Strange-Pulsar Model

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Deep modifications to the current strange-star structure can occur if strange matter is not stable all the way down to zero pressure. This would be the case, for example, if some stable particle is formed at relatively low pressure and/or temperature. We show that the inclusion of a likely specific candidate particle (quark α) in the strange-matter picture leads to stellar models that present more realistic behavior in the light of current pulsar understanding.

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Considerable attention has been recently paid to Witten's proposal[1] which states that the actual ground state of hadronic matter could be, indeed, "strange matter" (SM) instead of ^{56}Fe. This subject has been addressed in several papers concerning both theoretical understanding and expected experimental signals (see Ref. 2 for a review and references therein). While it is generally concluded that laboratory production of SM may be difficult, it is agreed that dense astrophysical objects are favorable environments where this matter could appear.

Stellar objects composed of SM have been called strange stars (SS). The theoretical analysis of their structure, developed in Refs. 3, indicates that the main observable features are very similar to those of conventional neutron stars. However, an important objection has been raised against the existence of SS: The equation of state (EOS) employed up to now for SM has yielded homogeneous stellar models (aside from the possible existence of a thin outer crust composed of normal matter below the neutron drip density ρ_D), having a very modest density versus radius variation. This lack of differentiated internal structure implies that current models for the glitch phenomenon (a sudden modification of the angular velocity Ω followed by a slow healing on quite long time scales) cannot be applied to them. This difficulty has been stressed and discussed by several authors in the past.[3,4]

The aim of this Letter is to show the feasibility of a strange-pulsar model when the EOS is modified to include new phases composed by the recently proposed stable quark complexes[5] (quark alphas, Q_α). The inclusion of these phases leads to important modifications of the SS structure, which may reproduce the main features of pulsar behavior including the glitch phenomenon, since the emerging structure shares several common features with neutron stars.[6] This appears to be necessary if we pursue an interpretation of the type-II supernova events and compact remnants based on the SM hypothesis. We shall begin by discussing the role of the Q_α particles in the SM picture and an approach to the finite-density EOS.

Quark-alpha thermodynamics and EOS.—The standard arguments showing the plausibility of the SM hypothesis mainly rely on a Fermi-gas analysis.[7] This model is supplemented by adding surface-energy corrections when objects of lower baryon number A are considered. Chunks of SM where surface corrections cannot be neglected have been called strangelets. Further reduction of A calls for a shell description of strangelets as performed, for instance, in Ref. 7.

Even if those calculations seem to indicate that stability is unlikely for very low A (with the possible exception of the H dihyperon),[8] several uncertainties concerning the inclusion of quark-quark interactions do not allow conclusive statements about configurations of somewhat larger A. Indeed, it is well known from atomic and nuclear physics that highly symmetric structures are associated with large binding energies, and this effect could lead to (yet unobserved) tightly bound objects whose existence cannot be revealed by phenomenological models. A likely specific candidate for this new form of matter has been recently proposed by Michel.[5] Because of the analogy with α particles, the eighteen-quark configuration with $S=-6$ completely symmetric in spin, color, and flavor space has been called Q_α. Estimations of their binding energy show that these (almost inert) bosons might be bounded by ~ 100 MeV/baryon, making them the most stable composed particle in Nature (if they exist at all).

The Q_α's would be very difficult to form in standard laboratory environments because of the strangeness barrier[9] separating the states $S=0,-1,\ldots$ from the bound state $S=-6$, but could indeed appear when SM rarifies and/or cools.

If we assume the stability of the Q_α state, a first approach to the Q_α structure can be given by a baglike model, writing (by dimensional reasons) the mass as

$M_Q(R) = 4\pi R^3 B/3 + \kappa/R$, where $B = 60$ MeV/fm^3 is the bag constant and κ is a dimensionless quantity containing the sum of quark kinetic, zero-point, and binding-energy terms of this tightly bound state. The standard procedure is to include interactions inside the bag to lowest order, but the nature of the problem makes this approach suspect (interactions should be far from being washed out for a tightly bound object). Instead of calculating the interaction energy perturbatively, we have conversely chosen to fix the constant κ by normalizing the mass to a (typically expected) value of ~ 5 GeV. κ is assumed to remain unchanged when the bag is subject to increasing external pressures up to fusing into the Fermi liquid (as $P_M \ll B$ results from the calculations, this should be a good approximation). Minimizing $M_Q(R)$ with respect to R yields values of $\kappa \sim 34$–36 (depending somewhat on the value of M_Q) and $R \sim 1.7$ fm for each case.

As we are interested in the finite-density EOS, we need to know the free-energy expression for each phase (Q_α and SM) in order to find which state is preferred at a given pressure. Hereafter we shall set $T = 0$ because the temperature is much lower than typical energies involved in our problem.

The simplest assumption on Q_α matter is to consider it as a collection of nonrelativistic Bose hard spheres, as no substantial interaction other than hard-sphere scattering seems possible. The complicated many-body problem in a finite-density regime has been solved in Ref. 10 where numerical results for the energy per boson E/n vs $x = na^3$ (with n the number density and a the Q_α scattering length) has been presented. Q_α matter would revert to bulk SM above a certain transition pressure P_M, where the quark-gluon plasma begins to be preferred. Thus, this bound state would occupy the low-temperature region labeled as "dilute gas of strangelets" in the phase diagram of Ref. 2.

Fitting appropriate analytical expressions to the E/n curves presented in Ref. 10 we have calculated the pressure of each phase (a fluid for $x \leq 0.25$ and a fcc solid for $x \geq 0.27$). Figure 1 shows the pressure as a function of the Gibbs energy per baryon $G = (E+P)/n$, for Q_α matter and SM, showing the existence of a fluid-solid and a solid-SM transition. Two different values of κ where used for Q_α matter, and the current values $M_s = 150$ MeV and $\alpha_c = 0.30$ were employed for the strange-quark mass and the color coupling constant in the SM phase. We find a Q_α-fluid–Q_α-solid transition at $P = 0.06$ and 0.1 MeV/fm^3, and a Q_α-solid–SM transition at $P = 2.5$ and 8.5 MeV/fm^3 for each value of κ, respectively. It is worthwhile to point out that if M_Q is > 5.55 GeV it is not possible to obtain any Q_α-SM transition because Q_α's would not be preferred to SM at $P = 0$, although this feature obviously depends on the adopted SM parameters. On the other hand, if $M_Q < 5$ GeV (extremely tightly bound) the transition would occur at very high pressures $P_M \gtrsim 50$ MeV/fm^3 where

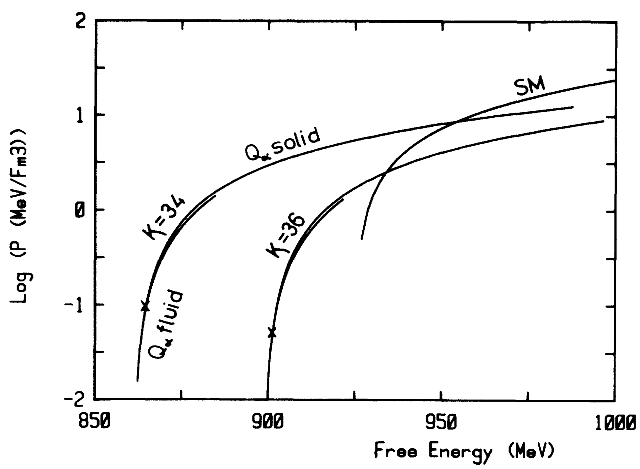

FIG. 1. Plot of the pressure vs free energy showing the preferred phases for a given physical condition. The adopted values of parameters for each EOS are quoted in the text. The crosses signal the actual location of the fluid-solid Q_α transition.

our analytical fit is extrapolated too far from the numerical results of Ref. 10 and even the hard-sphere model should be inadequate. This range gives an idea of the uncertainties involved in the thermodynamics and stellar models resulting from it.

Stellar-model results.—As can be seen from Fig. 1, the relatively low values of the transition pressures P_S and P_M will produce important changes in the structure of the outer layers of SS. In order to find these modifications we have integrated the Tolman-Oppenheimer-Volkoff equations of stellar structure. We have centered our interest in models of $1.4 M_\odot$ (see Fig. 2 for cross sections), a standard value expected both from formation arguments and available observations. We have also verified the stability of these models against radial perturbations.

It should be noted that the final structure of a SS is necessarily formation dependent: These stellar objects would naturally result from a supernova model driven by the appearance of SM which has been shown to convert nuclear matter to SM by means of a detonation wave.[11] Although the detonation front does not reach the edge of the star (the explosive SM formation stops at $R < R_{core}$ and thus avoids a huge ejection of quark matter), the Reynolds numbers of the materials after the expulsion of the stellar envelope (i.e., the supernova explosion) are so high that turbulent convection[12] is expected to mix strange and nuclear fluids with very high efficiency.[13] In this process normal matter will be converted to SM and Q_α matter. However, as the strangeness fraction per particle f_s is always slightly lower than the fraction of nonstrange quarks (due to the finiteness of the strange-quark mass M_s), the process of Q_α formation will leave some "residual" protons and neutrons formed by the u and d quarks in excess. This means that some tiny amounts of normal matter will survive the convective turbulent

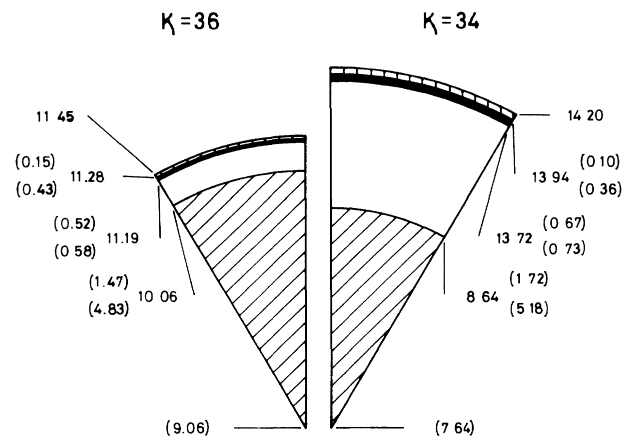

FIG. 2. Cross sections of a $1.4M_{\odot}$ strange star showing the internal structure due to the Q_α's inclusion. The corresponding shells are SM (oblique hatched), Q_α solid (white), Q_α fluid (black), and normal matter (vertical hatched). Numbers quote the values of the radius (in km) at which each interface occurs. The densities on both sides of each interface (in units of 10^{14} g/cm^3) are given in parentheses.

stage, but most of the star will be converted to SM and Q_α's since the time scale of the turbulent convection is much longer than the time scale of the strangeness-formation reaction.

Unfortunately, the actual fraction of the surviving normal matter is impossible to calculate without a detailed numerical model of the complex proto-SS behavior, which is deeply related to the ratio of the Q_α to nucleon formation rates at finite temperature in a turbulent environment. For the moment, we shall treat this quantity as a free parameter. If SS are required to reproduce the observed ratios of moments of inertia I_i/I this amount of normal matter should not exceed 10^{-2} of the total baryon number (see below). In fact, we expect this quantity to be an extreme upper bound and we have used 10^{-3} in our calculations. This adopted value is much smaller than the initial nonstrange-quark fraction $1-f_s$ of a homogeneous SS. The process of convective-turbulent burning to SM and the formation of Q_α with their large binding energy produces such an increase of f_s.

In the steady state, most of the normal matter will be forming an outer crust that can provide the plasma present in current magnetospheric models.[14] Note that this crust is not supported by electrostatic forces as in former models of SS, but coexists in thermal and mechanical (but *not* chemical) equilibrium with a Q_α shell immediately below it, and thus its inner edge can be much denser than ρ_D because the dripped neutrons will not react with the inert Q_α's. Below the normal-matter shell, one finds a Q_α fluid which should exhibit the important property of *superfluidity* because the low-energy excitation spectrum is phononic.[15] Normal matter should not exist inside this fluid phase, because very short diffusion time scales for normal particles should be expected in a superfluid shell. However, some of the normal matter will remain trapped inside the solid Q_α layer which starts below the superfluid Q_α phase, and its charge will provide a strong magnetic coupling with the SM core. Indeed, the time scale for diffusion of normal particles at these densities towards the stellar surface is much longer than the age of the Universe.

It should be noted that, despite several uncertainties about the actual values of the parameters, these models have valuable properties that help to overcome the major objection against the SS existence, related to the appearance of a differentiated internal structure which is a necessary ingredient for explaining the glitch observations. The fractional change $\Delta\dot{\Omega}/\dot{\Omega}$ accompanying the change of Ω suggests the sudden decoupling of an internal component with fractional moment of inertia $I_i/I \sim 10^{-2}$–10^{-3}. The moment of inertia of the Q_α fluid shell present in our models is precisely in this range, and thus may be identified as responsible for the observed behavior. This shell exists for a normal-matter mass fraction smaller than 10^{-2}, and is not very sensitive to its precise value. This appears to be independent of any particular model for the glitch phenomenon, and in fact the applicability of the successful vortex-creep theory,[16] a two-component model, or any other proposal remains to be investigated. We note that the very different values of $\Delta\dot{\Omega}/\dot{\Omega}$ observed, for example, in Crab and Vela pulsars could be attributed in this proposal to slightly different efficiencies in the conversion at the formation stage.

Because of the stiffness of the solid-Q_α EOS, our stellar models have a relatively large radius, a feature which is known to disfavor the stability at high rotation rates. If the recently reported signal from the SN 1987A pulsar[17] is confirmed and interpreted as a rotating source at $\Omega = 1968.625$ sec^{-1}, we should test these SS models by performing detailed calculations of the type presented in Ref. 18. Modeling of this pulsar would clearly favor large κ and/or more massive strange-pulsar models.

Besides the possible accommodation of the glitch phenomenon, the existence of a high-strangeness bound state of QCD such as the Q_α opens the possibility of the existence of a whole new class of compact stars entirely composed of these massive bosons. Preliminary calculations show the stability of these new kind of stars against radial perturbations and detailed structural features will be presented elsewhere.

Although it seems very difficult to imagine a unique signature for identifying this kind of internal structure in a given compact object, we anticipate that, due to the very different form of the EOSs for SM and Q_α matter with respect to the nuclear ones, we can expect well differentiated oscillation spectra. For instance, a distinctive feature could be provided by the identification of very-high-frequency oscillations from compact objects, arising in our models from acoustic waves in the very stiff solid-Q_a region, but a detailed study of this point (of the type presented in Ref. 19) is needed to draw firm conclusions. If pulse microstructure is interpreted as arising from oscillations of the underlying compact object,[20] careful observations are potentially a powerful tool to elucidate the issue of the actual pulsar composition.[21]

Finally, it is necessary to point out that formation of bound states as SM cools or rarifies invalidates several bounds on SM abundance in terrestrial experiments and astrophysical environments devised in the past,[22] a subject which would need further investigation.

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