarrow \nu_e + s, \quad d + u \rightarrow s + u \tag{7}$$

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.(7). Third, depending on the time scale for conversion, which is rather uncertain [28], 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. The universe is likely to be contaminated by a small amount of strangelets, not primordial as first envisioned by Witten, for these would have evaporated before the universe had cooled to a few MeV in temperature, but 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)[30]. 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^3 $\approx \epsilon_0/500$), 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.(7). However, once the density reaches about 10^{12} g/cm^3 the prodigous 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.(7). I expect therefore that the neutrino signal of conversion by this path will be weak and hidden by that of the collapse.

The spin up of a neutron star that accompanies a conversion to a quark star has interesting ramifications. Using Fig.8 as an illustration, we see that more massive neutron stars will 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 ($\approx 0.05 M_\odot$) 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 [13, 11] and for which some evidence appears in the the reanalysis of the data on the new pulsar [14].

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 [25] 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 [25]. 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 [31]. 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.

4 Summary

We have come to some remarkable conclusions. Let me state them briefly under two categories, the one concerning the nature of the new pulsar and its implications for the ground state of matter, and the other concerning the circumstances and consequences of the conversion of a neutron star to a strange star.

Nature of the fast pulsar:

1. The new sub-millisecond pulsar cannot be a neutron star if (as all others) it is rotating.
2. It is unlikely that it is a hybrid star consisting of a quark core *in equilibrium* at the interface with a neutron star exterior.
3. The hypothesis that most comfortably fists this star is that it is a pure strange quark matter star.
    (a) In this case it does not have to be fine tuned in baryon number, 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.

• Corollary: strange quark matter in sufficient bulk to overcome finite number effects is the absolute ground state of the strong interactions, not hadronic matter.

Conversion of a neutron star to strange star:

1. If a neutron star is born with sufficient mass and therefore core pressure that the core undergoes a transition from hadronic matter to (u,d)-quark matter, then the conversion to a strange star is inevitable through the weak interaction conversion of u and d quarks until the lower energy state of strange quark matter is reached.

2. Otherwise, if the progenitor star contained a seed of strange matter, the seed would gravitate to the center and remain dormant until the core collapse, at which time the presence of free neutrons and the high density of the new environment would cause rapid conversion of the core.

3. Otherwise it may live out its life as a neutron star, unless conversion takes place by accidental capture of a seed of interstellar strange matter.

4. Conversion will be accompanied by neutrino production. However it is not likely to be prodigous, is likely to occur during the supernova and proto-neutron star era and is likely to be masked by neutrinos produced during collapse of the presupernova.

5. If conversion takes place the star will undergo a second small scale collapse.

6. Doing so it will undergo a substantial spin-up, possibly by a factor ~ 3.

7. If it converts and spins up during the history of observations on the pulsar the degree of spin-up is easily distinguished from star quake spin-ups ($\sim 10^{-4}$ %).

8. If it has already converted, before first being observed, it will not be noticeable as a strange star unless its progenitor neutron star was a millisecond pulsar. Then because of the additional spin-up it will become a sub-millisecond pulsar and be identifiable for that reason as a strange star.

9. Conversion will likely be accompanied by a neutrino burst. However prior conversion of nucleons to hyperons in the core may mute neutrino production.

10. If the mass of the neutron star that converts exceeds the mass limit of strange stars, it must shed matter or become a black hole.

11. The matter that is shed is most likely hadronic, but could also be strangelet(s). Presumably only the strangelets would survive intact the strong tidal forces of the quark star. They may constitute the companion(s) that cause the frequency modulation of the half-millisecond pulses.

12. Rapidly rotating stars can easily shed matter upon conversion to a quark star. In the second collapse of the core to strange matter, the hadronic matter near the surface of the star will spin-up as it spirals toward the core, approaching Kepler velocity. A mild shock would suffice to expel it.

13. If sufficient excess mass is not expelled it may become an accretion disk, spelling eventual disaster (black hole).

14. If the mass of the converted neutron star, less any matter that is expelled, is less than the mass limit of the quark star, it will form a stable star, perhaps with some unconverted neutron star matter held in suspension out of contact with the quark star by the centrifugal and electric force at the surface of the quark star. The angular velocity of quark core and nuclear halo can and probably will be different. Coupling is very weak. Viscosity will likely cause slow accretion from halo to core.

15. The temperature of the star will drop during conversion because of the greater number of degrees of freedom in the strange quark matter.

16. Cooling characteristics of a strange star will otherwise be similar to a neutron star because of the nuclear halo.

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 the absolute ground state of the strong interactions is strange quark matter, is one that will be carefully scrutinized for compatibility with whatever relevant observations can be brought to bear.

It is interesting to note that Witten made the hypothesis that strange quark matter is the absolute ground state in connection with the problem of missing mass in the universe. It is believed, partly for aesthetic reasons, that the universe is closed. There is enough matter that can be accounted for to make this a tantalizing conjecture, almost enough to arrest the present expansion of the universe at some distant time in the future. Witten supposed that the missing mass was distributed in primordial strange quark nuggets which according to hypothesis are stable but too small to be detected (dark matter). However it has been shown that primordial strangelets, if produced when the universe was very hot, would have evaporated before it cooled, the energy per baryon number being higher in hot quark matter than the mass of the nucleons [32]. So strange quark matter cannot be the missing dark matter. However as noted above, other than the interpretation given here of the new pulsar, there is no evidence one way or the other which is the absolute ground state, hadronic or strange quark matter. That is why the new pulsar is such an important discovery, having such a profound implication which makes it much more significant than the supernova event in which it was born.

The outlook for laboratory and terrestrial searches for quark matter, that are underway by many groups working at CERN and Brookhaven [33], could be much improved if strange quark matter is the ground state because a very promising signature would be strangelet production [34, 35]. One problem however is that the strangelets are presumably created at high temperature and may suffer the same fate as the primordial strangelets, evaporation.

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Appendix

For the equation of state we construct a very general form[20]. We use a modification of the BCK equation of state [36]. To this we add the flexibility of introducing local softening or stiffening, *and* first 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 $\rho_0 = 0.15$ fm^{-3}. There remain 6 parameters. These are the compression modulus, K, the adiabatic index, γ, 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 sever softening with a form as of a first order phase transition. Its parameters define its central location in density, ρ_c, its width in density Δ, and its strength, f which is defined below.

In terms of the variables,

$$u = \rho/\rho_0, \qquad x = \rho_e/\rho = Z/A \tag{8}$$

where ρ_e denotes the electron number density, the nuclear contribution to the pressure and energy density are

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

The contribution of the leptons is,

$$p_e = \frac{1}{4}(3\pi^2)^{1/3}(x\rho)^{4/3}, \qquad \epsilon_e = 3p_e \tag{10}$$

and the condensate contribution is,

$$p_c = -2E_0(\rho/\Delta)^2(\rho - \rho_c)e^{-w}, \qquad \epsilon_c = \rho E_0 e^{-w}, \qquad w = \left(\frac{\rho - \rho_c}{\Delta}\right)^2 \tag{11}$$

where

$$E_0 = f\left\{\frac{\epsilon_n(\rho_c)}{\rho_c} - \frac{\epsilon_n(\rho_c - 2\Delta)}{\rho_c - 2\Delta}\right\} \equiv f\Delta\epsilon \tag{12}$$

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 ρ_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 ρ_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,

$$\frac{\partial p}{\partial \epsilon} = 1, \quad p_s \equiv p(\rho_s), \quad \epsilon_s \equiv \epsilon(\rho_s), \quad p = \rho^2 \frac{\partial(\epsilon/\rho)}{\partial \rho} \tag{13}$$

yield for the region above ρ_s,

$$p = \frac{1}{2}\left\{p_s - \epsilon_s + (p_s + \epsilon_s)\left(\frac{\rho}{\rho_s}\right)^2\right\}, \qquad \epsilon = \epsilon_s + p - p_s \tag{14}$$

The above formulae 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 [37] for the region of the crystalline lattice of heavy metals, and below this, that of Harrison and Wheeler [38] for the range of the crystalline lattice of light metals and electron gas, as described in ref.[39]. It should be noted that ρ is really only a parameter in the above equation of state, and plays no role whatsoever in the structure of the star, which depends only on $p = p(\epsilon)$.

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 1470 models whose parameters were all the combinations of the following values:

$$\begin{aligned} K &= 50, 80, 100, 150, 200, 300\text{MeV} \\ \gamma &= 2, 2.5, 3, 3.5, 4 \\ f &= 0, -.2, -.5, -1, -1.5, -2, -2.5, -3 \\ \rho_c/\rho_0 = 3, &\quad \Delta/\rho_0 = 1 \\ \rho_c/\rho_0 = 4, &\quad \Delta/\rho_0 = 1, 1.5 \\ \rho_c/\rho_0 = 5, &\quad \Delta/\rho_0 = 1, 1.5, 2 \end{aligned} \tag{15}$$

The results of this search are stated in the main text.

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