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Luminosity evolution of strange dwarf stars

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We study the evolution of strange dwarf stars of 0.4, 0.55, and 0.8 $M_\odot$ in the range of luminosities attributed to white dwarf stars. It is shown that, if the density at the base of the normal matter envelope is slightly lower than the density at which the onset of neutron drip occurs, these objects will have an evolution observationally indistinguishable from that corresponding to normal white dwarfs. This result is independent of the chemical composition of the high density, normal matter layers. However, strange dwarfs should behave very differently from white dwarfs in mass exchanging close binary systems.

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The possibility of the absolute stability of strange matter (SM) (an almost symmetric plasma of u, d, and s quarks) has been extensively explored since the seminal paper of Witten [1]. Because SM is expected to occur in extreme conditions, most of the research has been devoted to the role of SM in cosmology and astrophysics. At present it seems that, if the SM conjecture is indeed correct, most of the currently believed to be neutron stars should be strange stars (SS's) [2, 3]. Moreover, it seems possible that SM formation prompts type II supernova explosions [3, 4]. For general reference on the early works on SM see Ref. [5].

Very recently, Glendenning *et al.* [6] have proposed another kind of astrophysical object involving SM: stellar configurations with a small, dense SM core surrounded by an extended normal matter envelope whose bottom has a density ρ_B equal to that of the neutron drip ($\rho_{\rm drip} = 4 \times 10^{11}$ g cm^{-3}). This is the highest density for normal matter and SM coexistence to be possible [2]. In Refs. [6], the authors claim that these objects are stable against radial perturbations, and thus their existence may be feasible (however, see below). Such objects have been called strange dwarf (SD) stars. For earlier discussion about the relation between white dwarf (WD) stars and SS's see Ref. [2].

From the astrophysical point of view, SD's resemble the well- known WD's. Because of the very similar mass-radius relationships, SD's are hardly distinguishable from WD's [6]. In principle, a way to perform such a differentiation may be to study the cooling of both kind of objects and to compare them to each other and with observations as well.

We should note that, in order to make powerful this approach, we should be able to calculate the relative fraction of normal WD and SD population. This is not possible at present. In spite of this fact, if the evolution of WD and SD models were very different, we could imagine some disctinctive observable feature to detect SD's, e.g., in galactic open clusters, where the objects are expected to share many common features (e.g., their ages).

It is worthwhile to comment on a very important property of SD's, clearly different from WD's. Let us imagine that a SD suffers a tiny accretion. Then, ρ_B will increase, fulfilling $\rho_B > \rho_{\rm drip}$ and releasing dripped neutrons to be quickly burnt to SM. Let us assume that this event does not produce any kind of violent hydrodynamical process able to prompt some mass loss. Then, for a greater mass, we shall have a star with a *larger* SM core, opposite to the requirements of equilibrium [6]. Such a star will have thus no way to acquire another equilibrium structure as SD, but will burn dripped neutrons into SM continuously up to reach the only available equilibrium structure, as a (much more compact) SS. This event should release approximately the binding energy of a SS ($\sim 10^{53}$ erg) in neutrino emission. We shall not be concerned on this process in this work.

Owing to the foregoing argument, quiescent SD's with $\rho_B = \rho_{\rm drip}$ will be *unstable* to radial perturbations, simply because these perturbations would force $\rho_B > \rho_{\rm drip}$ at a semiperiod with the above discussed catastrophic consequences.

Because ρ_B increases as cooling proceeds, the only case of interest is a SD with ρ_B *slightly lower* than $\rho_{\rm drip}$. Thus, we have evolved SD and WD models of 0.4, 0.55, and 0.8 $M_\odot$ masses with $\rho_B = \eta \rho_{\rm drip}$ provided $\eta < 1$ ($\eta = 0.9$ in this work) even at $T = 0$ ($t \to \infty$). We note that η is not a critical parameter and if $\eta \lesssim 1$, SD evolution will be essentially that presented below. The range of masses considered in this work covers most of the observed distribution attributed to WD stars (at least for the case of hydrogen-rich envelopes, the so-called DA spectroscopic type [7]). The technique for constructing SD and WD initial models is similar to the employed in a previous work [8] and will not be described here.

The problem of the chemical composition of the SD envelope is not a trivial one. We show in Fig. 1 the

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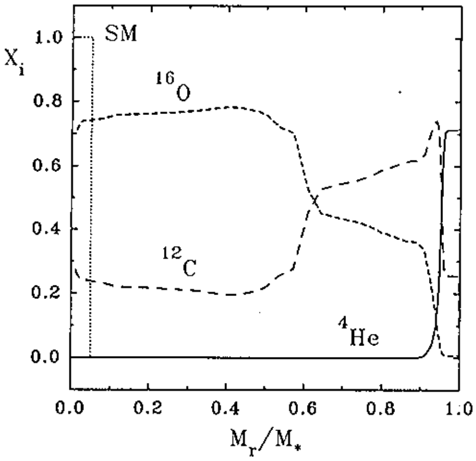

FIG. 1. The chemical composition of models vs the fractional mass. Solid line corresponds to ^{4}He, medium dashed lines to ^{12}C, and short dashed lines to ^{16}O. In the case of SD models, the approximate size of the SM core is denoted by a dotted line. For discussion about the composition of the high density, normal matter layers in SD's, see text.

composition of WD models we employed [9]. In Refs. [6] the Baym-Pethick-Sutherland (BPS) [10] equation of state, which corresponds to nuclear statistical equilibrium, was employed. However, it is obvious in no way that this should be the actual case. In fact, stellar evolution predicts a carbon-oxygen dominated interior as shown in Fig. 1. Likewise, the maximum WD mass in equilibrium conditions is $M_{\rm WD}^{\rm max} \approx 1 M_\odot$ [11] in strong contradiction with observations [7]. Moreover, for some particular objects, assuming them to be normal WD's (Sirius B, 40 Eri B, Stein 40), their masses and radii are known accurately enough to find them inconsistent with the equilibrium composition hypothesis (see Fig. 3.1 of the book [11]). In view of the above considerations, we considered a ^{12}C-^{16}O dominated composition as shown in Fig. 1 for $\rho \leq 10^9$ g cm^{-3} (i.e., in the initially non-solid layers). Higher density, crystallized layers have undergone pycnonuclear reactions [12], producing heavier elements. These reactions are *not* important in the range of luminosities here considered (see below), because from the beginning, the zone where non-negligible rates for $^{12}\text{C}+^{12}\text{C}\rightarrow {}^{24}\text{Mg}$ (for example) occur is already crystallized. So, because of the extremely steep dependence of the pycnonuclear rates upon density and temperature, this zone has already been completely burnt. Such heavy elements are expected in a very thin shell of ~ 15 km of thickness (type A SD). This layer embraces a tiny amount of matter ($\sim 2 \times 10^{-4}\ M_\odot$) which retains so little heat that is unable to modify significatively the SD cooling.

However, in view of the lack of previous evolutionary computations considering the modifications induced by the presence of a compact SM core, the chemical composition remains still an open question. Then, for the sake of completeness, we also considered (type B) SD models employing the BPS equation of state for $\rho \geq 10^7$ g cm^{-3}.

For the cooling calculations, we used a WD evolutionary code (see Ref. [8] for a description) modified to allow for the properties of the SM core adequately. Fortunately, $GM/rc^2 \sim 10^{-2}$ in the SM core surface, so that we can safely neglect general relativistic effects on the SD models here studied.

In order to describe SM, we adopted the equation of state of the MIT bag with $B = 60$ MeV fm^{-3}. For the thermal conductivity $\kappa_{\rm cond}$ and neutrino emissivity ε_β of SM, we adopted the expressions given by Heiselberg and Pethick [13],

$$\kappa_{\rm cond} = 9.79\times10^{21}\left(\frac{\alpha_c}{0.1}\right)^{-1}\left(\frac{\mu}{300\ \rm MeV}\right)^{2}\frac{\rm erg}{\rm cm\ s\ K}, \tag{1}$$

and Haensel [14],

$$\varepsilon_\beta = 2.2\times10^{26}\,\alpha_c\,Y_e^{-1/3}\,T_9^6\,\frac{n}{n_0}\,\frac{\rm erg}{{\rm cm}^3\,{\rm s\,K}}, \tag{2}$$

respectively, where α_c is the QCD coupling, μ is the quark chemical potential, Y_e is the number of electrons per baryon, T_9 is the temperature in 10^9 K units, and n (n_0) is the baryon (saturation) density. In the present work we assumed the typical values $\alpha_c = 0.1$ and $Y_e = 10^{-3}$. It will be clear from the analysis here presented that the results are not strongly dependent upon the assumed ε_β.

Also, we note that due to the very high conductivity, the SM core remains almost isothermal throughout the entire evolution of the SD models. In fact, in a previous version of the present work, we considered the conductive opacity given in Ref. [14], which is larger than the given by Eq. (1) in, at least, 2 orders of magnitude. In such case we found evolutionary results completely indistinguishable from the ones presented below. It is clear that this would have also been the case if we had considered $\kappa_{\rm cond} \rightarrow \infty$ (i.e., a completely isothermal SM core).

We have evolved SD and WD models in the range of luminosities from 1 $L_\odot$ to 10^{-5} $L_\odot$ where a wealth of observational data has been compiled. Of particular interest is the observed luminosity function $\Phi_{\rm obs}$ [15], defined as $\Phi_{\rm obs} = \log_{10}(N)$, where N is the number of stars per unit volume and per unit of magnitude (brightness). Theoretically, in the case of constant birthrate, $\Phi \propto dt_{\rm cool}/d\log_{10}(L/L_\odot)$ for a given stellar mass. In Fig. 2 we show Φ as function of $\log_{10}(L/L_\odot)$ for each WD (solid lines), type A SD (short dashed lines), and type B SD (dotted lines) model (denoted as $\Phi_{\rm WD}$, $\Phi_{\rm SD}^A$, and $\Phi_{\rm SD}^B$, respectively) normalized at the observed value of $\Phi[\log_{10}(L/L_\odot) = -2.616] = -3.821$ pc^{-3} $M_{\rm bol}^{-1}$. In this plot, at $\log_{10}(L/L_\odot) = 0$ the larger the mass the lower the Φ, and the same at $\log_{10}(L/L_\odot) \leq -4.0$. This is valid for both kind of stars. We note that, for a given mass, $\Phi_{\rm SD}^{A,B}$ and $\Phi_{\rm WD}$ are very similar and the largest differences occur at very low luminosities, at which the objects are almost completely solid (see Fig. 3). At such low luminosities, the specific heat at constant volume is $C_V \propto \rho^{-3/2}T^3$ which leads to a fast (Debye) cooling. Because, in the case of SD, the density near the SM core is by far larger than for a WD of the same mass, in these layers $C_V^{\rm SD} \ll C_V^{\rm WD}$, which explains the slightly faster falling down of $\Phi_{\rm SD}^{A,B}$ compared to $\Phi_{\rm WD}$. Unfortunately,

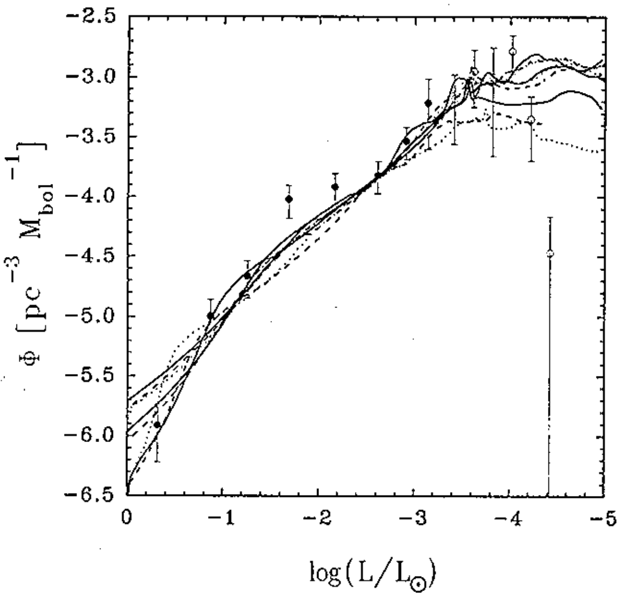

FIG. 2. The theoretical luminosity function (for constant birthrate) vs logarithm of the luminosity for type A SD (short dashed lines), type B SD (dotted lines), and WD (solid lines) models. The observed LF values with their respective error bars [15] are also included. See text for explanation. The logarithm is to base 10.

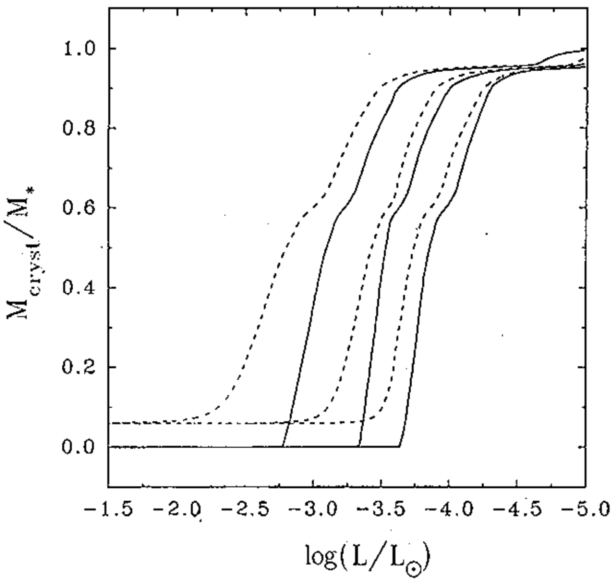

FIG. 3. The evolution of the crystallization front in the Lagrangian coordinate as a function of the luminosity for type A SD (short dashed lines) and WD (solid lines) models. Type B SD lines are almost coincident with the corresponding to type A SD and are not shown. For both kind of objects, the growth of the crystallized core begins at higher luminosities the higher the stellar mass is. However, for a given mass, SD's crystallize at higher luminosities than WD's because of their higher internal densities. The logarithm is to base 10.

at these low luminosities, the uncertainties upon Φ_{obs} are by far the largest, much larger than the differences between $\Phi_{\mathrm{SD}}^{A,B}$ and Φ_{WD} preventing us from distinguishing SD's to WD's. Also note that, for a given mass, the slopes of $\Phi_{\mathrm{SD}}^{A,B}$ and Φ_{WD} in the neutrino-dominated epoch ($\log_{10} L/L_{\odot} \geq -1$) are almost the same, showing that it is independent of the SM neutrino emissivity.

We should mention that, in order to make a careful comparison between theoretical Φ and Φ_{obs}, we would have to perform an average of the constant birthrate theoretical Φ's over, among other things, the stellar formation rate, and the initial mass function [Eq. (2) of Ref. [16]]. Such an average is fundamental if we want to compute the age of the galactic disk by adjusting the sudden drop of Φ_{obs} at $\log_{10}(L/L_{\odot}) \approx -4.5$ (see, e.g., Refs. [16, 17]). Whatever the average we choose, it is obvious that we shall not be able to distinguish $\Phi_{\mathrm{SD}}^{A,B}$ from Φ_{WD} if the error bars upon Φ_{obs} are larger than the differences between these two models for each stellar mass. This is indeed the case, as can be noticed from Fig. 2. Consequently, even with the deep differences in the innermost structure of both kind of objects, provided $\rho_B < \rho_{\mathrm{drip}}$ even at $t \to \infty$, it seems impossible to distinguish SD from WD stars with the currently available observational data. Moreover, it is impossible to distinguish between SD's of type A and B with the above performed analysis. Consequently, it is important to note that, as stated in Refs. [6], the SM hypothesis is not in contradiction with observations. This is the main conclusion of the present work.

Large differences between the behavior of SD and WD models should be expected in the evolution in close binary systems at the mass exchanging stage. At such stage, an accreting SD suffers a global compression and in particular the dense normal matter layers should fullfil $\rho_B \gtrsim \rho_{\mathrm{drip}}$. In this case, we expect some explosive phenomena because there are two energy sources that should begin to heat the SD interior simultaneously. One is the burning of the dripped neutrons into SM, which should release about 20 MeV per particle (see, e.g., Ref. [18]) (and also makes the SM core grow instabilizing the structure as discussed above) and the other is the pycnonuclear reactions [12] that should also operate in the just crystallization-induced layers. In this context, a stellar explosion resembling a faint Type Ia supernova is expected. Note that SD stars may undergo such explosive behavior without necessarily being near the Chandrasekhar mass as is the case of normal WD's. This surely deserves further attention.

Finally, we note that if SM has a bound state at some critical baryon number A (see Ref. [19] for discussion of this intriguing possibility and also Ref. [3]) there may also exist stellar configurations with strange cores. However, these objects would not be subject to the strong constraint $\rho_B < \rho_{\mathrm{drip}}$ avoiding the possibility of catastrophic burning discussed above.

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