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Strange dwarfs: possible strange-matter cores in ultracompact white dwarfs

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Abstract. Motivated by astronomical observations of white dwarfs with anomalously small radii, which are not reproduced by standard stellar models, this work investigates whether the presence of a strange-matter core inside these stars can account for such ultracompact structures. Using the MIT bag model to describe the strange core and modeling the crust as in a standard white dwarf, we compute the mass–radius relations for a sequence of hybrid configurations and compare them with those of conventional white dwarfs. We find that the presence of a strange core leads to more compact stellar configurations for a given mass.

Resumo. Motivados por observações astronômicas de anãs brancas com raios anormalmente pequenos, que não são reproduzidos por modelos estelares padrão, este trabalho investiga se a presença de um núcleo de matéria estranha dentro dessas estrelas pode explicar tais estruturas ultracompactas. Utilizando o modelo de bag do MIT para descrever o núcleo estranho e modelando a crosta como em uma anã branca convencional, calculamos as relações massa–raio para uma sequência de configurações híbridas e as comparamos com aquelas de anãs brancas tradicionais. Constatamos que a presença de um núcleo estranho leva a configurações estelares mais compactas para uma dada massa.

Keywords. Dense matter – Stars: interiors – White dwarfs

1. Introduction

White dwarfs (WDs) are compact stellar remnants, generally composed of fully ionized carbon and oxygen ions, whose structure is supported by electron degeneracy pressure (e.g., Sagert, Hempel, Greiner & Schaffner-Bielich 2006). However, astronomical observations indicate that some of these stars exhibit radii smaller than those predicted by standard mass–radius relations (e.g., Provencal et al. 1998; Mathews et al. 2006; Fontaine, Bergeron & Brassard 2007), suggesting exceptionally high internal densities and opening room for discussion about the origin of such ultracompact structures.

Under extreme density conditions, Bodmer (1971) proposed the possible existence of a new state of matter, more stable than the ^{56}Fe nucleus, in which quarks are deconfined from hadrons. This idea was later developed in the context of so-called strange matter, a hypothetical phase that may be energetically favored over ordinary nuclear matter (Witten 1984). In this scenario, at sufficiently high densities, up and down quarks become deconfined, forming a globally colorless volume. Chemical equilibrium under the weak interaction then favors the production of strange quarks, accompanied by electrons to ensure charge neutrality (Glendenning 2000).

Based on this possibility, a new class of compact objects, called strange dwarfs, may exist: hypothetical stars composed of a self-bound core of strange quark matter (up, down, and strange quarks) surrounded by a crust of ordinary nuclear material, with both regions kept in equilibrium by a strong electric dipole at the core–crust interface (Glendenning, Kettner & Weber 1995; Vartanyan, Grigoryan & Sargsyan 2004; Weber 2005). Unlike neutron stars, whose interiors can naturally undergo a phase transition to strange matter at sufficiently high densities, white dwarfs do not reach such conditions spontaneously. However, during earlier evolutionary stages, the progenitor main-sequence star could accrete strange-matter nuggets, which may subsequently sink to the center and catalyze the gradual conversion of the stellar core into strange matter (Glendenning, Kettner & Weber 1995).

In this work, we investigate whether the ultracompact structure inferred for some white dwarfs can be consistently interpreted within the strange-dwarf scenario.

2. Methods

2.1. Relativistic hydrostatic modeling

The comparison between strange dwarfs and ordinary white dwarfs is carried out through relativistic hydrostatic modeling, based on the relation between pressure and energy density. The corresponding mass–radius curves follow from solving the Tolman–Oppenheimer–Volkoff (TOV) equation and the mass continuity equation in units where $G = c = 1$ (Glendenning 2000):

$$\frac{dP}{dr} = -\frac{\left[\epsilon(r) + P(r)\right]\left[m(r) + 4\pi r^3 P(r)\right]}{r\left[r - 2m(r)\right]}, \qquad \frac{dm}{dr} = 4\pi r^2 \epsilon(r), \quad (1)$$

where $P(r)$ is the pressure, $\epsilon(r)$ the energy density, and $m(r)$ the enclosed mass at radius r.

2.2. Equation of state of the strange-matter core

The strange dwarf interior is modeled as a strange-matter core surrounded by a hadronic crust, each region being described by an appropriate equation of state (EoS). For the core, we adopt the MIT bag model in the massless, non-interacting limit, in which quarks behave as an ultrarelativistic Fermi gas confined by the bag pressure B and subject to chemical equilibrium among different flavors (Glendenning, Kettner & Weber 1995; Alcock, Farhi & Olinto 1986; Farhi & Jaffe 1984) . The description is carried out at $T = 0$, since thermal contributions are negligible compared with the Fermi energy at the relevant densities. Under these assumptions, the core EoS reduces to the linear relation

$$\epsilon = 3P + 4B. \quad (2)$$

We take $B^{1/4} = 145$ MeV, a value for which three-flavor strange matter is self-bound within this model and possesses an energy per baryon lower than that of ^{56}Fe (Glendenning 2000). Other choices of B would modify the compactness and stability domain of strange dwarfs, but this value remains widely used in the literature.

2.3. Equation of state of the crust

The strange-dwarf crust is supported by the degeneracy pressure of an electron gas, as in ordinary carbon–oxygen white dwarfs. The density in this layer is limited by the neutron-drip value,

$$\rho_{\text{drip}} \approx 4 \times 10^{11} \text{ g cm}^{-3}, \qquad (3)$$

above which neutrons become unbound from nuclei (Baym, Pethick & Sutherland 1971). Following Glendenning, Kettner & Weber (1995), matter at subnuclear densities below neutron drip is described by the BPS EoS, which includes electron degeneracy pressure, Coulomb effects, and lattice corrections. Consequently, the strange-dwarf crust and the structure of a conventional white dwarf are treated consistently within the same microphysical framework, though we note that this choice neglects possible refinements in the light-element composition and electron-capture processes (see, e.g., Perot, Chamel & Vallet 2023).

3. Results

Hybrid equations of state were computed for strange dwarfs under various central conditions. As an illustration, Fig. 1 shows the EoS for a model with $M = 1.36\,M_{\odot}$, a carbon crust, and a maximum density at the neutron drip limit, using $B^{1/4} = 145$ MeV:

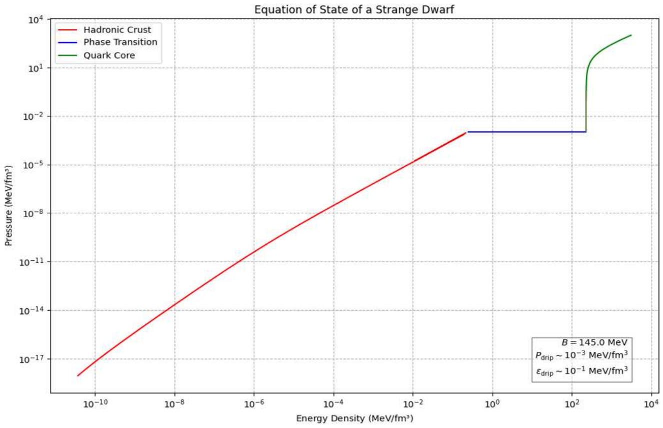

Figure 1. Variation of pressure with energy density for a strange dwarf with mass $M = 1.36\,M_{\odot}$.

The mass–radius relation of strange dwarfs obtained from the adopted EoS is shown together with the standard white dwarf sequence for comparison, as illustrated in Fig. 2:

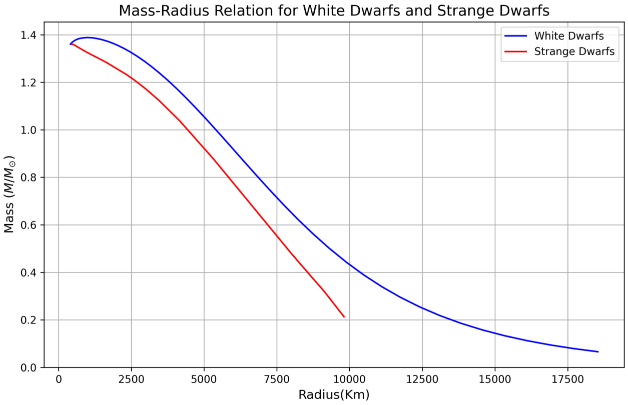

Figure 2. Mass–radius relation for white dwarfs and strange dwarfs.

For conventional white dwarfs, typical central energy densities lie in the range

$$\epsilon_c \sim 10^{-7} - 10^{-2} \text{ MeV fm}^{-3},$$

depending on the stellar mass, whereas strange dwarfs exhibit much higher central densities, of the order of

$$\epsilon_c \sim 10^{2} \text{ MeV fm}^{-3}.$$

This reflects the presence of a self-bound strange core at nearly nuclear densities. The resulting mass–radius relation shows that, for a given mass, strange dwarfs systematically have smaller radii than ordinary white dwarfs.

Our results indicate that, when a strange-matter core is embedded inside a WD-like crust, the resulting sequence of hybrid configurations is systematically more compact than that of conventional WDs. This finding is consistent with previous studies of strange dwarfs and strange-matter-core white dwarfs (Glendenning, Kettner & Weber 1995; Vartanyan, Grigoryan & Sargsyan 2004; Mathews et al. 2006; Fontaine, Bergeron & Brassard 2007). Future work including strong magnetic fields, pressure anisotropies, more detailed treatments of the core–crust transition, and realistic crust compositions with electron captures and pycnonuclear reactions (Perot, Chamel & Vallet 2023) will be essential to refine the model and to confront it with high-precision observations of compact WDs and their tidal deformabilities.

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