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Fast Pulsars, Strange Stars

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1 Introduction

The initial motivation for this work was the reported discovery in January 1989 of a 1/2 millisecond pulsar in the remnant of the spectacular supernova, 1987A. The status of this discovery has come into grave doubt as of data taken by the same group in February, 1990. At this time we must consider that the millisecond signal does not belong to the pulsar. The existence of a neutron star in the remnant of the supernova is suspected because of recent observations on the light curve of the remnant, and of course by the neutrino burst that announced the supernova. However its frequency is unknown.

I have had a second motivation for some time, which now becomes the single one, and it is quite strong. Spectacular advances in technology in the last few years have revolutionized all sciences, and perhaps no one more dramatically than astronomy. These include both space based and ground observation. Of particular relevance to my topic is the rapidity with which millisecond pulsars are being discovered. It was only twenty three years ago that the first pulsar was discovered, and for many years thereafter the fastest one known was the Crab, with a period of 33 ms. Then in 1982, at a time when about three hundred pulsars had been found, the first truly millisecond pulsar was discovered, with period $P = 1.56$ ms. Since then there have been eight additional discoveries and altogether 18 with periods $P < 100$ ms, that is to say in the extreme tail of the distribution whose mean is about 0.7 seconds, as shown in Fig.1. The discovery frequency is therefore between one and two a year and increasing. Why am I so excited by these prospects? Because I can make a strong case that a pulsar rotation period of about 1 ms divides those that can be understood quite comfortably as neutron stars, and those that cannot. What we will soon learn is whether there is an invisible boundary below which pulsar periods do not fall, in which case, all are presumably neutron stars, or whether there exist sub-millisecond pulsars, which almost certainly cannot be neutron stars. Their most plausible structure is that of a self-bound star, a strange-quark-matter star. The existence of such stars would imply that the ground state of the strong interaction is not, as we usually assume, hadronic matter, but rather strange quark matter. Let us look respectively at stars that are bound only by gravity, and hypothetical stars that are self-bound, for which gravity is so to speak, icing on the cake.

2 Stars bound only by gravity

Fast rotation places a limit on the mean density of a star, and conversely for any given star, or equation of state, there is an absolute upper limit on the rotation frequency imposed by stability to mass loss at the equator, the Kepler frequency. Other general relativistic instabilities lower the limit to about 90 percent of the Kepler frequency. I have carried out a general study of the attributes of the equation of state and star that will allow it to rotate very rapidly. A full report of this work has been given elsewhere [1]. A grided search over more than 1400 models of the equation of state in a very flexible parameterization, which included the possibility of a first or second order phase transition was performed. Here I merely summarize the results. As general attributes of the equation of state it must be soft at low or intermediate density and very stiff at high density, at or near the causal limit. Such equations of state seem unphysical in the sense that physical systems exploit processes that lower the energy [2, 3] 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

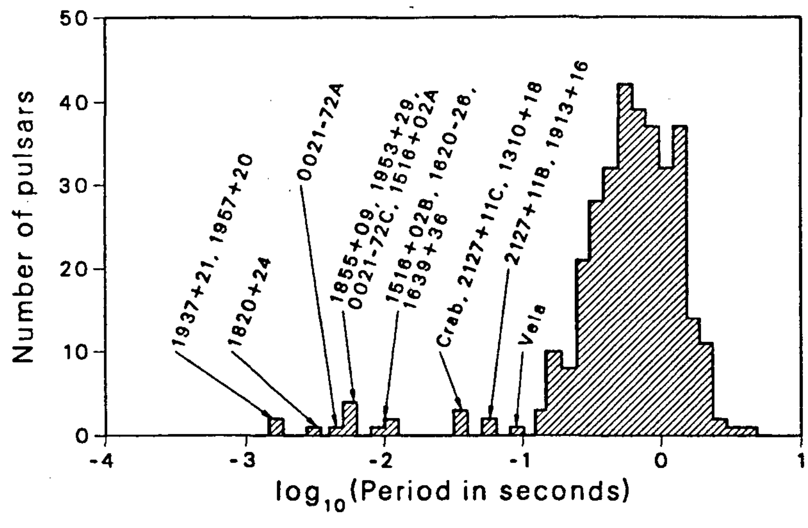

Figure 1: Distribution of pulsar periods.

looking for a central density that is low enough to make a description in terms of hadrons seem plausible. Moreover, the minimum central density of a star that is bound only by gravity and can withstand fast rotation at 1/2 ms is 13.2 ϵ_0 if GR instabilities are ignored, and 16 ϵ_0 if account of them is taken. It is implausible that matter at such a high multiple of nuclear density can consist of individual hadrons!

2.1 Generic relations for neutron stars

Let us 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 [2]. In Fig.2 we show the mass-radius relationship that is typical of a neutron star, whose only binding force is gravity. This is the typical and inevitable relationship when gravity alone binds the star; for small mass, gravity is weak and the star large, for large mass, gravity is strong and the star small. The termination point for collapse to a black hole is marked by a dot. Note that the mass of the neutron star, or in other words its baryon number, $A \sim M/m$, must be very precisely tuned to achieve the fastest rotation while remaining stable to mass loss at the equator.

2.2 Hybrid stars

We have learned that to satisfy the double constraint of 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?

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 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 seem to be incompatible with the findings of this study. Since the binding of the star is provided by gravity alone, the mass-radius relation has the generic form discussed before (see Fig.3).

2.3 Conclusions for stars bound only by gravity

To satisfy the double constraint of sufficient limiting mass and stability to fast rotation we are led to conclude that;

1. The equation of state must be soft at low density and stiff at high.

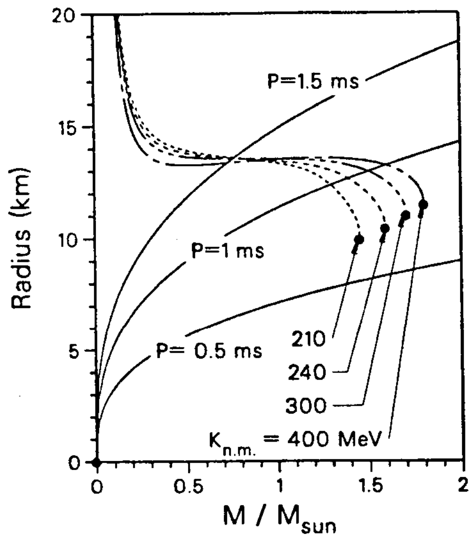

Figure 2: Generic relation for neutron stars for several equations of state as labeled according to compression of ***nuclear matter.*** The limits imposed by a 1.5, 1.0 and 0.5 ms pulsar are shown. Stars below these curves are stable for still shorter periods.

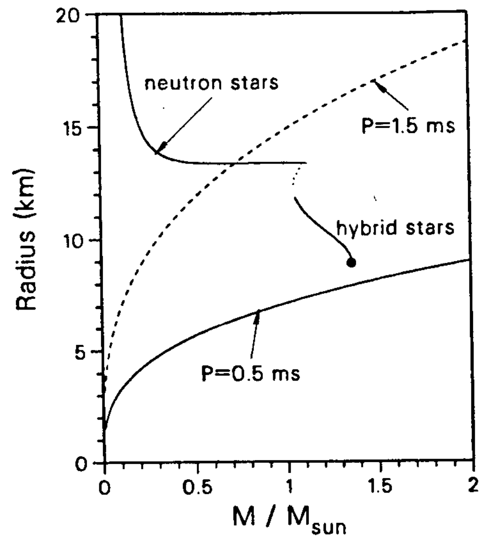

Figure 3: Hybrid stars with a first order phase transition between hadron and quark phases (dotted region between solid lines are unstable mixed phase).

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.

To account for a collapsed star with sub-millisecond period that is bound only by gravity we arrive at an impasse. Perhaps the assumption that the star is bound only by gravity leads us into all these difficulties!

3 Self-Bound Stars

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 [4] 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 nuclei would have an expected lifetime exceeding the age of the universe by far, Witten's hypothesis does not violate our experience. However, it is not possible to decide on theoretical grounds whether ordinary matter or strange matter is stable. Lattice QCD cannot be solved with sufficient accuracy. For example, to decide whether the energy per baryon in strange matter is less than it is in Fe^{56} (930.4 MeV) or greater than the proton mass (938.3 MeV) requires an accuracy of less than one percent. At best theory can give us guidance at the ten percent level (100 MeV)! Since neither assumption contradicts any known fact, we must look to experiment and astrophysical observation for the answer, 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 [5, 6]. Because strange matter is self-bound, say at energy density ϵ_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.4. We show three

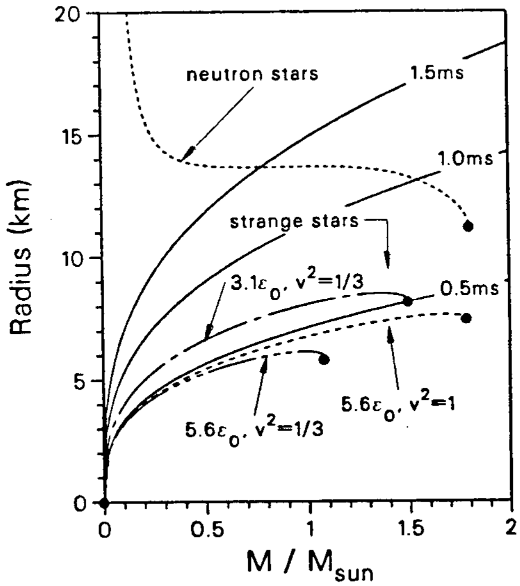

Figure 4: The mass-radius relation for a typical neutron star equation of state and for strange quark matter cases. The solid lines denote limits for the 1.5, 1.0 and 0.5 ms pulsars. Stars below these lines respectively are stable for shorter periods of rotation. [7, 8]

strange star sequences marked according to the value of the self-binding energy density ϵ_b. If $\epsilon_b > 5.4\epsilon_0$ the whole family of strange stars can rotate at $P = 1/2$ ms. 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. 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.

We have come to some remarkable conclusions [7, 8]! In addition to those enumerated earlier,

6. All known pulsar masses and periods 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 ϵ_0 [1].

7. The hypothesis that most comfortably would fit a submillisecond pulsar 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 $5.4\epsilon_0$.

4 Cosmological considerations

If strange-quark matter is the true ground state, why have we not known about it? In fact when one looks in detail at this question one finds that the universe would be imperceptibly different whether the ground state is hadronic or quark matter. Virtually no primordial nuggets are expected; strange-quark-matter would have evaporated at the high temperatures of the early universe. Strange stars, if sub-millisecond pulsars are discovered would indicate that strange matter is the ground state as would the discovery of stable strange nuggets in laboratory relativistic collisions. Here I look at cosmological evidence. If strange matter is the ground state and if the density in the heavier neutron stars is high enough to convert the core to quark matter, the entire star will rapidly convert to strange- quark-matter. About 1/100 compact stars are in binaries in which both partners are compact. Since all orbits decay by gravitational radiation (eg. PSR1913+16), these compacts will ultimately collide, and some material may be expelled into the galaxy. In mildly relativistic head on collisions of compact stars it is expected that 1/10 of the mass will be expelled. This provides an extreme upper limit for decay of a binary. Taking account of the frequency of type II supernova ($\sim$ 1/40/year), the age of the galaxy (10^{10} yr), and the fraction of compacts that are in binary compacts, we can estimate the amount of such debris in the galaxy as $10^5 M_\odot$, a surprisingly large fraction of the mass of the galaxy ($10^{11} M_\odot$). The corresponding density of debris is about 10^{-30} g/cm^3. (The volume of the galaxy is about 10^{68} cm^3). As an extreme overestimate we can assume that all debris is in strange nuggets and that all nuggets produced in star collisions have the minimum mass while remaining massive enough to be stable ($A \sim 1000$). We find 10^{59} nuggets. With a typical galactic velocity of 10^7 cm/sec, we can calculate a flux, and find the number/cm^2 striking the earth over its lifetime. Matter mixes to a considerable depth over geologic times. Assume a mixing depth of 1 km. We find a density of nuggets of $\sim 10^7$/cm^3, or a ratio of nuggets to nucleons of 10^{-17}. This is an extreme upper limit, which lies below the upper bound presently imposed by experiment (10^{-14}) [9], and it is problematical that a sufficiently sensitive experiment can be designed to detect such a feeble ratio. In this way we see how imperceptibly different the galaxy would appear, whichever is the ground state, hadronic or strange quark matter!

5 Outlook

Given the present discovery rate of millisecond pulsars, within the next few years we can anticipate sufficient data to provide evidence concerning the fundamental question as to the nature of the true ground state. The accumulated evidence will either provide a statistical basis for doubting that sub-millisecond pulsars exist, or one or more such pulsars will be discovered. Laboratory searches for strange debris from star collisions seem impractical unless samples can be identified that would be enriched, such as perhaps moon rock. Searches in relativistic collisions are underway, but the production of cold strange nuggets depends on fluctuations. It appears that the best chance of deciding this arcane but fundamental issue is through the search for fast pulsars.

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