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N.K. Glendenning, Ch. Kettner, and F. Weber

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N. K. Glendenning, Ch. Kettner and F. Weber

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
One Cyclotron Road
Berkeley, California 94720

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Possible New Class of Dense White Dwarfs[1]

N. K. Glendenning, Ch. Kettner and F.Weber

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

If the strange quark matter hypothesis 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.

Independently, Bodmer (2) and Witten (3) 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 ^{56}Fe). 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. Careful study has shown that the universe would have evolved essentially as it did, no matter whether ordinary hadronic matter is the ground state or strange quark matter (4–7)). Little or no primordial strange matter would have survived evaporation in the hot era. Any, or most of what exists now must have been regenerated in the cores of neutron stars on the time-scale of stellar evolution.

Strange stars, – the counterparts of neutron stars, – with central densities above nuclear saturation density, have been extensively discussed. Here we discuss 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 (8) 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. So, *outside* the edge of quark matter, which itself is slightly positively charged, there being fewer strange quarks than up or down on account of the strange quark mass, there is a surface negative charge, while *inside* a layer of positive charge. This creates a dipole layer of very high voltage. It can support, out of contact with the core, ordinary matter, which it polarizes. The gap between core and crust of heavy ions is estimated to be of the order of several hundred fermis (8). 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 (9) 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 (10). Normally, for a given equation of state, there is one unique sequence of stars, the mass increasing as the central density is increased – a single parameter family. However, because of the dipole field, a crust of any inner density up to the drip density can be supported by the core and out of contact with it. Thus strange stars with nuclear crusts form a two parameter sequence. In practice we fix the inner density of the crust and vary the central density to generate the corresponding sequence. 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 ordinary neutron stars to ordinary white dwarfs and then to planets, and *two* out of a continuum of strange star sequences extending from strange stars to strange dwarfs, for which, in the one case, the inner crust density is equal to the neutron drip density, the maximum possible value, and another much smaller inner crust 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. Of Course the central density and therefore the radius of the strange core shrinks along members of a sequence from the maximum mass strange star toward the dwarfs. In the limit that it has shrunk to zero, the star is identical to a white dwarf and therefore the strange sequence terminates at a point on the white dwarf sequence.

The only astronomically interesting objects are those that are in hydrostatic equilibrium and are stable against radial oscillations. We solve for the eigen-

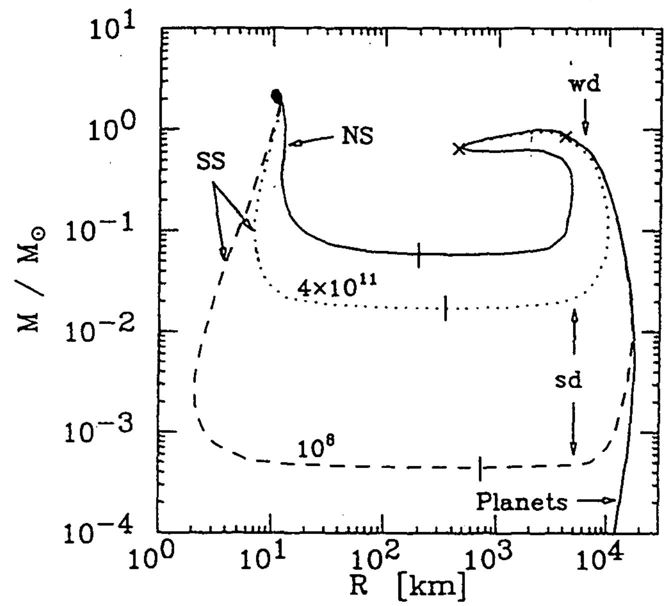

FIG. 1. Neutron star (NS) - white dwarf (wd) sequence, (solid line). Two strange star (SS) - strange dwarf (sd) sequences, for which the inner crust density of nuclear material has the indicated values (in gm/cm^3). The higher value is the drip density. Vetical bars mark minimum mass stars. Crosses mark termination of the strange star sequences where the strange core shrinks to zero. At those points they become identical to ordinary white dwarfs.

freqencies of the normal radial modes of vibration. We refer to the catalogue of methods provided by Bardeen, Thorne, and Meltzer (11). 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 (12), has the Sturm-Liouville form

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

where the functions

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

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

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

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

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

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

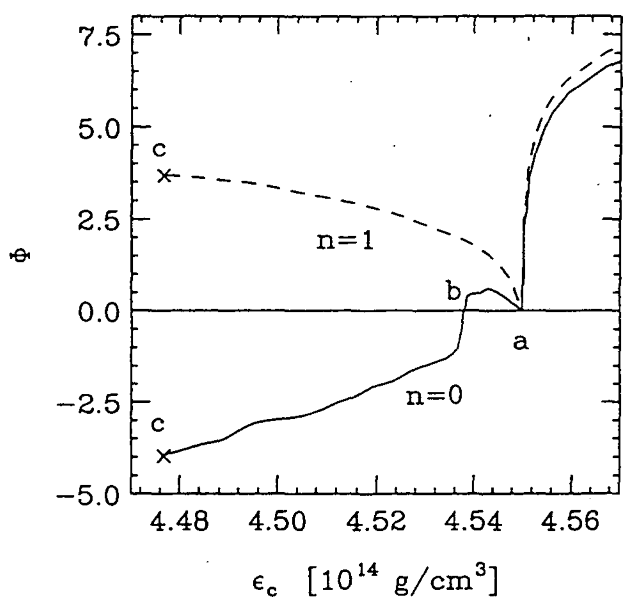

FIG. 2. Pulsation frequencies for $n = 0, 1$ measured by $\Phi(x) \equiv \text{sign}(x)\,\log(1 + |x|)$ where $x \equiv (\omega_n/sec^{-1})^2$ as a function of central star density in the vicinity of strange dwarfs having inner crust density equal to neutron drip. For $\Phi < 0$, the squared frequency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

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*, $e^{\text{Im}(\omega)t}$, growing amplitude of oscillation. Such stars are unstable. We have computed the frequencies for the sequence of strange stars having an inner crust density equal to the drip, exhibited in Fig. 1. They are shown in Fig. 2 for the central density range relevant to the strange dwarfs. The point 'a' corresponds to the minimum mass star of the 'drip density' crust of Fig. 1 and 'b' to the maximum mass strange dwarf of that sequence. 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. The *entire* sequence of strange stars to strange dwarfs between the maximum star of each class are stable. This has an interesting contrast with ordinary neutron stars and white dwarfs shown by the solid line of Fig. 1. All stars in the sequence from the *minimum* mass neutron star to the *maximum* mass white dwarf are unstable. The stable part of the branch of white dwarfs are those that extend from the maximum mass toward the region labled 'planets' – viz, the dwarfs with larger radii than that possesed by the one at the maximum mass. The unstable region spans about five orders in magnuitude of central 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, ϵ_{crust}, of nuclear material in the range from the neutron drip density down to the central density of the limiting-mass white dwarf, 4×10^{11} g/cm$^3 \approx \epsilon_{\text{drip}} > \epsilon_{\text{crust}} > \epsilon_{\text{wd}} \approx 10^9$ 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, $\epsilon_{\text{crust}} < \epsilon_{\text{wd}}$, 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, – interesting candidates for gravitational micro-lensing searches. 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.

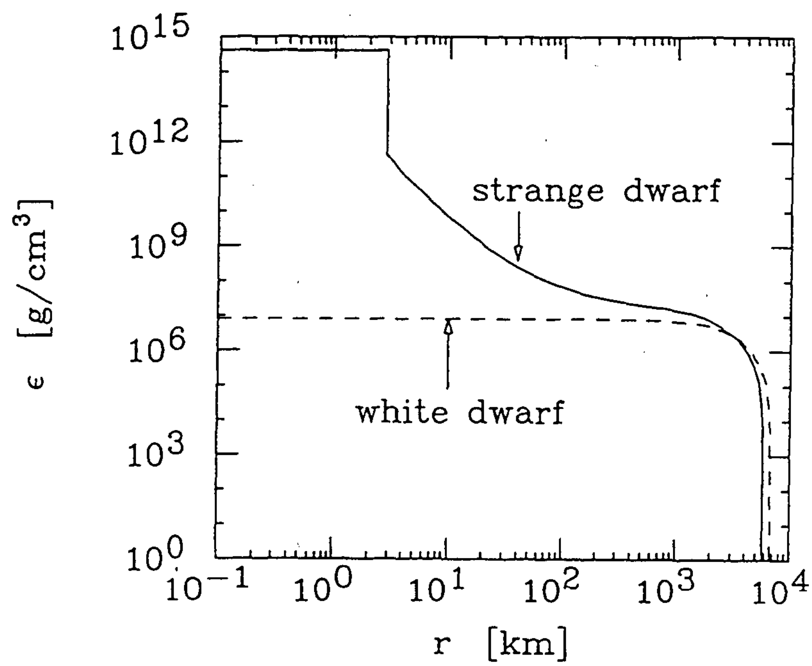

FIG. 3. Mass-energy profile of a strange dwarf and a white dwarf of the same mass, $0.6M_{\odot}$. Quark core of strange dwarf is the structure within 3 kilometers. Outside is nuclear material of inner density equal to the neutron drip density.

We say a few words about some ways in which such objects as we have described here might be made. There may be others which we have not imagined, and the history of astronomical discovery cautions us that the laws of nature are explored by the universe in many unanticipated ways. The capture of strange nuggets by main-sequence stars is probably an inevitable consequence if Witten's hypothesis is correct (13,14) because then the galaxy would be filled with a flux of strange nuggets, which would contaminate every object they come into contact with, i.e., planets, neutron stars, white dwarfs, main-sequence stars, etc. Naturally, due to the large radii of the latter, they are ideal large-surface long-integration-time detectors for the strange-matter flux (13,14). In contrast to neutron stars and ordinary white dwarfs, whose material is characterized by a large structural constant so that the nuggets never reach their cores, the nuggets accreted onto main-sequence stars can indeed gravitate to their centers, accumulate there and form a strange-matter core that grows with time until the star's demise as a main-sequence star. Those whose mass lies in the approximate mass-range, $\sim 1 - 5M_{\odot}$ would then give birth to a strange dwarf. As well, it has been discussed how primordial bodies of mass between 1/100 and 1 $M_{\odot}$ can be formed in the early universe and survive to the present epoch (15). Such objects will occasionally be captured by a main-sequence star and form a significant core in a single and singular event. Finally we mention that in the very early evolution of the universe lumps of hot strange quark matter will evaporate nucleons which are plausibly gravitationally bound to the lump. The evaporation will continue until the quark matter has cooled sufficiently. Depending on the original baryon number of the quark lump, a strange star or dwarf, both with nuclear crusts will have been formed (16).

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL AND ELECTRONIC
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BERKELEY, CALIFORNIA 94720