Strange, quark, and metastable neutron stars

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(Submitted 13 May 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 1, 5–8 (10 July 1987)

Limitations are found on the binding energy of stable strange quark matter. Observational consequences of the possible existence of strange, quark, and metastable neutron stars are examined. The possibility of a Bose condensation of dibaryons in dense nuclear matter is taken into consideration.

The production of strange baryons becomes favored from the energy standpoint at high pressures in massive neutron stars.[1] Witten[2] has pointed out that strange quark matter might be stable at a zero temperature and at a zero external pressure. In this letter we derive limitations on the binding energy of stable strange quark matter, and

0021-3640/87/130003-04$01.00

we examine the observational consequences of the possible existence of strange stars[2–4] consisting of stable, strange, quark matter and of quark stars whose interior consists of weakly unbound strange quark matter and an outer shell of ordinary hadronic matter.

Strange stars cannot experience disruptions in their rotation periods.[3] If strange quark matter is stable, then the pulsars for which disruptions of this sort are observed must be identified with neutron stars which are metastable with respect to conversion into strange stars or black holes. The lifetime of metastable neutron stars is long, since the coherent production of a large number of strange quarks is required for the formation of a critical-size nucleating region of strange quark matter.[2] The central density of metastable neutron stars must be lower than the critical density for a phase transition into nonstrange quark matter. This condition can be written in the form

$$B > \frac{\mu^4}{4\pi^2(1+2^{4/3})^3}\left(1-\frac{2\alpha_c}{\pi}\right) - P. \qquad (1)$$

Here μ and P are the chemical potential and pressure of the neutrons at the center of the star, B is the pressure of the QCD vacuum, and α_c is the QCD coupling constant.

For the pulsar in the Crab Nebula, disruptions occur at intervals $\Delta t \cong 5$ yr. The age of this pulsar is $T = 930$ yr. The lifetime of nuclei (T_{nucl}) with respect to decay into strange quark matter is $M_\odot/m$ (^{56}Fe) times the lifetime of metastable neutron stars, so we find $T_{\text{nucl}} \gtrsim 10^{60}$ yr. The sensitivity of detectors at the earth, $\sim 10^{30}$ yr, is inadequate for observing such decays. In the tensor interaction model we would have $\Delta t = 5$ yr with $\mu = 1088$ MeV, $P = 21$ MeV/fm^3, and $M = 1.3 M_\odot$ (Ref. 5), where M is the mass of the pulsar. From relation (1) we find $B > (85 - 67\alpha_c)$ MeV/fm^3. If the mass of the strange quark is $m_s = 150$ MeV, the energy of stable strange quark matter per unit baryon number is $E/A > m + (18 - 59\alpha_c)$ MeV, where m is the mass of the nucleon. The binding energy of stable strange quark matter apparently could not exceed 30–40 MeV.

The growth rate of strange quark matter in nuclear matter with a temperature $T = 10$ MeV is $v = (10–6) \times 10^3$ cm/s (Ref. 4). Larger values of E/A correspond to smaller values of v. The conversion time for a metastable neutron star can be estimated to be $t \sim (10\ \text{km})/v = 0.05–30$ h. The conversion of a neutron star with a mass exceeding the maximum mass of strange stars,[2] $\overline{M} \cong 2M_\odot$, terminates in the collapse of the core of the strange quark matter. The collapse of an ordinary star may give rise to a gravitationally stable neutron star with $M > \overline{M}$ containing an admixture of strange quark matter. In such a case, a second collapse should occur in a time $t \sim (10\ \text{km})/v = 0.05–30$ h. Strange quark matter can form in a neutron star through (for example) an intermediate phase transition into nonstrange quark matter. The two neutrino bursts which were detected a few hours apart during the explosion of supernova SN1987A (Ref. 6) can be identified with the collapse of an ordinary star and the collapse of the core of strange quark matter of a metastable neutron star.

Strange stars can have an arbitrarily small radius.[2–4] The minimum radius of neutron stars or quark stars is $R \cong 10$ km (Fig. 2), and their rotation period must be greater than $P_1 \sim 2\pi R/c = 0.2$ ms. Radiopulsars with periods $P \cong 1–10^4$ ms are known.

The observation of a pulsar with a period $P < P_1$ would be direct proof of the existence of strange stars. A search for pulsars with ultrashort periods would be extremely interesting.

Let us examine a model of quark stars which is a very simple modification of Witten's strange stars.[2] We describe the hadronic phase of the matter as a degenerate ideal Fermi gas of neutrons, protons, and electrons, while the quark phase is described as a degenerate ideal, ($\alpha_c = 0$) Fermi gas of u, d, and s quarks and electrons. The applicability of a model of this sort must be restricted to low critical densities for the phase transition[7]; such a restriction is equivalent to the condition that the strange quark matter is weakly unbound. Figure 1 shows the pressure in the hadronic and quark phases versus the chemical potential of the d quarks. At $\mu_d > \mu_d^D = 338$ MeV, the hadronic phase is metastable. With $\mu_d = \mu_d^C$, it is favorable from the energy standpoint for two nucleons to leave the Fermi surface and to fuse into a $6q$ bag. An increase in the density of hadronic matter leads to the formation of a dibaryon Bose condensate. Dibaryons do not contribute to the pressure since they have a zero momentum; the pressure accordingly does not increase with increasing density. The hadronic matter loses its elasticity. Stable neutron stars with a dibaryon Bose condensate do not exist. Among the dibaryon resonances which have been established most reliably, the first to condense is $\Lambda N(2130)$ with $I, J^P = 1/2, 1^+$ (Ref. 8) with $\mu_d = \mu_d^C = 360$ MeV. Figure 2 shows the mass versus the radius of quark stars and neutron stars. The maximum mass of the neutron stars which would be set by the Bose condensation of $\Lambda N(2130)$ is less than the OV limit.

If we ignore the interactions of dibaryons with neutrons and with each other, we conclude from the condition that the pulsar in the Crab Nebula is a neutron star that the masses of the dibaryons must be greater than $m(6q)^{\min} = 2\mu = 2176$ MeV. At an accuracy acceptable for our purposes, we can assume that the resonance $\Lambda N(2130)$

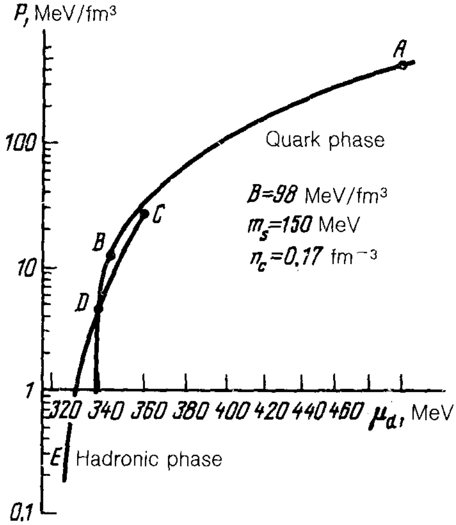

FIG. 1. Pressure in the quark phase (ABD) minus the pressure of the QCD vacuum, $B = 98$ MeV/fm^3 and pressure in the hadronic phase (CDE) as functions of the chemical potential of the d quarks for $m_s = 150$ MeV and for the value $n_c = 0.17$ fm^{-3} for the critical density for the phase transition to the strange quark matter. Points A and B correspond to the state of the strange quark matter at the center of quark stars with the maximum and minimum masses (Fig. 2). Gravitationally stable quark stars do not exist on arc 8D.

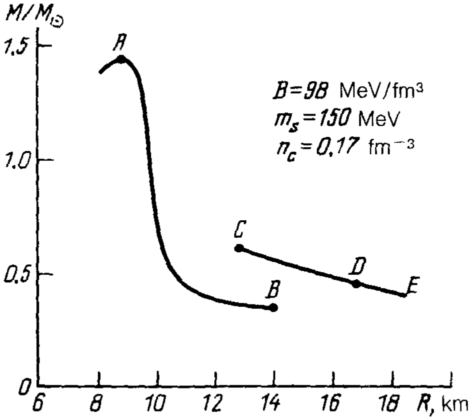

FIG. 2. Masses of quark stars and neutron stars versus the radius; the notation is the same as in Fig. 1. AB and CDE are branches of gravitationally stable quark stars and neutron stars; CD represents long-lived metastable neutron stars.

satisfies this limitation. The condition $m(6q) > 2176$ MeV casts doubt on the existence of an $NN(1960)$ resonance.[8] A dibaryon with such a mass should have condensed at a density $n \cong 0.1\ \mathrm{fm}^{-3}$, which is less than that which prevails in ordinary nuclei.

As a result of the conversion of a metastable neutron star into a quark star or a strange star, there is a change in the characteristic age of the pulsar. In the old remnants of the supernova MSH 15–52 ($\tau_{\mathrm{rem}} = 2 \times 10^4$ yr) there is a young pulsar PSR1509–58 ($\tau_{\mathrm{char}} = 1.7 \times 10^3$ yr). The age of this pulsar can be reconciled with the age of the nebula by assuming that after the explosion of the supernova a metastable neutron star formed and that this star spontaneously converted into a quark star or a strange star $\cong 1.7 \times 10^3$ yr ago.

I wish to thank S. I. Blinikov, M. B. Voloshin, V. I. Zakharov, I. Yu. Kobzarev, L. A. Kondratyuk, I. M. Narodetskiĭ, L. B. Okun', K. G. Selivanov, and M. A. Shifman for useful discussions and Ya. B. Zel'dovich for valuable comments.

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Translated by Dave Parsons