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Strange-Matter Stars

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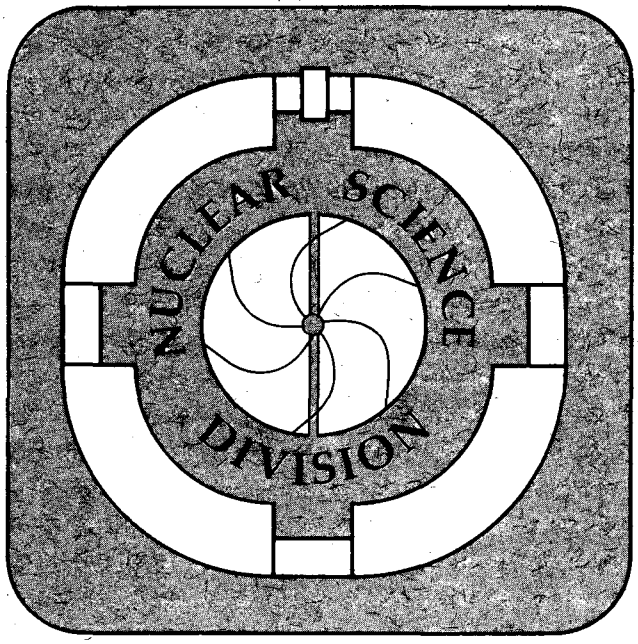

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Strange-Matter Stars*

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STRANGE-MATTER STARS

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ABSTRACT

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, should be seen by the presently performed gravitational microlensing searches.

1. Introduction

The theoretical possibility that strange quark matter may be absolutely stable with respect to iron, that is, the energy per baryon is below 930 MeV, has been pointed out independently by Bodmer[1] and Witten[2]. This so-called strange matter hypothesis constitutes one of the most startling ideas about the behavior of dense nuclear matter, which, if true, would have implications of fundamental importance for cosmology, the early universe, its evolution to the present day, astrophysical compact objects, and laboratory physics (for an overview, see Ref. [3]). Even to the present day there is no sound scientific basis on which one can either confirm or reject the hypothesis, so that it remains a serious possibility of fundamental significance for rare but exotic phenomena. On theoretical scale arguments, strange quark matter is as plausible a ground state as the confined state of hadrons[2,4,5]. Unfortunately it seems unlikely that QCD calculations will be accurate enough in the foreseeable future to give a definitive prediction on the stability of strange matter, and one is left with experiment and astrophysical tests 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)[2,4,6,7]. Part of this paper deals with an investigation

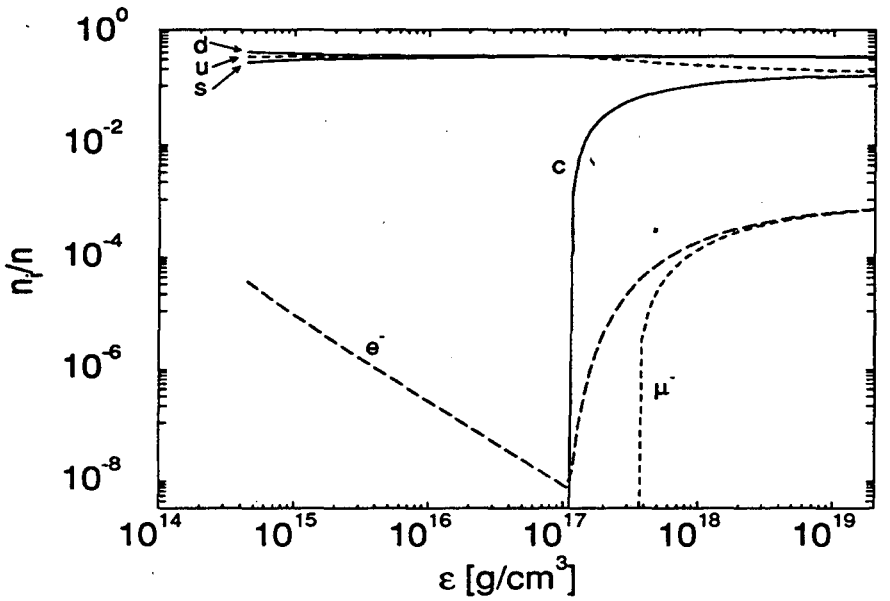

Figure 1: Relative densities of quarks and leptons, n_i/n, where n denotes the total quark density, in cold, beta-stable, electrically charge neutral quark-star matter as a function of energy density ($B^{1/4} = 145$ MeV)[11].

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 vibrations[8,9]. The properties with respect to which strange-matter stars differ from their non-strange counterparts are discussed, and observable signatures of strange stars are pointed out.

2. Quark-lepton Composition of Strange Matter

The relative quark/lepton composition of quark-star matter at zero temperature is shown in Fig. 1. All quark flavor states that become populated at the densities shown are taken into account. (Strange and charm quark masses of respectively 0.15 GeV and 1.2 GeV are assumed.) Since stars in their lowest energy state are electrically charge neutral to very high precision[10], 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 s-quark mass which leads to a deficit of net negative quark charge, and at densities beyond which the c-quark state becomes populated which increases the net positive quark charge.

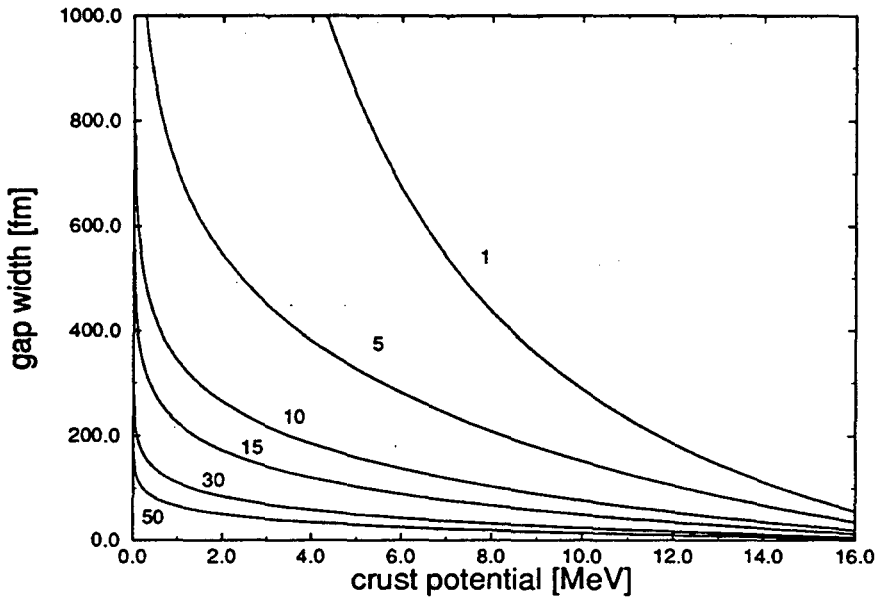

Figure 2: Gap width, $R_{\rm gap}$, versus electrostatic crust potential, $eV_{\rm crust}$. The labels refer to temperature (in MeV).

3. Nuclear Crusts on Strange Stars

The presence of electrons in strange quark matter is crucial for the possible existence of a nuclear crust on such objects. As shown in Ref. [6] (see also Alcock's contribution elsewhere in this volume), the electrons, because they are bound to strange matter by the Coulomb force rather than the strong force, extend several hundred fermis beyond the surface of the strange star. Associated with this electron displacement is a electric dipole layer which can support, out of contact with the surface of the strange star, a crust of nuclear material, which it polarizes [6]. The maximal possible density at the base of the crust (inner crust density) is determined by neutron drip, which occurs at about 4.3×10^{11} g/cm^3.

The determination of the electrostatic electron potential at the surface of a strange star performed in Ref. [6] has been extended to finite temperatures only recently[11]. The results obtained there for the gap between the surface of the star's strange core and the base of the inner crust are shown in Fig. 2. A minimum value of $R_{\rm gap} \sim 200$ fm was established in Ref. [6] as the lower bound on $R_{\rm gap}$ necessary to guarantee the crust's security against strong interactions with the strange-matter core. For this value one finds from Fig. 2 that a hot strange pulsar with $T \sim 30$ MeV can only carry nuclear crusts whose electrostatic potential at the base is rather smaller, $eV_{\rm crust} \lesssim 0.1$ MeV. Crust potentials in the range of 8–12 MeV, which are expected for a crust at neutron drip density[6], are only possible for core temperatures of $T \lesssim 5$ MeV. Therefore we conclude that only strange stars with rather low temperatures can carry the densest possible crusts.

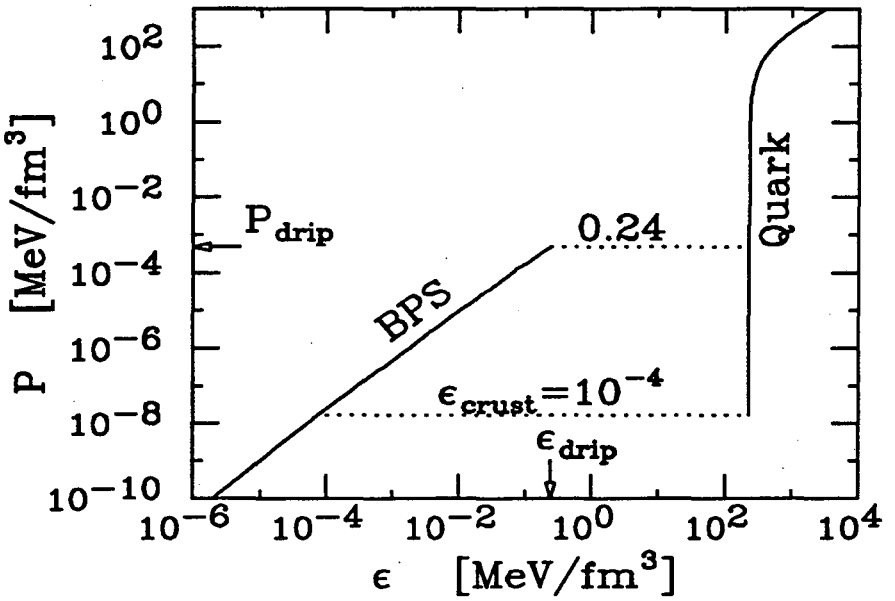

Figure 3: Equation of state of a strange star surrounded by a nuclear crust. $P_{\rm drip}(\epsilon_{\rm drip})$ denotes the pressure at the maximum possible inner crust density determined by neutron drip, $\epsilon_{\rm crust} = 0.24$ MeV/fm^3 (4.3×10^{11} g/cm^3). Any inner crust value smaller than that is possible. As an example, we show the equation of state for $\epsilon_{\rm crust} = 10^{-4}$ MeV/fm^3 (10^8 g/cm^3).

4. Equation of State of Strange Stars with Crust

The somewhat complicated situation of the structure of a strange star with crust described above can be represented by a proper choice of equation of state[12], 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 strange-matter core is described by the bag model (for details, we refer to Refs. [13,5,11,12]). The graphical illustration of such an equation of state is shown in Fig. 3. Notice that there is a discontinuity in energy density between strange quark matter and hadronic matter across the electron surface (dipole gap) inside the star where the pressure of the hadronic crust at its base equals the pressure of the strange core at its surface[12].

5. Properties of Strange-Matter Stars

5.1. Strange and Charm Stars

Figure 4 shows the impact of the bag constant on the masses of sequences of dense quark-matter stars. Stars with central densities smaller than a few times 10^{15} g/cm^3 are composed of quark matter made up of up, down and strange quarks and are thus referred to as strange stars. Charm quarks are present at central

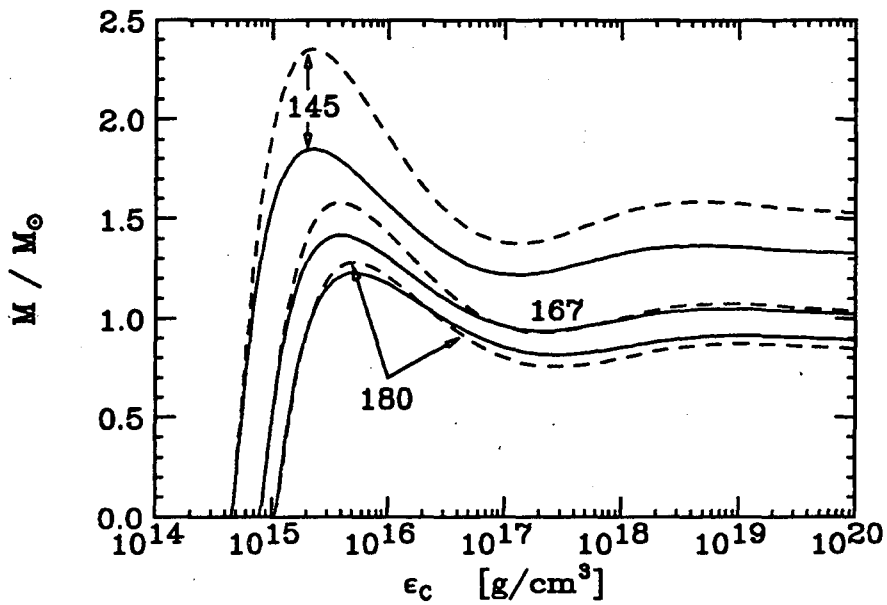

Figure 4:. Gravitational mass (solid curves) of strange and charm stars compared to mass at infinity, M_A (dashed), of the equivalent number of neutrons as corresponding to quark number. The bag constants are $B^{1/4} = 145$ MeV, 167, and 180.

densities larger than $\sim 10^{17}$ g/cm^3. Stars with densities larger than that are denoted charm stars. Recall that only those sequences constructed for $B^{1/4} = 145$ MeV consist of matter that is absolutely stable at zero external pressure with respect to iron. The other two sequences correspond to strange matter whose energy per baryon number is about ~ 960 MeV ($B^{1/4} = 167$ MeV) and ~ 1030 MeV ($B^{1/4} = 180$ MeV). For the absolutely bound sequence, the dispersed mass of the equivalent number of nucleons, defined by $M_A \equiv m_{\rm H} \times \int dV_{\rm prop} n_A$ ($m_{\rm H}$ and n_A denote the mass of the hydrogen atom and baryon number density, respectively), is clearly larger at all densities than the gravitational mass. Consequently the strange and charm stars of this sequence are stable against evaporation of baryons, which is different for the other two sequences where $M_A \lesssim M$ at higher densities[14]. Charm stars however turn out to be unstable against radial oscillations[9] and thus cannot exist stably in the universe. So the only type of quark stars that could possess physical significance are strange-matter stars.

5.2. 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. 5. The strange-star sequence is computed for the maximal possible inner crust density, $\epsilon_{\rm crust} = \epsilon_{\rm drip}$. Of course there are other possible sequences of strange stars with any smaller value

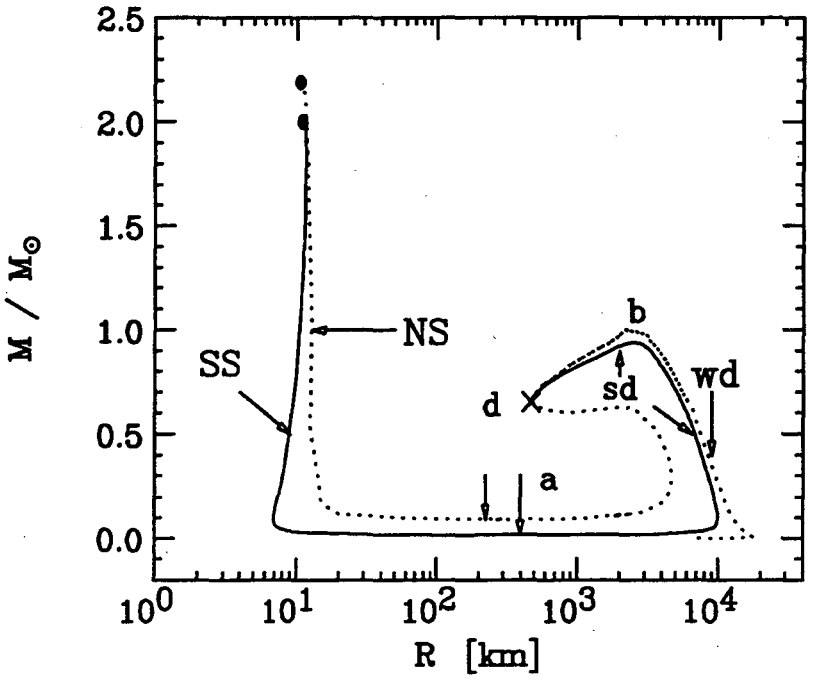

Figure 5: Mass versus radius of strange-star configurations with nuclear crusts (solid curve) and gravitationally bound stars (dotted). (NS=neutron star, SS=strange star, wd=white dwarf, sd=strange dwarf.) The cross denotes the termination point of the strange-dwarf sequence ($\epsilon_{\rm crust} = \epsilon_{\rm drip}$). The dots and vertical arrows refer to the maximum- and minimum-mass star of each sequence.

of inner crust density. These will be discussed below[8]. 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 (HFV of Ref. [15]), which has been combined at subnuclear densities with the Baym-Pethick-Sutherland equation of state. Hence the white dwarfs shown in Fig. 5 are computed for the latter. (For an overview of the bulk properties of neutron stars, constructed for a representative collection of modern nuclear equations of state, we refer to Refs. [16,17,18,19].) Those gravitationally bound stars with radii $\lesssim$ 200 km and $\gtrsim$ 3000 km represent stable neutron stars and white dwarfs, respectively. The fact that strange stars with crust possess smaller radii than neutron stars leads to smaller rotational mass shedding (Kepler) periods $P_{\rm K}$, as indicated by the classical expression $P_{\rm K} = 2\pi\sqrt{R^3/M}$. Of course the general relativistic expression, which is to be applied to neutron and strange stars, is considerably more complicated. However the qualitative dependence of $P_{\rm K}$ on mass and radius remains valid[20]. 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

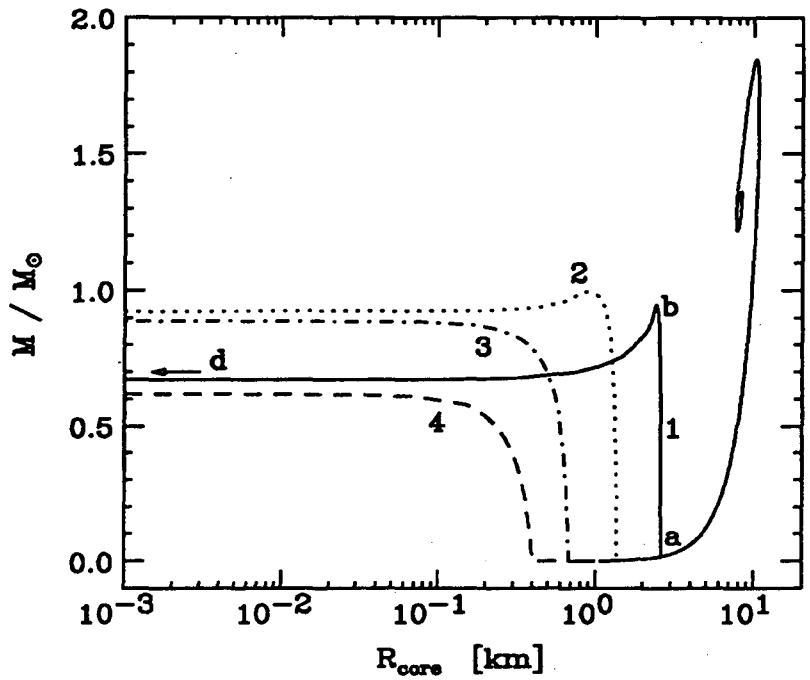

Figure 6: .Gravitational mass versus strange-core radius of sequences of strange stars with inner crust densities of: (1) 4.3×10^{11} g/cm^3, (2) 5×10^9, (3) 10^8, and (4) 10^7. The mass-radius relationship of sequence '1' is shown in Fig. 5. Only sequences with $\epsilon_{\rm crust} \gtrsim 10^9$ g/cm^3 possess a maximum-mass strange dwarf (labeled 'b'), where the sequence in the direction of decreasing $R_{\rm core}$ changes from stability to instability against radial oscillations. Conversely all stars along sequences with $\epsilon_{\rm crust} \lesssim 10^9$ g/cm^3 (sequences '3' and '4') are stable.

sustain extremely rapid rotation[8]. In particular, a strange star with a typical pulsar mass of $\sim 1.45\,M_\odot$ can rotate at (general relativistic) Kepler periods as small as $0.55 \lesssim P_{\rm K}/{\rm msec} \lesssim 0.8$, depending on crust thickness and bag constant[8,12]. This range is to be compared with $P_{\rm K} \sim 1$ msec obtained for neutron stars of the same mass[18,19].

The minimum-mass configuration of the strange-star sequence (labeled 'a' in Fig. 5) has a mass of about $M_{\rm min} \sim 0.017\,M_\odot$ (about 17 Jupiter masses). More than that, we find stable strange-matter stars that can be even by orders of magnitude lighter than this star, depending on the chosen value of inner crust density[8]. If abundant enough in our Galaxy, such low-mass strange stars could be seen by the gravitational microlensing searches that are being performed presently. Strange stars located to the right of 'a' consist of small strange cores ($R_{\rm core} \lesssim 3$ km) surrounded by a thick nuclear crust (made up of white dwarf material) which follows from Figs. 5 and 6. We thus call such objects strange dwarfs. Their cores have shrunk to zero at 'd'. What is left is a ordinary white dwarf with a central density equal to the inner crust density of the former strange dwarf[8,21]. A detailed stability analysis of

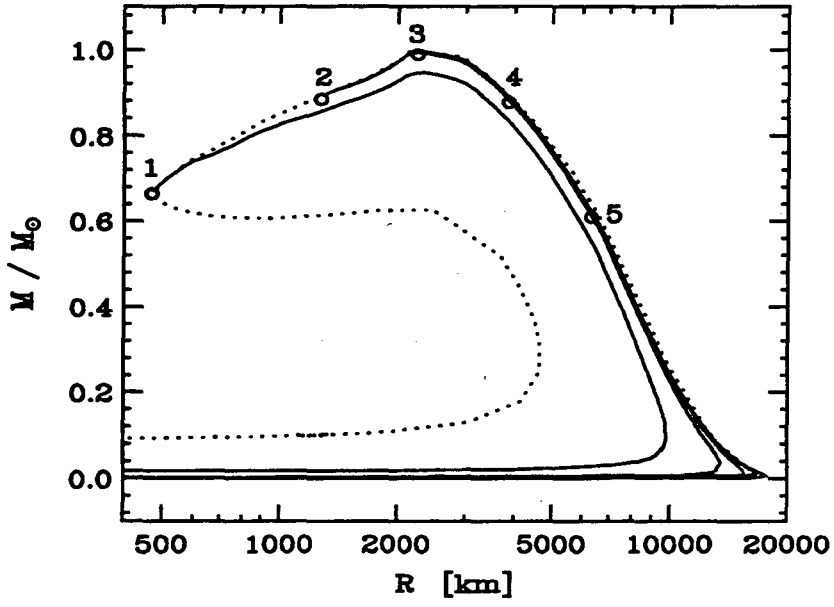

Figure 7: Mass-radius relationship of sample strange dwarfs with inner crust densities (1) 4.3×10^{11} g/cm^3, (2) 10^{10}, (3) 10^9, (4) 10^8, and (5) 10^7. The dotted curve corresponds to white dwarfs, the open circles denote the termination points of strange-matter sequences. Only stars beyond the mass peak (in the direction of increasing radii) are hydrostatically stable.

strange stars against radial oscillations[8,9] shows that the strange dwarfs between 'b' and 'd' in Figs. 5 and 6 are unstable against the fundamental eigenmode. Hence such objects cannot exist stably in nature. However all other stars of this sequence ($\epsilon_{\rm crust} = \epsilon_{\rm drip}$) are stable against oscillations. So, in contrast to neutron stars and white dwarfs, the branches of strange stars and strange dwarfs are stably connected with each other[8,22].

So far our discussion was restricted to inner crust densities equal to neutron drip. The impact of $\epsilon_{\rm crust} < \epsilon_{\rm drip}$ on strange dwarfs is shown in Fig. 7. One sees that for decreasing inner crust densities the termination point (open circle) of the strange-dwarf sequence with $\epsilon_{\rm crust} = \epsilon_{\rm drip}$ ('1') moves from left to right, since this is the direction in which the central density along the white-dwarf sequence decreases. We divide the strange dwarfs into two distinct categories. The first one consists of a core of strange matter enveloped within ordinary white dwarf matter ('3' to '5'), the second forms a entire new class of stars that contain nuclear material up to $\sim 4 \times 10^4$ times denser (sequence '1') than in ordinary white dwarfs of average mass[8], $M \sim 0.6\, M_\odot$, whose central density is $\sim 10^7$ 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 stars[22].

6. Summary

This work deals with an investigation of the properties of the complete sequences of strange-matter stars that carry nuclear crusts. The facets of these sequences have not been studied before. We arrive at the following important findings:

- 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!
- If the strange matter hypothesis is correct, observed white dwarfs should contain strange-matter cores in their centers. Their maximal possible baryon number compatible with hydrostatic stability is smaller than $A_{\rm core} \lesssim 2 \times 10^{55}$!
- The masses and radii of stable strange stars lie in the ranges $10^{-4} \lesssim M_{\rm SS}/M_{\odot} \lesssim 2$ and $2 \lesssim R_{\rm SS}/{\rm km} \lesssim 10^3$. Those of the strange dwarfs are given by $10^{-4} \lesssim M_{\rm sd}/M_{\odot} \lesssim 1$ and $10^3 \lesssim R_{\rm sd}/{\rm km} \lesssim 10^4$. Thus, if their abundance in our Galaxy is sufficiently large enough, the presently performed gravitational microlensing experiments should see them all!
- Strange stars can possess nuclear crusts of thickness $\sim (1 - 10^4)$ km! This will be of great importance for their cooling behavior (presently under investigation [23]).
- Elsewhere (Ref. [12]) we have shown that the moment of inertia of the crust on a strange star can account for both the observed relative frequency changes of pulsars (glitches) as well as the relative change in spin-down rate!

There remain many interesting aspects of strange pulsars and strange dwarfs that need to be worked out in detail. From their analysis one may hope to arrive at definitive conclusion about the behavior of dense nuclear matter and the true ground state of the strong interaction.

7. Acknowledgement

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