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A Possible New Class of Dense White Dwarfs†

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Abstract

If the strange matter hypothesis of Bodmer and Witten is true, then a new class of white dwarfs can exist whose nuclear material in their deep interiors can have a density as high as the neutron drip density, a few hundred times the density in maximum-mass white dwarfs and 4×10^4 the density in dwarfs of typical mass, $M \sim 0.6 M_\odot$. Their masses fall in the approximate range 10^{-4} to $1 M_\odot$. They are stable against acoustical modes of vibration. A strange quark core stabilizes these stars, which otherwise would have central densities that would place them in the unstable region of the sequence between white dwarfs and neutron stars.

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A Possible New Class of Dense White Dwarfs

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Bodmer [1] and Witten [2] independently hypothesized that strange quark matter, an approximate equal mixture of u,d,s quarks, may be the absolute ground state of the strong interaction (rather than ^{54}Fe). Even to the present day there is no unequivocal scientific basis on which one can either confirm or reject this hypothesis, – it remains a serious possibility of fundamental significance for rare but exotic phenomena. (For recent work, and earlier references see [3].)

If the hypothesis is true, then there could exist compact stars containing such matter. Strange stars, – the counterparts of neutron stars, – with central densities above nuclear saturation density, have been extensively discussed. Here we point out the possible existence of a new class of very dense white dwarfs whose stability is established solely by a strange quark core.

A strange quark star or core has a sharp edge of thickness defined by the range of the strong interaction. Alcock, Farhi and Olinto [4] pointed out that the electrons, which neutralize the positive charge of strange quark matter and are bound to it by the Coulomb attraction, extend several hundred fermis beyond the edge, thus creating a dipole layer of very high voltage. It can support, out of contact with the core, ordinary matter, which it polarizes. The maximum density of such a 'crust' is limited by the neutron drip density, above which neutrons would gravitate to the strange core and be converted to quark matter. So there could exist ordinary white dwarfs which envelop a strange quark core since their inner densities of nuclear material fall much below this critical limit. However they are not very interesting since they would differ imperceptibly from a white dwarf of similar mass but without the core. What is interesting is that, as part of the continuum of equilibrium configurations from compact strange stars with nuclear crusts, there are acoustically and hydrostatically stable strange dwarfs having densities of nuclear material as high as the neutron drip, – a few hundred times larger than would be found in the maximum-mass white dwarf [5] and 4×10^4 times larger than in a typical $M = 0.6 M_\odot$ white dwarf. They owe their stability solely to the quark core, without which they would lie on the unstable region of the sequence between white dwarfs and neutron stars.

We have described elsewhere, in connection with strange stars with nuclear crusts, how equilibrium configurations of this general character can be calculated using the well known Oppenheimer-Volkoff stellar structure equations of General Relativity [6]. The stellar solutions fall into sequences characterized by two parameters, – the central density of the core and the inner density of the crust. For a particular equation of state and each pair of such parameters, there is a unique stellar structure with a particular mass and radius. We show the mass-radius relation in Fig. 1 for a sequence extending from neutron stars to white dwarfs, and a sequence extending from strange stars to strange dwarfs, for which the inner crust density is equal to

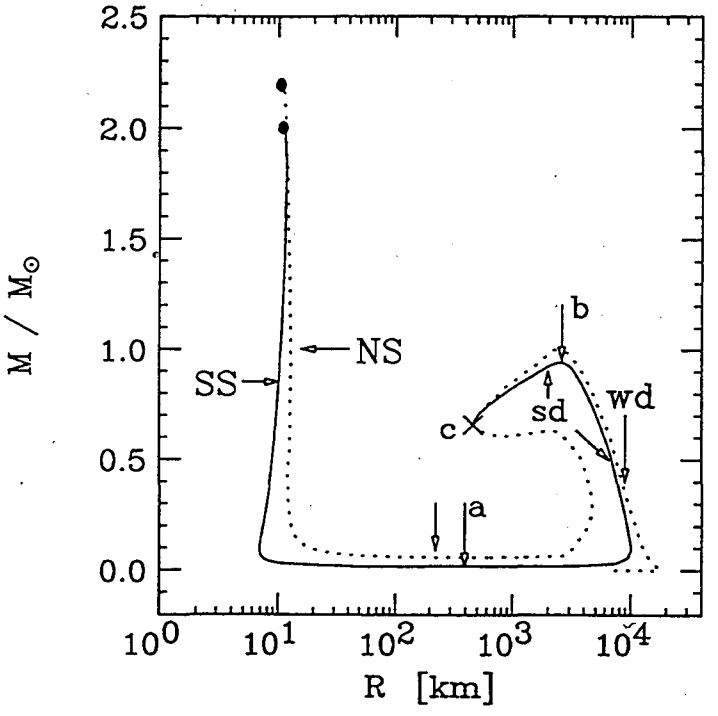

Figure 1: Neutron star (NS) - white dwarf (wd) sequence shown by dots and strange star (SS) - strange dwarf (sd) sequence, for which the inner crust density of nuclear material is equal to the neutron drip density, shown by solid line.

the neutron drip density. The strange stars consist primarily of a strange quark core surrounded by a thin nuclear crust; the strange dwarfs, of a very small core and a nuclear envelope of nuclei in a Coulomb lattice that is up to a few thousand kilometers thick. The only astronomically interesting objects are those that are in hydrostatic equilibrium and are stable against radial oscillations. In this connection, it will be noticed that the direction of decreasing density along each sequence, starting at high density for the compact stars and decreasing toward the dwarfs, is in the opposite sense for ordinary white dwarfs and strange dwarfs. Since $dM/d\epsilon_c$ has opposite signs on the adjacent white dwarf and strange dwarf segments at the large radius portions of the sequences, one might at first think that, the white dwarfs being stable along this segment, the strange dwarfs are unstable. This is not true however. The same qualitative arguments that lead one to 'reason' that $dM/d\epsilon_c$ must be positive along the stable sequence of neutron stars and white dwarfs, lead one to conclude that it is $dM/d\epsilon_{\rm crust}$ that must be positive for strange dwarfs. This is because the acoustic modes propagate mostly in the compressible nuclear material which comprises most of the strange dwarfs, not in the much higher density and incompressible quark core of a few kilometers in radius for which the local adiabatic index, $\Gamma(\epsilon)$, defined below, is very large. This can be understood by reference to Fig. 1 of ref. [6].

However we shall not rely on the schematic arguments but solve for the eigenfreqencies of the normal radial modes of vibration. We refer to the catalogue of

methods provided by Bardeen, Thorne, and Meltzer [7]. For a metric of the form $ds^2 = e^{2\nu}dt^2 - e^{2\lambda}dr^2 - r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$, the adiabatic motion of the star in its n'th normal mode, where $n = 0$ is the fundamental mode, is expressed in terms of an amplitude $u_n(r)$ by $\delta r(r,t) = e^{\nu}u_n(r)e^{i\omega_n t}/r^2$ which denotes small perturbations in r. The quantity $\omega_n(t)$ is the star's oscillation frequency, which we want to compute. The eigenequation for $u_n(r)$ which governs the n'th normal mode, first derived by Chandrasekhar [8], has the Sturm-Liouville form

$$\frac{d}{dr}\left(\Pi\,\frac{du_n}{dr}\right) + \left(Q + \omega_n^2\, W\right) u_n = 0 \ , \tag{1}$$

where the functions

$$\Pi = e^{(\lambda+3\nu)}\, r^{-2}\, \Gamma P \ , \tag{2}$$

$$Q = -4\, e^{(\lambda+3\nu)}\, r^{-3}\, \frac{dP}{dr} - 8\pi\, e^{3(\lambda+\nu)}\, r^{-2}\, P\,(\epsilon + P) \tag{3}$$

$$+\, e^{(\lambda+3\nu)}\, r^{-2}\, (\epsilon + P)^{-1} \left(\frac{dP}{dr}\right)^2 \ , \tag{4}$$

$$W = e^{(3\lambda+\nu)}\, r^{-2}\, (\epsilon + P) \ , \tag{5}$$

$$\Gamma = \frac{(\epsilon + P)}{P}\,\frac{\partial P}{\partial \epsilon} \ , \tag{6}$$

are expressed in terms of the equilibrium configuration of the star. The quantities ϵ, P and dP/dr denote the energy density, the pressure and pressure gradient as measured by a local observer. They are obtained from the Oppenheimer-Volkoff equations. The symbol Γ denotes the varying adiabatic index at constant entropy. The boundary conditions are $u_n \sim r^3$ at the star's origin and $du_n/dr = 0$ at the star's surface. The second of these assures that the Lagrangian change in the pressure at the surface is zero. Solving the eigenvalue equation leads to the frequency spectrum ω_n^2 ($n = 0, 1, 2, \ldots$) of the normal radial modes. As a characteristic feature, the squared eigenfrequencies ω_n^2 form an infinite discrete sequence, $\omega_0^2 < \omega_1^2 < \omega_2^2 < \cdots$. If any of these is negative for a particular star, the frequency is complex and its imaginary part yields an exponentially growing amplitude of oscillation. Such stars are unstable. We have computed the frequencies for the sequence of strange stars exhibited in Fig. 1. They are shown in Fig. 2 for the central density range relevant to the strange dwarfs. The points 'a' and 'b' correspond to the extrema of Fig. 1. It will be noticed that at the minimum mass the squared frequency of the fundamental mode becomes zero, but does not change sign. So the strange star configurations to the left of 'a' and the strange dwarf configurations to the right are all stable. However at 'b' the squared frequency of the fundamental mode does change sign. Configurations to the right of 'b' are stable and those to the left unstable. A similar result holds for all other strange sequences with values of inner crust density lower than the drip density.

So we have verified the statement made earlier, that there is a double continuum of strange dwarf configurations, parameterized by the central core density, and an *inner* crust density, $\epsilon_{\rm crust}$, of nuclear material in the range from the neutron drip density

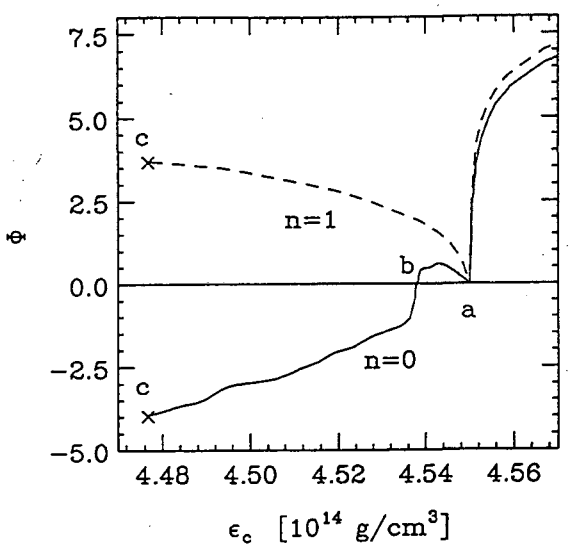

Figure 2: Pulsation frequencies for $n = 0, 1$ measured by $\Phi(x) \equiv \mathrm{sign}(x)\,\log(1 + |x|)$ where $x \equiv (\omega_n/sec^{-1})^2$ as a function of central star density in the vicinity of strange dwarfs having inner crust density equal to neutron drip. For $\Phi < 0$, the squared frequency is negative and the mode unstable.

down to the central density of the limiting-mass white dwarf, 4×10^{11} g/cm$^3 \approx \epsilon_{\rm drip} > \epsilon_{\rm crust} > \epsilon_{\rm wd} \approx 10^9$ g/cm^3, which are stabilized by the presence of the strange core. We call them strange dwarfs, and distinguish them from the trivial configurations consisting of a strange core and a white dwarf envelope, $\epsilon_{\rm crust} < \epsilon_{\rm wd}$, which would be stable with or without the core. The masses of the strange dwarfs range from values of about $10^{-4} M_\odot$ to about a solar mass. The lower limit can be compared to $\sim 1/10 M_\odot$ for a neutron star. They have strange cores of only several kilometers in radius and a baryon number in the range $54.2 < \log A < 55.4$, compared to $\log A \sim 57$ for a neutron star or white dwarf. The mass-energy profile of one of them is compared to a white dwarf profile in Fig. 3. In both cases they correspond to stable stars of a mass typical of observed white dwarfs, $0.6 M_\odot$. In the case of the strange dwarf the inner crust density is chosen to have its maximum possible value, the drip density. The inner density of nuclear material can be up to a few hundred times the maximum density possible in ordinary white dwarfs and about 4×10^4 times larger than the central density in the prevalent mass ($\sim 0.6 M_\odot$) white dwarfs.

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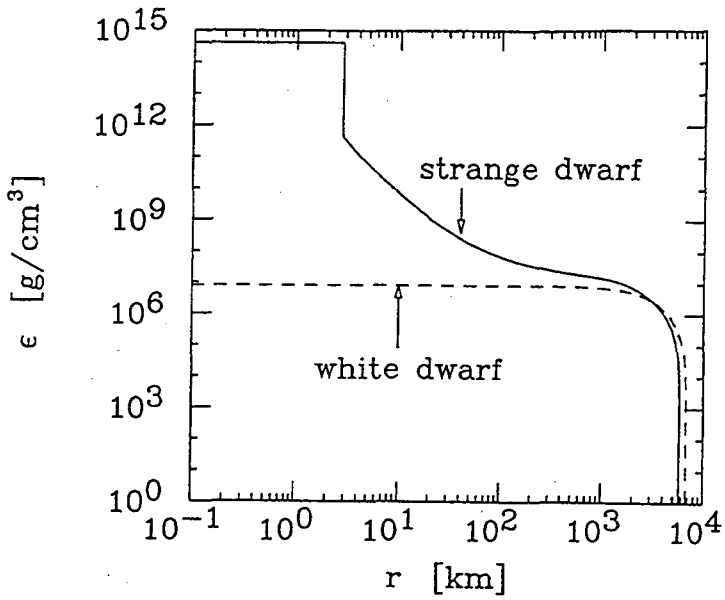

Figure 3: Mass-energy profile of a strange dwarf and a white dwarf of the same mass, $0.6M_{\odot}$. Quark core of strange dwarf is the structure within 3 kilometers. Outside is nuclear material of inner density equal to the neutron drip density.

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