LBL-29101

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Precis of an Invited Paper presented at American Physical Society, Joint Symposium of Nuclear Physics and Astrophysics, Washington, April 16–18, 1990, and American Chemical Society, Symposium on Nuclear Astrophysics, Boston, April 22–27, 1990

Fast Pulsars, Strange Stars: An Opportunity in Radio Astronomy

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July 1990

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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Fast Pulsars, Strange Stars: An Opportunity in Radio Astronomy†

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†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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Abstract

The world's data on radio pulsars is not expected to represent the underlying pulsar population because of a search bias against detection of short periods, especially below 1 ms. Yet pulsars in increasing numbers with periods right down to this limit have been discovered suggesting that there may be even shorter ones. If pulsars with periods below 1/2 ms were found, the conclusion that the confined hadronic phase of nucleons and nuclei is only metastable would be almost inescapable. The plausible ground state in that event is the deconfined phase of (3-flavor) strange-quark-matter. From the QCD energy scale this is as likely a ground state as the confined phase. We show that strange matter as the ground state is not ruled out by any known fact, and most especially not by the fact that the universe is in the confined phase.

PACS 97.60.Gb, 12.38.Mh, 97.60.Jd, 12.38.Aw

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There is presently no evidence to support the commonly held assumption, apparently anthropocentric, that the confined hadronic phase of individual nucleons and nuclei is the absolute ground state of the strong interaction. The fact that most of the mass in every object that we know, from our own bodies to all the visible galaxies resides in nucleons and nuclei tells us for certain only that this is a possible phase of matter and that it is very long lived; not necessarily that it is the lowest energy one. How misleading the present composition is in revealing the nature of the ground state is immediately exposed by noting that the lowest energy state of the confined phase is Fe^{56} and there is very little of that in the universe. From the QCD energy scale it is quite plausible that the deconfined (3-flavor) strange-quark-matter phase is lower in energy[1, 2], and we show that the present upper limit on the abundance of strange nuggets in the earth's crust does not rule out this possibility. Indeed the universe would be almost identical in either case. We are only just now entering an era in which advances in technology may allow the detection of the subtle signals that might be present if the universe exists in a metastable phase, albeit long-lived, instead of the ground state. The most promising signals, both from the point of view of prospects for their existence as well as for their detection, are submillisecond pulsars. The shorter the period of rotation the more secure the conclusion that the universe is in a metastable phase of matter[3, 4].

Of course the assumption that the confined hadronic phase is the ground state cannot be realistically challenged by resort to specific models of the equation of state of dense nuclear matter, nor of quark matter, but rather by use of model independent limits, and when it is necessary to invoke models of matter, by exploration of the most general forms subject only to the minimal generally accepted constraints. Our approach within this framework is to exhibit the difficulties and contradiction encountered in trying to understand very rapid rotation of pulsars if they are assumed to be neutron stars. We then show how these are naturally resolved under the assumption that strange matter is the absolute ground state.

1 Bias against short periods of present pulsar surveys.

As of this writing there are ten known millisecond pulsars with periods ranging between 1.6 ms to 7.9 ms, all of them discovered recently, and of course 400 others, with a mean period of 700 ms and a maximum period of 4 s. What is not generally realized however is that searches for radio pulsars are biased, being least sensitive to short periods[5]. The bias exists because of compromises involving choices of sampling rates of the radio signal, number of frequency channels, the sophistication of the algorithm for correcting the data because of the differential dispersion of the radio frequencies in the bandwidth of the receiver caused

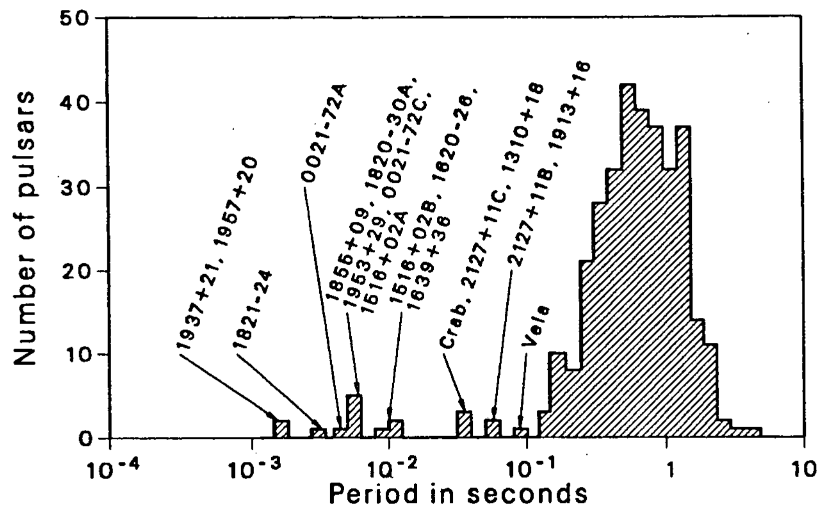

Figure 1: Distribution of pulsar periods. There is a relatively strong attenuation in sensitivity of radio pulsar surveys for periods below about 1 ms. Pulsars are identified by their celestial coordinates.

by the unknown column height of the interstellar plasma, the number of iterations over such corrections and the Fourier analysis of the corrected data that has to be carried out at each stage. Therefore the world's data on radio pulsars does not represent the underlying population because of this search bias against detection of short periods, especially below 1 ms[6], and most of the large surveys have had no sensitivity below about 4 ms[5]. And empirically fast pulsars are seen only at radio frequencies. The cutoff in short periods that appears in Fig. 1 is therefore possibly only an artifact of the search sensitivity. The growing number of pulsar discoveries with periods right down to the cutoff suggests that this is so and presents a special opportunity and challenge to radio astronomy! For while the discovery of additional millisecond pulsars is exciting, both because of their novelty and for what they may reveal of the evolutionary processes involved in their creation and the environment of galactic globular clusters, which are now understood to provide an environment that is especially favorable for the incubation of fast pulsars[7], the discovery of a single submillisecond pulsar, say below 1/2 ms, addresses the fundamental issue of the ground state, and would provide strong if not conclusive evidence that we inhabit a metastable phase.

2 Difficulty in reconciling fast pulsars with neutron stars.

The relevance of fast pulsars is easily understood in terms of their stability against mass loss, expressed as the dominance of gravity over centrifuge,

$$\Omega < \Omega_K \approx \alpha\sqrt{GM/R^3}, \tag{1}$$

where Ω is the angular velocity, and $\alpha \approx 0.65$ is an empirical GR correction to Newtonian physics[8]. This places a model independent constraint on the *average* energy density of the star. In actual stars the density increases monotonically toward the center. To discover the implication of fast rotation on the *central* density of the star, we must solve Einstein's equations for star structure using computed or hypothetical equations of state. For very high central densities, it is expected that matter consisting of individual nucleons will dissolve into quark matter, of which strange quark matter, an approximately equal mixture of u,d,s quarks, is lower in energy than non-strange 2-flavor quark matter. The problem resolves itself into understanding at what rotational period, stability requires a central density that exceeds the phase transition density. For this purpose we carried out an exhaustive grided search, similar to our earlier one [9], over a flexible parameterization of the equation of state that is constrained only by causality, its smooth matching to the sub-nuclear equation of state[10, 11] and the requirement that the maximum mass neutron star be at least $1.44M_{\odot}$. The result is summarized in Fig. 2, of a search over more that 1400 models of the equation of state spanning a broad spectrum of behavior from soft to stiff at low density and independently at high, and including first or second order phase transitions representing pion or kaon condensates, for example, subject only to the above minimal constraints. The least central density required by the condition of stability to rotation is shown as a function of rotation period. Particular theories of nuclear matter can yield results that lie above or on this curve, but not below! So as to be conservative, we have included the effect of gravitational radiation-reaction instabilities as a reduction in the Kepler frequency, $\Omega_{GR} = \beta\Omega_K$, at the *minimum* estimate, $\beta = 0.91$ [12]. The correction may be much larger, like $\beta \approx 0.7$, for realistic neutron star models[13]. Two important conclusions can be reached. Pulsars with periods longer than 1 ms can be understood as neutron stars having modest central densities as low as three times nuclear density. In contrast, pulsars with periods shorter than 1/2 ms must have very high central densities if they are bound only by gravity, as is the case for neutron stars since neutron matter is unbound, and so is nuclear matter above about A=250. For such short periods the density must be so high as to render implausible the contention that the star is composed of individual nucleons. We do not know from experiment at what density the phase transition to quark matter occurs, and we have no guide yet from lattice QCD simulations. But from geometric considerations it is implausible that nucleons survive at densities above a few times nuclear density[4].

The minimum rotation period found in the exhaustive search over equations of state was 0.42 ms. The dotted curve in Fig. 2 is merely an extrapolation. It appears that no star *bound only by gravity* can have $P < 0.4$ ms. These figures for the period correspond to the conservative estimate of GR instabilities. While we wish to be conservative in arriving at our conclusions, we also want to stress that for realistic equations of state the GR instabilities increase the scale of the period axis in Fig. 2 by about a factor 1.3 [13].

The least drastic conclusion that we can draw if pulsars with periods in the range $0.4\text{ms} \leq P \leq 0.5\text{ms}$ are discovered, is that they are neutron stars with quark cores, what we have called hybrid stars[9]. In the core of such stars the nucleons are dissolved into quarks by the high pressure induced by gravity. Such stars could exist if the confined phase is the ground state; they are bound only by gravity. Consequently the radius-mass relation is of the *generic* form shown in Fig. 3. For low masses, where the gravitational attraction is weak, the star is large. For higher masses, near the limit for collapse to a black hole, the radius decreases very rapidly with increasing mass. For such stars, only those very close to the mass limit can rotate rapidly because there the radius is least and the mass greatest (see Eq.(1)). In other words, a very rapidly rotating neutron or hybrid star must be very finely tuned in mass, or equivalently baryon number. Therefore if two very fast pulsars of about the same period but different masses are found, both cannot be a star bound only by gravity, that is to say a neutron or hybrid star. However, there are theoretical grounds to doubt that hybrid stars are plausible candidates for fast pulsars, but no proof at this time[14, 15].

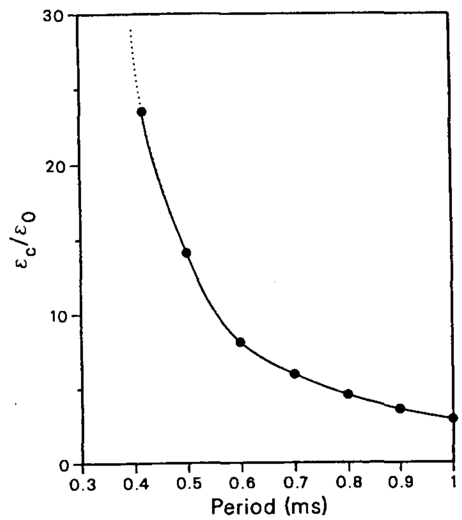

Figure 2: Least central density of 'neutron' star as a function of shortest stable rotation period. Each dot represents a 'neutron' star whose equation of state satisfies constraints described in the text and has least possible central density, ϵ_c, consistent with stability down to the rotational period shown, including GR instabilities.

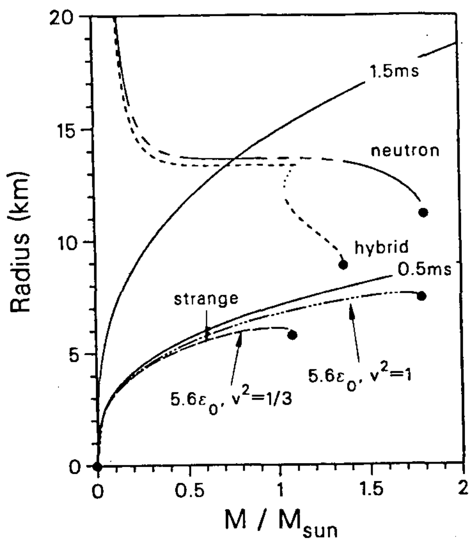

Figure 3: Generic relations for compact stars bound by only by gravity (neutron and hybrid) and stars made of self-bound matter (strange). Stars below solid lines can rotate at or faster than the indicated period. Equation of state for strange matter parameterized as $\epsilon = p/v^2 + \epsilon_b$, and star families labeled by value of ϵ_b and v^2.

Very briefly, the attributes of an equation of state that would allow a star bound only by gravity to have stable rapid rotation is that it be soft at low and intermediate density, and very stiff at high, at or near the causal limit. The last requirement seems incompatible with the notion of asymptotic freedom in the deconfined phase. In view of the difficulties, the implausibly high density for neutron matter, the stiffness at high density required of the equation of state that seems incompatible with quark matter, the fine tuning in mass of the star so as to place it close to the termination point, all of which arise in trying to reconcile a star that is bound only by gravity with fast rotation, an altogether different possibility needs to be examined.

3 Strange quark stars.

We know that non-strange quark matter is higher in energy per baryon than nuclear matter, otherwise nuclei would decay promptly into it. It must be higher by about the QCD energy scale, ~ 100 MeV, established by lattice simulations. As a rough estimate treat the quarks as a Fermi gas. The energy density scales as $\epsilon \sim \gamma\mu^4$ and the baryon density as $\rho \sim \gamma\mu^3$, where γ is the degeneracy, 2 or 3. Comparing the two types of quark matter at the same baryon density, then $\mu \sim \gamma^{-1/3}$ so that 3-flavor quark matter has an energy per baryon, ϵ/ρ, of about a factor $(2/3)^{1/3} \sim 0.9$ times that of 2-flavor, or about 100 MeV *lower*. That places 3-flavor quark matter at about the same energy as nuclear matter. However, even if strange matter is lower in energy, ordinary nuclei can decay into the strange quark phase phase only on a time scale long in comparison with the age of the universe, since it is inhibited by the need for A *simultaneous* strangeness changing weak interactions where A is the atomic number[2]. This is because it is energetically unfavorable for the transition to take place one quark at a time since this would only produce hypernuclei.

If strange-quark matter is self-bound and absolutely stable as as has been suggested[1, 16], the structure of compact stars made of it would be entirely different from that discussed above[1, 17, 18]. For strange stars gravity merely prevents them from fissioning into smaller bodies, and of course imposes a mass limit: they are otherwise bound by the strong interaction. Denote the normal energy density of such matter, the density at which the internal pressure vanishes, by ϵ_b. A small nugget therefore has mass $M = \frac{4}{3}\pi R^3 \epsilon_b$, so that, unlike neutron stars, or more generally stars bound only by gravity, the mass radius relation for small mass is $R \propto M^{1/3}$, and has a *generically* different form as shown in Fig. 3. Therefore the entire family of strange stars can rotate rapidly, not just those near the limit of collapse to a black hole[4], since for such a radius-mass relation the expression for the Kepler frequency, Eq.(1), is a constant for low mass stars and changes for those near the mass limit only in the sense of increasing. Also from Eq.(1) we can derive a condition on the normal density of self-bound stable matter that will allow all such stars to rotate with period P: [14]

$$\epsilon_b \geq \frac{3}{4\pi G}\left(\frac{\Omega}{\alpha}\right)^2 = 1.3\epsilon_0\left(\frac{\mathrm{ms}}{\mathrm{P}}\right)^2. \tag{2}$$

For example, all strange stars can rotate with $P = 1/2$ ms if $\epsilon_b > 5.2\epsilon_0$ (where $\epsilon_0 = 2.5 \times 10^{14}\mathrm{g/cm}^3$ is normal nuclear density). Gravitation radiation-reaction instabilities are unimportant for quark stars because of the expected high viscosity[19], so the correction β quoted earlier for neutron stars does not need to be applied. Thus three problems are solved if strange quark matter is the ground state; very short periods are possible, below 0.4 ms, provided only that the normal density satisfies the above model independent relation, high central densities as required by fast rotation are natural for quark matter and a star does not have to be finely tuned in mass to be stable at very fast rotation.

Based on the bag model of confinement and the range placed on its parameters by the condition that strange quark matter is the ground state, several authors have asserted that strange stars cannot rotate very rapidly[15, 20, 21] or can do so only marginally[22]. There is an unfortunate confusion in logic there in translating a statement that is true of a crude model to a statement about nature. We have emphasized elsewhere that whether or not strange stars can rotate very rapidly is entirely an experimental question, not a theoretical one[4]. For to determine on theoretical grounds whether the energy per nucleon in strange matter lies below that in Fe^{56} with $E/A = 930$ MeV, which would make it absolutely stable, or lies above the nucleon mass at 939 MeV, would require one percent accuracy, an accuracy certainly not possessed by the bag model, nor indeed by lattice QCD now or in the foreseeable future. Neither theory nor confinement models can rule out the hypothesis that strange matter is stable, nor conversely can they be used to assert that it is.

If the hypothesis is true, then some or all pulsars may be strange stars rather than neutron stars. Strange stars can be produced in at least two ways[23, 24]. If the density in the core of the more massive neutron stars exceeds the transition density to quark matter, the core will spontaneously convert to non-strange quark matter. In turn, this will weak decay to strange matter, and then conversion of the entire star will occur on a short time scale. If a nugget of strange matter falls into a star, it will gravitate to the center and lie dormant until the star collapses. When the density exceeds the neutron drip density, the nugget will begin to grow, and convert the entire neutron star produced in the supernova. It is possible that the universe is sufficiently contaminated by strange nuggets, whose abundance is discussed in the next section, that the second process will always preempt the first.

4 Strange matter as ground state is compatible with observation.

If strange stars exist, there will be present on earth some abundance of strange nuggets accumulated as cosmic rays over the earth's lifetime. We now estimate an upper limit to see if strange matter as the ground state is ruled out by present experimental limits. From 16 years of observations on the binary pair of compact stars with celestial coordinates 1913+16, the decay of the binary orbit has confirmed Einstein's gravitational radiation to an accuracy of less than one percent[25]. Eventually the decay of this orbit will cause the compact stars to collide, and some fraction of their material will be injected into the galaxy. The decay time is short compared to the galactic age. In our estimate of the abundance of such material that has accumulated on earth, we employ accepted cosmological figures for those items that are available, and overestimates of others, so as to get an upper bound on the concentration of strange nuggets. For this purpose we need the age of the galaxy (10^{10} years), the frequency of type II supernovae (1/(100 yr)) [26], the fraction of pulsars that occur in binary compacts ($< 1/100$), the fraction of mass ejected from a collision (1/10) [27]. We find a mass density of debris from compact star collisions of $< 10^{-29}$g/cm^3. (For the volume of the galaxy in which the ejecta is contained we take $\pi \times 8^2 \times 2$ kpc^3). As an extreme overestimate, assume that all such compacts were strange and that all mass is ejected in minimum mass fragments ($A \approx 1000$ [2]). We find a number density of strange nuggets of $< 10^{-8}$/cm^3. Assuming a typical galactic velocity of 10^7 cm/s, there would be an influx of $< 10^{15}$/cm^2 over the age of the earth. (However, the velocity assumed corresponds to the measured typical velocity of pulsars transverse to the galactic plane[28]. If the isotropic component is less, then our flux is an overestimate.) The earth's crust is not tranquil. Mountains are cast up and then eroded, continents drift, tectonic plates collide, slide one over the other. Material that can be recognized as once having been at the earth's surface, resurfaces in the lava of volcanic eruptions, having been subducted to the molten core below the mantle[29]. Estimating a geologic mixing depth of the order ten kilometers, a very conservative one, then even if all such nuggets were stopped at the surface, they would be diluted to a concentration of $< 10^9$/cm^3 or less over geologic times, or $<< 10^{-15}$ nuggets per nucleon. This *extreme* overestimate falls short of the upper limit established by experiment of 10^{-14}[30]. The hypothesis cannot be ruled out by present experimental limits on the abundance of strange nuggets in the earth's crust!

It has been understood for several years that even if strange matter is the lowest energy state when cold, and that the early universe passed through this phase, it was so hot at the time that strange matter would have evaporated into hadrons[23, 31]. Little if any primordial material is expected to have survived. For these reasons and those developed in the preceding paragraphs we understand that the universe would have evolved along essentially the same path and aside from very subtle signals would appear the same now, no matter which is the ground state. Only at the death of massive stars when dense matter that is cold on the nuclear scale is produced in the resulting neutron stars, may conditions for the creation of *cold* strange matter occur for the first time. Whether such conditions have *ever* been achieved depends on the unknown phase transition density, and whether it has been reached in the core of any neutron star.

5 Motivation for submillisecond pulsar searches.

It is not possible to prove that the ordinary confined hadronic phase of nucleons and nuclei is the ground state. It can only be disproved with the discovery of a lower one. As remarked, the QCD energy scale makes strange matter an equally plausible ground state. A strong indication that it is so would be the discovery of submillisecond pulsars, especially several of different masses. While mass measurements are scarce, we note that the recent discoveries in globular clusters and the expected high population of fast binary pulsars in them may change this situation dramatically. It could of course be a coincidence that the lower limit on the period sensitivity of radio pulsar surveys, resulting from the particular compromises chosen in present day searches, matches the *actual* cutoff in pulsar periods. But the accelerating discovery rate of millisecond pulsars *with periods right down to the limit of present day sensitivity* suggests the tantalizing prospect that there are even faster ones. Improvement of the sensitivity is not beyond present technology and as physicists and astronomers we may learn as a result something that we do not know but ought to, the structure of the true ground state of the strong interaction.

6 Accelerator searches for strange nuggets.

Having motivated, hopefully, a search for submillisecond pulsars, we wish to affirm the importance of accelerator based attempts[32, 33] to produce strange nuggets in relativistic nuclear collisions[34, 35]. These are long-shot experiments: the dense matter produced for $\approx 10^{-22}$ s is hot and has no time to develop a net strangeness. Strange nuggets, if strange matter is stable, could be produced only as the result of two types of simultaneous fluctuations that separate strange and anti-strange quarks, and that also cool the nugget so that it does not evaporate. Moreover the number of quarks accessible to nuclear collisions may be too small to defeat the finite number destabilizing effects[2]. Cross sections in any case will be very small. But the production and capture of a strange nugget, besides being incontrovertible evidence, may prove important as a compact energy source[36]. So while the astronomical prospects for discovery of strange matter appear better to us, the practical consequences of laboratory production are potentially enormous.

Acknowledgements: I appreciate discussions with D. C. Backer, Astronomy, UC at Berkeley, on pulsar searches and B. M. Smith, Earth Sciences Division, LBL, Berkeley, on geologic mixing of material in the earth's crust. 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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