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QUARK MATTER, MASSIVE STARS AND STRANGE PLANETS

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This paper gives an overview of the properties of all possible equilibrium sequences of compact strange-matter stars with nuclear crusts, which range from strange stars to strange dwarfs. In contrast to their non-strange counterparts, -neutron stars and white dwarfs-, their properties are determined by two (rather than one) parameters, the central star density and the density at the base of the nuclear crust. This leads to stellar strange-matter configurations whose properties are much more complex than those of the conventional sequence. As an example, two generically different categories of stable strange dwarfs are found, which could be the observed white dwarfs. Furthermore we find very low-mass strange stellar objects, with masses as small as those of Jupiter or even lighter planets. Such objects, if abundant enough in our Galaxy, should be seen by the presently performed gravitational microlensing searches. Further aspects studied in this paper concern the limiting rotational periods and the cooling behavior of neutron stars and their strange counterparts.

1 Introduction

The theoretical possibility that strange quark matter may be absolutely stable with respect to iron (energy per baryon below 930 MeV) has been pointed out by Bodmer¹, Witten², and Terazawa³. This so-called strange matter hypothesis constitutes one of the most startling possibilities of the behavior of superdense nuclear matter, which, if true, would have implications of greatest importance for cosmology, the early universe, its evolution to the present day, astrophysical compact objects, and laboratory physics⁴. Unfortunately it seems unlikely that QCD calculations will be accurate enough in the foreseeable future to give a definitive prediction on the absolute stability of strange

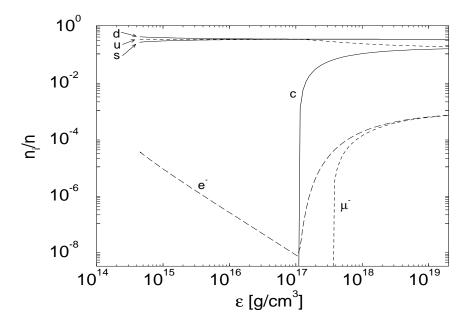


Figure 1: Relative densities of quarks and leptons in absolutely stable strange-quark-star matter versus density. n_i and n denote partial and total densities, respectively.

matter, such that one is left with experiments and astrophysical tests, as performed here, to either confirm or reject the hypothesis.

One striking implication of the hypothesis would be that pulsars, which are conventionally interpreted as rotating neutron stars, almost certainly would be rotating strange stars (strange pulsars). Part of this paper deals with an investigation of the properties of such objects. In addition to this, we develop the complete sequence of strange stars with nuclear crusts, which ranges from the compact members, with properties similar to those of neutron stars, to white-dwarf-like objects (strange dwarfs) and discuss their stability against acoustical vibrations⁵. The properties with respect to which strange-matter stars differ from their non-strange counterparts are discussed.

2 Quark-lepton Composition of Strange Matter

The relative quark–lepton composition of quark-star matter at zero temperature is shown in Fig. 1⁶. All quark flavor states that become populated at the densities shown are taken into account. Since stars in their lowest energy state

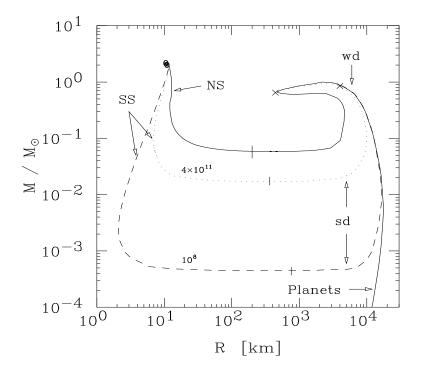


Figure 2: Neutron star (NS)–white dwarf (wd) sequence (solid line). The dotted and dashed curves refer to strange star (SS)–strange dwarf (sd) sequences with inner crust densities as indicated (in g/cm³). Vertical bars mark minimum mass stars, crosses mark the termination points of the strange star sequences.

are electrically charge neutral to very high precision, any net positive quark charge must be balanced by leptons. In general, as can be seen in Fig. 1, there is only little need for leptons, since charge neutrality can be achieved essentially among the quarks themselves. The concentration of electrons is largest at the lower densities of Fig. 1, due to the finite strange-quark mass which leads to a deficit of net negative quark charge, and at densities beyond which the charm-quark state becomes populated which increases the net positive quark charge.

3 Nuclear Crusts on Strange Stars and Equation of State

The presence of electrons in strange quark matter is crucial for the possible existence of a nuclear crust on such objects. As shown in Refs.^{6,7}, the electrons,

because they are bound to strange matter by the Coulomb force rather than the strong force, extend several hundred fermi beyond the surface of the strange star. Associated with this electron displacement is a very strong electric dipole layer which can support – out of contact with the surface of the strange star – a crust of nuclear material, which it polarizes. The maximal possible density at the base of the crust (inner crust density) is determined by the neutron drip density ($\epsilon_{drip} = 4.3 \times 10^{11} \text{ g/cm}^3$), at which neutrons begin to drip out of the nuclei and form a free neutron gas. Being electrically charge neutral, the neutrons do not feel the repulsive Coulomb force and hence would gravitate toward the quark matter core, where they become converted, via hypothesis, into strange quark matter. So neutron drip sets a strict upper limit on the crust's maximal inner density.

The somewhat complicated situation of the structure of a strange star with crust can be represented by a proper choice of equation of state⁸, which consists of two parts. At densities below neutron drip it is represented by the low-density equation of state of charge-neutral nuclear matter, for which we use the Baym-Pethick-Sutherland equation of state. The star's strangematter core is described by the bag model. The graphical illustration of such an equation of state can be found in Ref.⁸.

4 Complete Sequences of Strange-Matter Stars

Since the nuclear crusts surrounding the cores of strange stars are bound by the gravitational force rather than confinement, the mass-radius relationship of strange-matter stars with crusts is qualitatively similar to the one of purely gravitationally bound stars –neutron stars and white dwarfs–, as illustrated in Fig. 2^{5,9}. The strange-star sequences are computed for the maximal possible inner crust density, $\epsilon_{\rm crust} = \epsilon_{\rm drip}$, as well as for an arbitrarily chosen, smaller value of $\epsilon_{\rm crust} = 10^8$ g/cm³, which may serves to demonstrate the influence of less dense crusts on the mass-radius relationship⁵. From the maximum-mass star (dot), the central density decreases monotonically through the sequence in each case. The neutron-star sequence is computed for a representative model for the equation of state of neutron star matter, the relativistic Hartree-Fock equation of state of Ref. ¹⁰, which has been combined at subnuclear densities with the Baym-Pethick-Sutherland equation of state. Hence the white dwarfs shown in Fig. 2 are computed for the latter. The gravitationally bound stars with radii ≤ 200 km or ≥ 3000 km represent stable neutron stars and white dwarfs, respectively.

The fact that strange stars with crusts tend to possess somewhat smaller radii than neutron stars leads to smaller rotational mass shedding (Kepler) periods $P_{\rm K}$ for the former, as is indicated classically by $P_{\rm K} = 2\pi \sqrt{R^3/M}$. Of course the general relativistic expression,

$$P_{\rm K} \equiv 2\pi/\Omega_{\rm K}, \text{ with } \Omega_{\rm K} = \omega + \frac{\omega'}{2\psi'} + e^{\nu - \psi} \sqrt{\frac{\nu'}{\psi'} + \left(\frac{\omega'}{2\psi'}e^{\psi - \nu}\right)^2}, \quad (1)$$

which is to be applied to neutron and strange stars, is considerably more complicated. It is to be computed simultaneously in combination with Einstein's equations (see Ref. ⁵ for details and further references),

$$\mathcal{R}^{\kappa\lambda} - \frac{1}{2} g^{\kappa\lambda} \mathcal{R} = 8\pi \mathcal{T}^{\kappa\lambda}(\epsilon, P(\epsilon)), \qquad (2)$$

However the qualitative dependence of $P_{\rm K}$ on mass and radius as expressed by the classical expression remains valid. So one finds that, due to the smaller radii of strange stars, the complete sequence of such objects (and not just those close to the mass peak, as is the case for neutron stars) can sustain extremely rapid rotation⁵. In particular, our model calculations indicate for a strange star with a typical pulsar mass of ~ 1.45 M_{\odot} Kepler periods as small as $0.55 \lesssim P_{\rm K}/{\rm msec} \lesssim 0.8$, depending on crust thickness and bag constant^{8,5}. This range is to be compared with $P_{\rm K} \sim 1$ msec obtained for neutron stars of the same mass.

The minimum-mass configurations of the strange-star sequences in Fig. 2 have masses of about ~ 0.017 M_{\odot} (about 17 Jupiter masses) and $10^{-4} M_{\odot}$, depending on inner crust density. More than that, for inner crust densities smaller than 10^8 g/cm^3 we find strange-matter stars that can be even by orders of magnitude lighter than Jupiters. If abundant enough in our Galaxy, all these light strange stars could be seen by the gravitational microlensing searches that are being performed presently. Strange stars located to the right of the minimum-mass configuration of each sequence consist of small strange cores ($\lesssim 3$ km) surrounded by a thick nuclear crust, made up of white dwarf material. We thus call such objects strange dwarfs. Their cores have shrunk to zero at the crossed points. What is left is an ordinary white dwarf with a central density equal to the inner crust density of the former strange dwarf^{5,9}. A detailed stability analysis of strange stars against radial oscillations⁵ shows that all those strange-dwarf sequences that terminate at stable ordinary white dwarfs are stable against radial oscillations. Strange stars that are located to the left of the mass peak of ordinary white dwarfs, however, are unstable against oscillations and thus cannot exist stably in nature. So, in sharp contrast to neutron stars and white dwarfs, the branches of strange stars and strange dwarfs are stably connected with each other 5,9 .

Finally the strange dwarfs with $10^9 \text{ g/cm}^3 < \epsilon_{\text{crust}} < 4 \times 10^{11} \text{ g/cm}^3$ form entire new classes of stars that contain nuclear material up to $\sim 4 \times 10^4$ times denser than in ordinary white dwarfs of average mass, $M \sim 0.6 M_{\odot}$ (central density $\sim 10^7 \text{ g/cm}^3$). The entire family of such strange stars owes its stability to the strange core. Without the core they would be placed into the unstable region between ordinary white dwarfs and neutron stars⁹.

5 Thermal Evolution of Neutron Stars and Strange Stars

The left panel of Fig. 3 shows a numerical simulation of the thermal evolution of neutron stars. The neutrino emission rates are determined by the modified and direct Urca processes, and the presence of a pion or kaon condensate. The baryons are treated as superfluid particles. Hence the neutrino emissivities are suppressed by an exponential factor of $\exp(-\Delta/kT)$, where Δ is the width of the superfluid gap (see Ref.¹¹ for details). Due to the dependence of the direct Urca process and the onset of meson condensation on star mass, stars that are too light for these processes to occur (i.e., $M < 1 M_{\odot}$) are restricted to standard cooling via modified Urca. Enhanced cooling via the other three processes results in a sudden drop of the star's surface temperature after about 10 to 10^3 years after birth, depending on the thickness of the ionic crust. As one sees, agreement with the observed data is achieved only if different masses for the underlying pulsars are assumed. The right panel of Fig. 3 shows cooling simulations of strange quark stars. The curves differ with respect to assumptions made about a possible superfluid behavior of the quarks. Because of the higher neutrino emission rate in non-superfluid quark matter, such quark stars cool most rapidly (as long as cooling is core dominated). In this case one does not get agreement with most of the observed pulsar data. The only exception is pulsar PSR 1929+10. Superfluidity among the quarks reduces the neutrino emission rate, which delays cooling¹¹. This moves the cooling curves into the region where most of the observed data lie.

Subject to the inherent uncertainties in the behavior of strange quark matter as well as superdense nuclear matter, at present it appears much too premature to draw any definitive conclusions about the true nature of observed pulsars. Nevertheless, should a continued future analysis in fact confirm a considerably faster cooling of strange stars relative to neutron stars, this would provide a definitive signature (together with rapid rotation) for the identification of a strange star. Specifically, the prompt drop in temperature at the very early stages of a pulsar, say within the first 10 to 50 years after its formation, could offer a good signature of strange stars¹². This feature, provided it withstands a more rigorous analysis of the microscopic properties of quark matter,

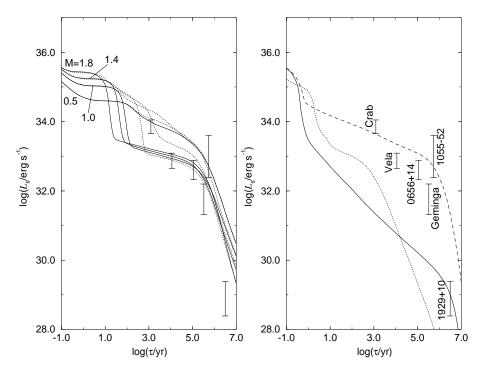


Figure 3: Left panel: Cooling of neutron stars with pion (solid curves) or kaon condensates (dotted curve). Right panel: Cooling of $M = 1.8 M_{\odot}$ strange stars with crust. The cooling curves of lighter strange stars, e.g. $M \gtrsim 1 M_{\odot}$, differ only insignificantly from those shown here. Three different assumptions about a possible superfluid behavior of strange quark matter are made: no superfluidity (solid), superfluidity of all three flavors (dotted), and superfluidity of up and down flavors only (dashed). The vertical bars denote luminosities of observed pulsars.

could become particularly interesting if continued observation of SN 1987A would reveal the temperature of the possibly existing pulsar at its center.

6 Summary

This work deals with an investigation of the properties of the complete sequences of strange-matter stars that carry nuclear crusts. The following items are particularly noteworthy:

1. The complete sequence of compact strange stars can sustain extremely rapid rotation and not just those close to the mass peak, as is the case for neutron stars!

- 2. If the strange matter hypothesis is correct, the observed white dwarfs and planets could contain strange-matter cores in their centers. The baryon numbers of their cores are smaller than $\lesssim 2 \times 10^{55}!$
- 3. The strange stellar configurations would populate a vast region in the mass-radius plane of collapsed stars that is entirely void of stars if strange quark matter is not the absolute ground state!
- 4. If the new classes of stars mentioned in (2) and (3) exist abundantly enough in our Galaxy, the presently performed gravitational microlensing experiments could see them all!
- 5. Due to the uncertainties in the behavior of superdense nuclear as well as strange matter, no definitive conclusions about the true nature (strange or conventional) of observed pulsar can be drawn from cooling simulations yet. As of yet they could be made of strange quark matter as well as of conventional nuclear matter.

Of course, there remain various interesting aspects of strange pulsars, strange dwarfs and strange planets, that need to be worked out in detail. From their analysis one may hope to arrive at definitive conclusion about the behavior of superdense nuclear matter and, specifically, the true ground state of strongly interacting matter.

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