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Can very compact and very massive neutron stars both exist?

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The existence of neutron stars with masses of $\sim 2M_\odot$ requires a stiff equation of state at high densities. On the other hand, the necessary appearance also at high densities of new degrees of freedom, such as hyperons and Δ resonances, can lead to a strong softening of the equation of state with resulting maximum masses of $\sim 1.5M_\odot$ and radii smaller than ~ 10 km. Hints for the existence of compact stellar objects with very small radii have been found in recent statistical analyses of quiescent low-mass X-ray binaries in globular clusters. We propose an interpretation of these two apparently contradicting measurements, large masses and small radii, in terms of two separate families of compact stars: hadronic stars, whose equation of state is soft, can be very compact, while quark stars, whose equation of state is stiff, can be very massive. In this respect an early appearance of Δ resonances is crucial to guarantee the stability of the branch of hadronic stars. Our proposal could be tested by measurements of radii with an error of ~ 1 km, which is within reach of the planned Large Observatory for X-ray Timing satellite, and it would be further strengthened by the discovery of compact stars heavier than $\sim 2M_\odot$.

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The recent discovery of compact stars (CSs) having a mass of the order of $2M_\odot$ [1,2] puts rather severe constraints on the equation of state (EOS) of matter at large densities. It is clear that matter inside a CS, i.e. β-stable and charge neutral matter, has to be stiff to allow such massive configurations. On the other hand, we know that by increasing the density new degrees of freedom come into the game, for instance hyperons and maybe deconfined quarks. These new ingredients soften the EOS close to their production threshold, but by introducing repulsive interactions, the EOS can be stiff enough at large densities to support a $2M_\odot$ configuration. Examples of hyperonic stars [3,4] and of hybrid stars [5–8] satisfying that constraint exist in the literature, although special limits on the parameters' values have to be imposed. Also quark stars (QSs), stellar objects composed entirely of quark matter (which could exist if the so called Bodmer-Witten hypothesis holds true) [9–11], can satisfy the constraint [5,12]. It is however unlikely that all CSs are QSs: the latter are probably unable to exhibit glitches [13,14] and to explain the data on quasiperiodic oscillations [15]. It is therefore clear that, while the $2M_\odot$ limit allows for exclusion of entire classes of EOSs which are just too soft, by itself it is not able to single out the EOS of matter at large densities.

A way to strongly reduce the uncertainty on the EOS would be to measure the radius of a few CSs, but unfortunately the precise measurement of the radius has up to now proved to be extremely difficult, since it is in most cases based on specific assumptions concerning e.g. the atmosphere and the distance of the object under investigation. Different analyses often lead to opposite conclusions. There have been therefore claims of very small radii, of the order of smaller than about 10 km [16], while other analyses suggest for the same objects significantly larger radii, of the order of 12 km [17]. It is clear that a precise and model-independent measurement of the radius of at least a few CSs is crucial to finally provide the necessary information which will allow the extraction of the EOS of stellar matter at large densities. New satellites have been proposed, and in particular the Large Observatory for X-ray Timing [18,19] claims to be able to measure the radius of a CS, in a few cases, with a precision of the order of 1 km, small enough to distinguish between the two possibilities discussed above.

From the theoretical side, the families of nucleonic [20], hyperonic [4] and hybrid stars [7,21,22], stiff enough to reach $2M_\odot$, all provide radii which are not too small, typically larger than about 11.5–12 km for the canonical $1.4M_\odot$ star. In studies based on piecewise polytropic extensions of EOSs derived within chiral effective field theory up to ρ_0 [23,24], even smaller radii can be obtained. In particular, if the maximum mass is fixed to $2M_\odot$, a $1.4M_\odot$ star can have a radius $R_{1.4}$ down to about 10 km, while if the maximum mass is $2.4M_\odot$ then $R_{1.4} \sim 11.5$ km. However, how to justify within a microscopic calculation the needed polytropic EOS still needs to be clarified.

This seems to put a theoretical bias against the existence of stars having very small radii. No single EOS exists at the moment which is able to provide at the same time large masses for a few CSs and small radii for others. Since the situation from the observational viewpoint is still rather open, in this article we discuss a model which satisfies

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those two conditions [25]. It is difficult to have a unique family of CSs allowing both very small radii and very massive configurations because to have small radii the EOS needs to be rather soft. Therefore, large densities are reached in the center of very CSs, typically of the order of $5 \div 6\rho_0$ or larger. On the other hand, to have very massive configurations, the EOS should be stiff at those same densities. No microscopic mechanism exists to allow a sudden stiffening of the EOS at those large densities. What we discuss in this article is instead a solution based on *two* families of CSs, one made of hadrons and the other made of deconfined quarks, QSs (we assume that the Bodmer-Witten hypothesis holds true). While in the literature many papers exist in which two families have been discussed [26,27], none takes into account the two constraints discussed above.

It is rather natural to imagine that CSs with small radii are composed of hadrons. As already mentioned above, at densities larger than about $2.5 \div 3\rho_0$ hyperons start appearing, and in principle also $\Delta(1232)$ resonances can be produced [28]. The production of these particles softens the EOS and allows very compact configurations. On the other hand, this same softening forbids this hadronic family of CSs to reach very large masses [29–33]. It is therefore very tempting to imagine that the most massive stars correspond to QSs, since quark matter is known to be rather stiff and to support massive configurations [12,34,35]. A crucial question concerns the stability of the stars populating the hadronic branch: when hyperons start being produced in the center of the star it is relatively easy to have a transition to the more stable QS configuration because droplets of strange quark matter can be formed. For instance, the extremely compact hyperonic stars obtained in Ref. [36] would be unstable against decay into QSs. In order to have stable stars with very small radii we resort to the production of Δ resonances which can shift the strangeness production (hyperons) to higher densities.

In relativistic heavy-ion collisions, where large values of temperature and density can be reached, a state of resonance matter may be formed and the Δs are expected to play a central role [37–41]. Moreover, it has been pointed out that the existence of Δs can be very relevant also in the core of neutron stars [32,33,42–44].

Concerning the hadronic EOS, we use the relativistic mean field model with the inclusion of the octet of lightest baryons (nucleons and hyperons) in the framework of the GM3 nonlinear Walecka-type model of Glendenning-Moszkowsky [45]. The values of the meson-hyperon coupling constants have been fitted to reproduce the potential depth of hyperons at saturation ($U_\Lambda^N = -28$ MeV, $U_\Sigma^N = +30$ MeV, $U_\Xi^N = -18$ MeV) [46,47]. To incorporate Δ isobars in the framework of effective hadron field theories, a formalism was developed to treat Δ analogously to the nucleon, taking only the on-shell Δs into account and the mass of the Δs are substituted by the effective one in the mean field approximation [48,49]. The Lagrangian density of the Δ isobars can then be expressed as [48,50,51]

$$\mathcal{L}_\Delta = \bar{\psi}_{\Delta\nu}[i\gamma_\mu\partial^\mu - (M_\Delta - g_{\sigma\Delta}\sigma) - g_{\omega\Delta}\gamma_\mu\omega^\mu]\psi_\Delta^\nu, \quad (1)$$

where ψ_Δ^ν is the Rarita-Schwinger spinor for the Δ baryon.

Due to the uncertainty on the meson-Δ coupling constants, we limit ourselves to considering only the couplings with σ and ω meson fields, which are explored in the literature [50–52]. If the SU(6) symmetry is exact, one adopts the universal couplings $x_{\sigma\Delta} = g_{\sigma\Delta}/g_{\sigma N} = 1$ and $x_{\omega\Delta} = g_{\omega\Delta}/g_{\omega N} = 1$. However, the SU(6) symmetry is not exactly fulfilled, and one may assume the scalar coupling ratio $x_{\sigma\Delta} > 1$ with a value close to the mass ratio of the Δ and the nucleon [51]. On the other hand, QCD finite-density sum rule results show that the Lorentz vector self-energy for the Δ is significantly smaller than the nucleon vector self-energy, implying, therefore, that $x_{\omega\Delta} < 1$ [52].

In this paper we adopt two different choices for the Δ-meson couplings ($x_{\sigma\Delta} = 1.25$, $x_{\omega\Delta} = 1$ and $x_{\sigma\Delta} = 1.15$, $x_{\omega\Delta} = 0.9$). Both parameterizations are consistent with the experimental flow data of heavy-ion collisions at intermediate energies [53]. Larger net attraction for Δ isobar can imply mechanical instabilities in the EOS, and this condition will be explored in detail in future investigations. In Fig. 1 we display the baryon density dependence of the particle's fractions. It is remarkable that the early appearance of Δ resonances, the first one being the Δ^-, considerably shifts the onset of hyperons which start to form at densities of $\sim 5\rho_0$ (see the curve for the Λs).

A final comment concerning the experimental constraints on the density dependence of the symmetry energy is in order [54]. Within the GM3 parametrization here adopted, only the experimental value of the symmetry energy at saturation S_v is used ($S_v = 32.5$ MeV in GM3) to fix the coupling between the ρ meson and the nucleons.

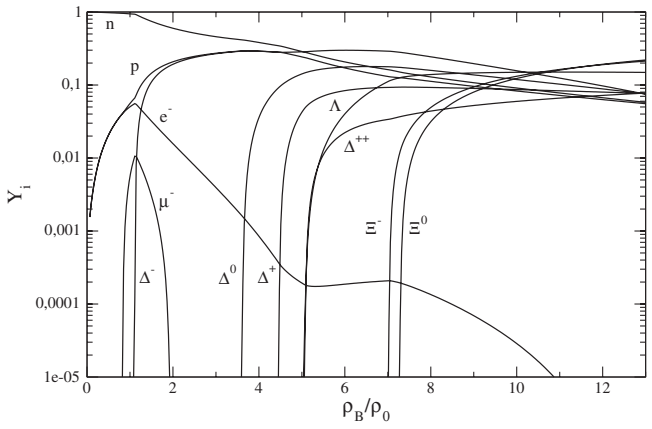

FIG. 1. Particle fractions as functions of baryon density, for $x_{\sigma\Delta} = 1.25$, $x_{\omega\Delta} = 1$.

However, as shown in Ref. [54], a remarkable concordance among experimental, theoretical, and observational studies has been found which allows us to significantly constrain also the value of L (the derivative with respect to the density of the symmetry energy at saturation). Extensions of the GM relativistic mean-field model have been implemented which include ρ meson self-interaction terms. These new parametrizations modify the density dependence of the symmetry energy at supranuclear densities [55] and satisfy all of the experimental constraints. It turns out that, for pure nucleonic stars, $R_{1.4} \sim 12$ km (see for instance [56]), significantly smaller than the GM3 result: this is due to the fact that the more refined model provides a softer EOS mainly in the density range $(1–2)\rho_0$. A softening of the EOS implies a delayed appearance of Δ resonances and hyperons. The main aim of our work is to provide examples of hadronic EOSs allowing for extremely CSs with radii smaller than 10 km, what cannot be achieved by using pure nucleonic EOSs. While it is mandatory for our future studies to update the hadronic model in order to take into account the symmetry energy experimental constraints, on the other hand, the formation of Δs should still be possible, although at larger densities.

For the quark matter EOS we rely, as is customary, on the simple MIT bag model description in which confinement is provided by a bag constant $B_{\rm eff}$ and the perturbative QCD interactions are effectively included in the coefficient a_4 [57]. The total thermodynamical potential reads [5]

$$\Omega = \sum_{u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1 - a_4) + B_{\rm eff}, \qquad (2)$$

where μ is the quark chemical potential and Ω_i are the thermodynamical potentials for noninteracting up, down, and strange quarks and electrons. The mass of the strange quark is fixed to 100 MeV while the up and down quarks are considered as massless. As shown in Ref. [5], in this scheme, it is possible to obtain stellar configurations up to two solar masses or heavier. Here we use the following parameters sets: $B_{\rm eff}^{1/4} = 142$ MeV–$a_4 = 0.9$ (set 1) and $B_{\rm eff}^{1/4} = 127$ MeV–$a_4 = 0.6$ (set 2), both taken from [5]. Set 1 allows a maximum mass for QSs of $2M_\odot$; set2 has been implemented to give an example of quark EOS for which the maximum mass reaches $2.4M_\odot$.

The mass–radius relations for QSs are displayed in Fig. 2 together with hadronic stars. The maximum mass of hadronic stars, containing both Δ resonances and hyperons, is close to $1.5M_\odot$ for the parameters' sets considered here. When excluding hyperons and Δ resonances, the maximum mass of neutron stars reaches instead a value of $\sim 2M_\odot$ but with a large radius. The appearance of Δ resonances is crucial to obtain very compact stellar configurations (as also shown in Ref. [33]) with radii down to 8 km (see the red dashed line): the corresponding mass–radius curves enter the area, framed by the two orange lines, of very

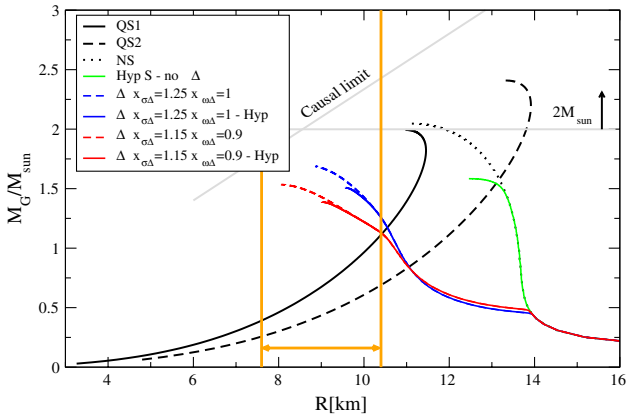

FIG. 2 (color online). Mass–radius relations of QSs (set 1 and set 2) and of hadronic stars. The two orange lines correspond to the 1σ limit for the radii extracted from the analyses of quiescent low-mass X-ray binaries [16].

compact objects inferred in Ref. [16]. The appearance of hyperons in the stars provides a further softening of the EOS, reducing the maximum mass of $\sim 0.1 \div 0.2 M_\odot$ (see the solid/dashed red and blue lines). On the other hand, the mass of QSs can reach values compatible with the recent limit of $2M_\odot$ (black solid line) or even higher values (black dashed line). Notice that QSs mass–radius relations also enter the area of very compact objects but for masses $\lesssim 1M_\odot$: such light stars are difficult to produce in standard supernova simulations, and moreover the lightest known neutron star has a mass of $\sim 1.2M_\odot$. The interpretation we propose here is that massive stars, $M \gtrsim 1.5 \div 1.6 M_\odot$, are QSs with radii $R \gtrsim 11$ km, whereas stars with $R \lesssim 10$ km are composed mainly of nucleons and Δ resonances, with a maximum mass of $\sim 1.5 \div 1.6 M_\odot$. The tension between measurements of large masses and small radii could be strengthened if a neutron star more massive than $2M_\odot$ is discovered favoring our interpretation of two coexisting families of CSs (a possible candidate is PSR B1957 + 20 with an estimated mass of $2.4M_\odot$ [58]).

A crucial question concerns the astrophysical scenarios in which hadronic and QSs are formed and how QSs can generate from hadronic stars. In Fig. 3 we display the gravitational and baryonic masses as functions of the radius for hadronic stars and QSs. On this plot it is possible to construct a path for the formation of QSs from cold hadronic stars accreting matter from a companion. The stellar configuration labeled with B on the solid red line represents the hadronic star for which hyperons start to form in the inner core (notice that at the corresponding point on the baryonic mass curves, the branch with hyperons deviates from the branch with only Δ resonances). The larger the mass of the star the larger is its hyperon content. Notice that (i) only in the presence of hyperons, which carry strangeness, can droplets of strange quark matter form via nucleation [59] and (ii) the star can "decay" into a QS with the same baryonic mass since this process is

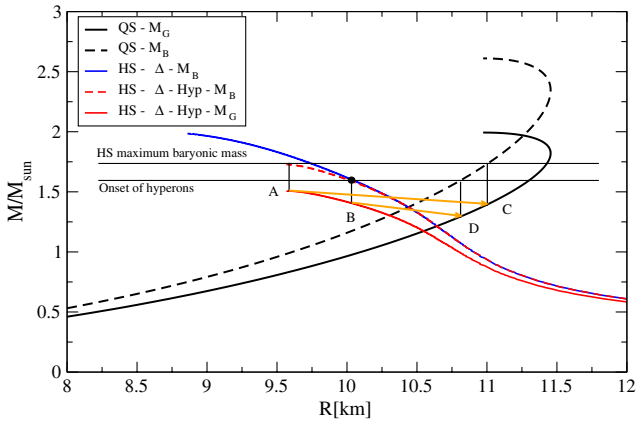

FIG. 3 (color online). Gravitational and baryonic mass–radius relations of QSs (set 1) and of hadronic stars (with and without hyperons, for $x_{\sigma\Delta} = 1.25$, $x_{\omega\Delta} = 1$). A is the maximum mass of hadronic stars containing hyperons. B is the gravitational mass for which hyperons start to form. The dot on the red dashed curve stands for the baryonic mass of B. The quark stellar configurations D and C have the same baryonic masses of B and A but smaller gravitational masses.

energetically favored because the gravitational mass of the configuration D is smaller than the one of B. The energy released in the conversion of a hadronic star into a QS has been estimated in many papers and can easily reach 10^{53} erg [26,27,60,61].

All of the hadronic stellar configurations between B and A can transform into QSs, the probability and velocity of conversion depending on the specific microphysics process of formation of the first droplets of quark matter and on the subsequent expansion of the newly formed phase. There are many studies in the literature addressing these issues. In the scenario here discussed, conversion of cold hadronic stars, quantum nucleation represents a possible mechanism for the formation of the first quark matter droplet [26,27,59–61]. Once a seed of quark matter is formed, the conversion of the whole hadronic star proceeds very fast, with time scales of the order of milliseconds, due to the development of hydrodynamical instabilities [62–64]. A detailed study of the conversion process with the new proposed EOSs is mandatory for future works.

Another scenario for the formation of QSs is related to the supernova explosion of massive progenitors. Large densities can be reached at the moment of the collapse, soon after the bounce, due to the large fallback, and hyperons can already appear at this stage, immediately triggering the formation of quark matter. There the energy released in the conversion can help supernovae to explode [60,65]. In general the conversion of a hadronic star into a QS will produce spectacular transient events such as neutrino and gamma-ray bursts.

There are many possible observables which could be used to test our proposal in which most of the known neutron stars (with masses close to $\sim 1.4 M_\odot$) are hadronic stars while massive stars are more likely QSs (bare or with a crust). We predict that massive CSs also have large radii and, being composed of a different type of matter with respect to the $1.4 M_\odot$ stars (in particular regarding strangeness), should show anomalous cooling histories and spinning frequency distributions; for instance, the photon emission from the surface of a bare QS is very different from the one of neutron stars [66,67]. Moreover, also quasiperiodic oscillations of very massive CSs should differ from the ones of hadronic stars [15].

Finally let us discuss a well-known argument against the coexistence of QSs and neutron stars, based on the production of strangelets during the merging of two CSs [68,69]. If at least one of the two CSs is a QS, it is possible that strangelets are emitted polluting the whole galaxy and triggering the conversion of all CSs into QSs. However recent numerical simulations of QSs' mergers have shown that, in many cases, a prompt collapse to a black hole occurs and no matter is ejected. In particular, this occurs for values of the total mass of the merger larger than $\sim 3 M_\odot$ [70]. It is clear that in the scenario here proposed this request is easily satisfied since for us QSs have masses larger than $\sim 1.5 M_\odot$. Another possibility to prevent the strangelets pollution is offered by the observation that the burning of a neutron star into a QS is uncomplete (at least in hydrodynamical simulations [62–64]): it is therefore possible that a thick layer of hadronic matter survives shielding the inner quark matter core and making it more difficult to release strangelets.

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