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SOLID QUARK STARS?

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ABSTRACT

It is conjectured that cold quark matter with very high baryon density could be in a solid state, and strange stars with low temperatures should thus be solid stars. The speculation could be close to the truth if no peculiar polarization of thermal X-ray emission (as in, e.g., RX J1856) or no gravitational wave in postglitch phases are detected in future advanced facilities or if spin frequencies beyond the critical ones limited by r-mode instability are discovered. The shear modulus of solid quark matter could be $\sim 10^{32}$ ergs cm^{-3} if the kilohertz quasi-periodic oscillations observed are relevant to the eigenvalues of the center star oscillations.

Subject headings: dense matter — elementary particles — pulsars: general — stars: neutron

1. INTRODUCTION

The gauge theory of strong interaction, quantum chromodynamics (QCD), is still developing; nevertheless, it is well known to have two general properties: asymptotic freedom at smaller scales (~0.1 fm) and color confinement at larger scales (~1 fm). These result in two distinct phases depicted in the diagram in terms of temperature T versus baryon chemical potential μ_b: hadron gas (in the region of low T *and* μ_b) and quark matter (of high T *or* μ_b). The former has been studied well in nuclear physics, but the latter is expected to be a new phase, which has not yet been found with certainty. There are actually two kinds of quark matter in research: the temperature-dominated phase, which may appear in the early universe or in relativistic heavy-ion colliders, and the density-dominated phase, speculated to exist only in astrophysical compact objects, which is the focus of this Letter.

One cannot naively think that the density-dominated quark matter is simply Fermi gas with weak interaction. In fact, the attraction, no matter how weak it is, between quarks renders the Fermi sea unstable to the quark Cooper pairing of the BCS type in a color superconducting state (Alford, Bowers, & Rajagopal 2001, and references therein). This kind of condensation in momentum space takes place in the case of the same Fermi momenta, whereas the "LOFF"-like state may occur if the Fermi momenta of two (or more) species of quarks are different. For three flavors of massless quarks, all nine quarks may pair in a pattern that locks color and flavor symmetries, called the color-flavor locked state.

We suggest, however, an alternative "condensation" in *position* space for quark matter with high baryon density and discuss the possibility of such matter in a solid state and its various astrophysical implications. We are concerned about the most probable compact objects composed entirely of deconfined light quarks, the so-called strange stars (e.g., Glendenning 2000). In fact, a few authors are involved in this possibility more or less. By extending the bag-model study to any color-singlet multiquark system, Jaffe (1977) predicted an S-wave flavor-singlet state of a six-quark cluster (H particle). An 18-quark cluster (called quark-alpha, Q_α) being completely symmetric in spin, color, and flavor space was also proposed (Michel 1988), which could be essential to reproduce pulsar glitches by modifying significantly the strange star structures (Benvenuto, Horvath, & Vucetich 1990).

2. CAN QUARK MATTER BE SOLID?

There are virtually two ingredients that affect the formation of the quark cluster in quark-gluon plasma: Pauli's exclusion principle and interactions. Suppose we "turn off" the interactions at first. Let us consider two quarks for simplicity. The wave function of quarks is $\Psi(1,\ 2) = \Psi^{\rm inner}(1,\ 2)\Psi^{\rm position}(1,\ 2)$, where $\Psi^{\rm inner}(1,\ 2)$ describes particles in inner space while $\Psi^{\rm position}(1,\ 2)$ describes particles in position space. Because of the identical principle of fermions, these two quarks exchange asymmetrically, i.e., $P_{12}\Psi(1,\ 2) = -\Psi(1,\ 2)$, with $P_{12} = P_{12}^r P_{12}^\sigma P_{12}^f P_{12}^c$, where r, σ, f, c denote the position, spin, flavor, and color degrees of freedom, respectively. Quarks have a tendency to condensate in position space if $\Psi^{\rm position}(1,\ 2)$ is exchange-symmetric,

$$\Psi_{\rm AB}^{\rm position}(1,\ 2) = \frac{1}{\sqrt{2}}[\Phi_{\rm A}(1)\Phi_{\rm B}(2) + \Phi_{\rm B}(1)\Phi_{\rm A}(2)], \qquad (1)$$

while $P_{12}\Psi^{\rm inner}(1,\ 2) = -\Psi^{\rm inner}(1,\ 2)$. Equation (1) shows that the possibility of one quark "hobnobbing" with another is high. But this possibility is almost zero if $\Psi^{\rm position}(1,\ 2)$ is exchange-antisymmetric. In order to see the significance of this exchange effect, Zhang & Yu (2002, and references therein) have calculated the matrix of operator P_{12} and find that for a system with two S-wave baryons, the formation of some bound states of a six-quark cluster is favored (e.g., ΩΩ, ΔΔ, etc.).

Whether quark clusters can form relies also on the model-dependent color, electromagnetic, and weak interactions, particularly the color-dominated one. We therefore conjecture the existence of n-quark clusters in quark matter, leaving n as a free parameter, possibly from 1 to 18 or even larger. Note that n may depend on temperature and baryon density and that more than one kind of quark cluster may appear at a certain phase (i.e., quark clusters with different n's could coexist). Although these hypothetical quark clusters may not form in terrestrial laboratory environments with low baryon density (or μ_b), it is very likely that quarks could be clustered in the "deconfined" phase, especially in the strange quark matter assumed to be absolutely stable.

The next step is to investigate the melting temperature T_m^n for the component of n-quark clusters. The quark matter could be solid as long as the temperature T is less than one of T_m^n values. The n-quark clusters might be divided into two classes: color singlet or not. The former would be the quark analog of molecules (e.g., H_2O and CO_2), the short-distanced color force (the color "Van der Waals force") between which could crystallize the clusters at low T (as an experiment example of H_2O, water boils at 100°C when density is $\sim$1 g cm^{-3}, but freezes even at 300°C when density is $\sim$1.5 g cm^{-3}), and the latter is of ionic lattice (e.g., NaCl, ZnS, something like a plasma *solid* rather than a fluid) when $T < T_m^n$. Because of the color screen in quark-gluon plasma, n-quark clusters with color charge cannot interact at long range but are also short-distanced. Phase transition, which could happen more than once, occurs when one component of the n-quark clusters begins to be fixed at certain lattices as the matter cools. We may assume a Van der Waals–type potential between n-quark clusters since both kinds of clusters interact at short distance. The melting temperature $T_m \sim \varepsilon_B$, where ε_B is the Van der Waals binding energy. For conventional solid matter bound with the electric interaction (Weisskopf 1985a, 1985b), $\varepsilon_B \sim$ 1–10 kcal mol^{-1} (or $\sim$0.05–0.5 eV), and the distance between two nearby atoms is $r_a \sim$ 2–4 Å. For two unit charges at this separation, the interaction energy could be $\epsilon \sim e^2/r_a \sim$ 7–4 eV. Therefore, due to the electric screen effect, the binding reduces by a factor of $S_e = \epsilon/\varepsilon_B \sim$ 10–200. If the interaction between quarks could be described as a Coulomb-like potential (e.g., Lucha, Schöberl, & Gromes 1991), $V(r) \sim \alpha_s/r$ with $\alpha_s \equiv g_s^2/4\pi$ and g_s the strong coupling constant, the Van der Waals–type binding energy between n-quark clusters could be $\varepsilon_B \sim \alpha_s(n_b/n)^{1/3}/S_c$, where S_c is the corresponding color screen factor and n_b the baryon number density. For quark matter with nuclear matter density about 2 times normal, $n_b \sim 0.3$ fm^{-3}, $n \sim 10$, $\alpha_s \sim 1$, and $S_c \sim S_e$, we have $T_m^n \sim \varepsilon_B \sim$ 0.3–6 MeV, which is much larger than the observed surface temperatures ($\sim$100 eV; e.g., Xu 2002) of potential strange star candidates. Newborn strange stars could thus be solidified soon after supernova. The nature of this kind solid quark matter may depend on the quark cluster structures (Liu, Li, & Bao 2003) as well.

3. TESTS FOR THE SOLID STRANGE STAR IDEAL

How can one determine whether a strange star candidate is solid? Although the possibility of solid cold quark matter cannot be ruled out, unfortunately, because of the complex nonlinearity of QCD, it is almost impossible to draw a certain conclusion yet from first principles. Nonetheless, possible critical observational tests are addressed, which may finally present a clear answer to the question.

Polarization of thermal photons?—For a hot bare strange star (BSS) with temperature $T > T_u \sim 10^9$ K ($\sim$0.1 MeV), the mechanism, proposed by Usov (1998), of pair production and their annihilation works (e.g., Usov 2001). Such a hot BSS is in a fluid state if $T > T_m$. However, a cold strange star with $T < T_m$ is solid, and the Usov mechanism does not work if $T < T_u$. The photon emissivity may not be negligible in this case since the opinion that the BSS surfaces should be very poor radiators at $T \ll \hbar\omega_p \sim 20$ MeV (ω_p is the plasma frequency) is for a fluid plasma rather than a solid one.

In a BSS, although part (or all) of the quarks are clustered in fixed lattices, electrons with number density $n_e \sim 10^{-4} n_b$ are free (the density of free electrons could be much smaller if part of electrons and clusters form "atoms" or "ions"). The interactions of one electron with another, or with the lattices (n-quark clusters), could be responsible to the thermal photon radiation. Electrons are in the levels of the energy bands (rather than discrete levels) because of their motion in a periodic lattice. This may result in a featureless spectrum as observed (Xu 2002). The thermal emission of such a solid could be analogous to that of metals (Born & Wolf 1980) to some extent. According to Kirchhoff's law of thermal radiation, the spectral emissivity

$$\psi(\nu, T) = \alpha(\nu, T) B(\nu, T), \qquad (2)$$

where $\alpha(\nu, T)$ is the spectral absorbance and $B(\nu, T)$ is the Planck function of blackbody thermal radiation. Therefore it is essential to calculate $\alpha(\nu, T)$ in order to have a thermal spectrum of BSSs. We are embarrassed if we try to obtain an exact absorbance $\alpha(\nu, T)$ from QCD phenomenological models. Nevertheless, $\alpha(\nu, T)$ can be calculated in classical electrodynamics, which is a function of electric conductivity (Born & Wolf 1980).

Within the realm of solid bare strange stars, Zhang, Xu, & Zhang (2003) have fitted well the 500 ks *Chandra* LETG/HRC data for RX J1856.5−3754 in the spectral model of equation (2), with a spectral absorbance of metals (Born & Wolf 1980), $\alpha(\nu) = 1 - (2\sigma/\nu + 1 - 2\sqrt{\sigma/\nu})/(2\sigma/\nu + 1 + 2\sqrt{\sigma/\nu})$, where σ is the conductivity, which could be a function of temperature T. They found a low limit of electric conductivity of quark matter $\sigma > 1.2 \times 10^{18}$ s^{-1}, with the fitted radiation temperature $T_\infty \sim$ 60 eV and radius $R_\infty > 7.4$ km. If the electrons near the Fermi surface are responsible for the conduction, one has $\sigma = n_e e^2 \tau/m_*$, where the electron number density $n_e \sim 10^{34}$ cm^{-3}, e the electron charge, τ the relaxation time, and m_* the effective electron mass. For the case of free degenerated gas, we have $\tau \gtrsim 8 \times 10^{-21}$ s. If electron-electron collisions are responsible for the conduction, one can obtain the relaxation time (e.g., Flowers & Itoh 1976; Potekhin, Chabrier, & Yakovlev 1997). Using Appendix A.1 by Potekhin et al. (1997) as an estimate, one has $\tau \sim 2.3 \times 10^{-16}$ s for typical parameters. The value could be larger or smaller if (1) some of the electrons are captured by lattices by Coulomb force or (2) other interactions (e.g., electron-phonon, electron-defect) are included. In summary, the conductivity fitted could be reasonable.

No atomic feature is found in the thermal spectra detected, which is suggested to be evidence for bare strange stars (Xu 2002; note that the absorptions in 1E 1207.4−5209 are very probably associated with cyclotron lines: see Bignami et al. 2003; Xu, Wang, & Qiao 2003). How can a neutron star reproduce such a spectrum? Strong magnetic fields may help, for instance, RX J1856 to do this, since a condensation transition in the outermost layers may occur if RX J1856 has a high magnetic field ($>10^{13}$ G for Fe and $>10^{14}$ G for H atmospheres; Turolla, Zane, & Drake 2003). However, in such a strong magnetic field, the surface thermal X-ray emission should have a peculiar nature of polarization (e.g., Gnedin & Sunyaev 1974; Lai & Ho 2003: the polarization plane at <1 keV is perpendicular to that at >3 keV). But if RX J1856 is a solid BSS with normal magnetic field ($\sim 10^{12}$ G), the surface density $\rho > 10^{14}$ g cm^{-3}, and the particle kinematic energy density is thus much greater than the magnetic one, $\rho c^2 \gg B^2$. We expect therefore, for solid BSSs, that the magnetic effect on the thermal photon emission is negligible and that the polarization of X-rays is much *lower*. These results provide a possibility to test neutron or strange star models (e.g., for RX J1856) by X-ray polarimetry in the future, if the depolarization effect in the magnetosphere is negligible. Rapid rotation may smear a possible spectral line, but a fast-rotating pulsar can hardly be "dead". Further differences between the high-energy emission of a solid BSS with $\sim 10^{12}$ G and a neutron star with $\gg 10^{12}$ G might be possible if vacuum nonlinear electrodynamic effects are included (Denisov & Svertilov 2003).

Pulsar timing?—The spin variation of Earth could be an effective probe of Earth's interior (e.g., the Chandler wobble and the 10 year timescale change of spin may show various kinds of coupling between the fluid core and the solid mantle). It is also possible to investigate pulsar interior by timing, the great precision of which is unique in astronomy. Apart from planets, radio pulsars are another example of solid state matter in the universe (glitch is clear and direct evidence for such a solid state). Radio pulsars, at lest part of them, could be BSSs for the peculiar nature of drifting subpulses (Xu, Qiao, & Zhang 1999) though these phenomena may also be explained if the actual surface magnetic field at the polar cap of neutron stars is very strong ($\sim 10^{13}$ G) and highly non-dipolar (Gil & Melikidze 2002). Furthermore, precessions and glitches observed may be well understood if pulsars are *solid* BSSs.

The equilibrium figures of rotating stars can be approximated by Maclaurin spheroids. For Earth, such an eccentricity is calculated as $e = 0.092$, which is of the same order observed ($e = 0.083$). PSR B1828−11 has a rotation frequency $\omega = 2\pi/0.405\ \mathrm{s}^{-1}$ and precesses with probably a frequency $\omega_p = 2\pi/500\ \mathrm{day}^{-1}$ (Stairs, Lyne, & Shemar 2000; Link & Epstein 2001). In the case of homogenous ellipsoid approximation, $\omega_p/\omega \approx 0.5e^2$ (for $e \ll 1$), with the eccentricity $e = (a^2 - c^2)^{1/2}/a$ (a, c are the semimajor and semiminor axes, respectively). We have $e = 1.4 \times 10^{-4}$ from the precession observation, but $e = 2.2 \times 10^{-3}$ from a calculation of a Maclaurin spheroid with one solar mass and 10 km in radius. This discrepancy could be due to (1) the homogenous approximation, (2) the general relativistic effect, (3) a very low mass, and (4) the strong interaction, if the pulsar is actually a strange star (no eccentricity if the centrifugal effect is negligible).

The observation of PSR B1828−11 precession means that the vortex pinning is much weaker than that predicted in pulsar glitch models. If PSR B1828−11 is a vortex unpinning neutron star with a spherical superfluid core, the observation may be of the crust precession (see eq. [32] of § 384 in Lamb 1932). But if it is with an elliptical fluid core (the crust mass $\sim 10^{-5}$ $M_\odot$ is negligible), the precession frequency could be $\omega_p \sim \omega/e \gg \omega$ (eq. [42] of § 384 in Lamb 1932) , which conflicts with observations. More than these, in both cases, the crust could be deformed irrecoverably by the inertial force of the fluid core, since the anelastic crust has a tendency to spin along one of the principal inertial axes.

For such a neutron star with radius R, the strain $\sim \dot{\alpha}\tau/\alpha$ and the stress $\sim (2\pi/3)e^{-2}R^2\rho\alpha^2\omega^2$, with α the angle between rotational and principal axes and τ the timescale of relaxation. One has thus $\alpha(t) \sim [(4\pi/3\mu\tau)e^{-2}R^2\rho\omega^2 t + \alpha_0^{-1}]^{-1/2}$, where the shear modulus of neutron star crusts could be (Fuchs 1936) $\mu^{\mathrm{NS}} = 2.8 \times 10^{28}\delta Z_{26}^2 A_{56}^{-4/3}\rho_{11}^{4/3}$ ergs cm^{-3} ($\delta = 0.37$, ions have charge $Z = 26Z_{26}$ and mass number $A = 56A_{56}$, and the density $\rho = \rho_{11}10^{11}$ g cm^{-3}), and $\alpha_0 = \alpha(0)$. In the case of $\alpha_0 \sim 3^\circ$ (Link & Epstein 2001), the timescale for α to change from α_0 to $\alpha_0/2$ is then

$$T_{1/2}^{\mathrm{NS}} \sim 9.1 \times 10^{-5}\tau^{\mathrm{NS}}\mu_{28}\rho_{11}^{-1}, \qquad (3)$$

where $\mu_{28} = \mu/(10^{28}$ergs cm^{-3}). However, if the pulsar is a solid strange star, the corresponding value is $T_{1/2}^{\mathrm{SS}} \sim 9.1 \times 10^3\tau^{\mathrm{SS}}\mu_{32}\rho_{15}^{-1}$, which should be more than 8 orders larger than $T_{1/2}^{\mathrm{NS}}$ [$\mu^{\mathrm{SS}} \sim 10^{32}$ ergs cm^{-3} [see eq. (4), and the stress of solid stars $\sim (2\pi/3)R^2\rho\alpha^2\omega^2$]. Such a great difference may be used to test the solid strange star model by obtaining the beamwidth change as the precession amplitude decays, although the absolute timescales of τ^{NS} and τ^{SS} are still uncertain.

Glitches observed may be well understood if pulsars are *solid* strange stars. As a pulsar slows down and therefore the centrifugal force decreases, stresses develop due to (1) a reduction in the stellar volume and (2) a less oblate equilibrium shape. Both should result in the decrease of the moment of inertia, but the star's rigidity resists the stresses until the star cracks when the stresses reach a critical value. Such a "starquake," an analog of an earthquake, rearranges the stellar matter and thus decreases abruptly the inertia momentum. This global starquake with mass $\sim 1\ M_\odot$ could reproduce large Vela-like glitches, while the crust ($\sim 10^{-5}\ M_\odot$) quake of neutron stars cannot. In addition, the starquake may excite precession.

Asteroseismology?—It is well known that oscillation modes can provide much information on stellar interior, the apotheosis of which is helioseismology, which has largely confirmed the main elements of the standard solar model. We then have a chance to test the solid strange star model via asteroseismology. According to the differences of restoring forces, oscillation modes can be divided into pressure mode, or *p*-mode (by pressure gradient), gravitational mode, or *g*-mode (by buoyancy in gravity), rotation mode, or *r*-mode (by Coriolis force in rotating stars), and shear mode, or *s*-mode (by shear force). The essence of a solid object is nonzero shear modulus, $\mu \neq 0$, which means that *p*- and *s*-modes can exist, but *g*- and *r*-modes do not.

Fortunately variety of pulsation modes of fluid neutron stars have been investigated previously (e.g., Andersson & Comer 2001), the results of which may provide an order-of-magnitude insight into fluid strange stars. It is found (Andersson & Comer 2001) that the glitches of pulsars can excite the modes large enough to be detected in future gravitational-wave detectors (EURO with or without photon shot noise) if they are in a superfluid state. However no gravitational wave can be observed if glitching pulsars are solid strange stars in EURO since, especially, no *r*-mode instability can occur there. It is not certain whether significant gravitational waves can be observed in EURO soon after a supernova if solid quark matter is possible, since we lack exact knowledge of the melting temperature T_m. The dynamics of supernova gravitational wave should (not) be changed significantly if $T_m > 10$ MeV ($T_m < 1$ MeV). It is true that a nascent hot strange star may be fluid, and its spin frequency is limited due to the gravitational radiation caused by *r*-mode instability (Madsen 1998). However, for cold recycled millisecond pulsars, if they are solid, the upper limit of rotation frequency could be much larger than that given by Madsen (2000).

Asteroseismology may validate the elastic properties of solid strange stars. Kilohertz quasi-periodic oscillations (kHz QPOs) are found in "neutron" stars but not in black hole candidates (BHCs) (van der Klis 2000). This might be an unique signature of the center "neutron" stars. In addition, a recent study with improved technique of data processing shows that QPOs of "neutron" stars are quite different from that of BHCs; the former could be originated by stochastic oscillations, but the latter by periodic modulations (T. P. Li & L. Chen 2003, in preparation). Could the kHz QPOs be caused by the global oscillations of a solid strange star?

We propose an alternative mechanism for kHz QPOs, that torsional oscillations, rather than radial ones, could excite effectively the transverse Alfvén waves in magnetospheres and then affect the accretion rates, while the global oscillations are excited by accretion of varying rates with randomicity. The solution of free oscillations of a uniform elastic sphere can be found in Garland (1979). The torsional oscillation frequency is $\nu = x(l)v_s/(2\pi R)$, with the velocity of shear waves $v_s =$

$(\mu^{SS}/\rho)^{1/2}$ and $x(l)$ a function of degree l of spherical harmonics $(\{x(1) = 5.8, 9.1, 12.3, \ldots\}$ and $\{x(2) = 2.5, 7.1, 10.5, \ldots\}$ for $l = 1, 2$, respectively). If kHz QPOs originates in this way, we can obtain the shear modulus for solid strange stars,

$$\mu^{SS} = 4 \times 10^{32} x_{10}^{-2} R_6^2 \rho_{15} \nu_3^2 \text{ ergs cm}^{-3}, \tag{4}$$

where $x = x/10$, $R_6 = R/(10^6 \text{ cm})$, $\rho_{15} = \rho/(10^{15} \text{ g cm}^{-3})$, and $\nu_3 = \nu/(10^3 \text{ Hz})$. That $\mu^{SS} \gg \mu^{NS}$ is unsurprising since quark matter is much denser than normal matter.

4. DISCUSSIONS

The ideal of solid quark matter is proposed, and three ways are addressed to test it are based on its various astrophysical implications. There may be other consequences of solid quark matter: (1) A strong magnetic field plays a key role in pulsar life, but there is still no consensus on its origin. It is worth noting that a ferromagnetism-like domain structure may appear in a solid strange star. This scenario could be a microscopic mechanism of pulsar magnetic fields. Actually Yang & Luo (1983) found that the quark-cluster phase with parallel spins is energetically favored due to the color-magnetic interaction and that the correspondent Curie temperature is ~10^2 MeV. The ferromagnetism issue has also been noted recently by Tatsumi (2000), who suggested that the Hartree-Fock state with the inclusion of spin polarization shows a spontaneous magnetic instability at low densities through the same mechanism as in electron gas. (2) The calculation of the cooling behavior of strange stars should include the energy release as quark matter solidifies.

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