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CAN COLD QUARK MATTER BE SOLID?

R. XU
School of Physics and State Key Laboratory of
Nuclear Physics and Technology, Peking University,
Beijing 100871, P. R. China.
r.x.xu@pku.edu.cn

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The state of cold quark matter challenges both astrophysicists and particle physicists, and even many-body physicists. It is conventionally suggested that BCS-like color superconductivity occurs in cold quark matter; however, other scenarios with a ground state rather than of Fermi gas could still be possible. It is addressed that quarks are dressed and clustered in cold quark matter at realistic baryon densities of compact stars, since a weakly coupling treatment of the interaction between constituent quarks would not be reliable. Cold quark matter is conjectured to be in a solid state if thermal kinematic energy is much lower than the interaction energy of quark clusters, and such a state could be relevant to different manifestations of pulsar-like compact stars.

Keywords: Dense matter; pulsars; elementary particles.

1. Introduction

First of all, I would like to note that the word "*solid*" in the title does not relate to solid evidence for quark matter, but represents a new *solid* state of quark matter. To identify a quark star should certainly be a milestone and could be possible in the future, but now there is no solid and model-independent evidence yet.

The state of cold quark matter is debated since 1970s, being interested by either particle physicists or astrophysicists. Because of asymptotic freedom, extremely dense and cold matter is supposed to be of a Fermi gas of free quarks, and a condensate of quark pairs near the Fermi surface (i.e., color superconductivity (CSC)) may occur according to perturbative quantum chromodynamics (pQCD) or QCD-based effective models. Astrophysically, however, realistic cold quark matter could only exist in pulsar-like compact stars, and these QCD-based speculations should be tested by different manifestations of such compact stars. I will explain why a solid state of realistic cold quark matter would be necessary from a view point of astrophysics in Secs. 2 and 3. More issues related are addressed in later sections.

2. What if Pulsars are Neutron Stars?

What is the nature of pulsars (PSRs)? The final answer to the question surely depends on the understanding of non-pertubative QCD, and relates to one of the 7 Millennium Prize Problems named by the Clay Mathematics Institute. Nevertheless, the models for pulsars can be classified into four kinds: hadronic stars (no quark matter), hybrid stars (quark matter in the cores), crusted and bare quark stars (quark matter dominates). The former two are usually called neutron stars (NSs), while the latter two quark stars (QSs). It is worth noting that hard and model-independent evidence to identify a QS may only be relevant to *bare* QSs because their quark surfaces have sharp difference distinguishable from others.[1]

Although it is still a matter of debate whether pulsars are neutron or quark stars, some individual PSR-like stars with mass of $\sim 1\mathrm{M}_\odot$ and $\sim 10\,\mathrm{km}$ in radius have certainly been detected. Historically, pulsars were supposed to be associated with oscillations of white dwarfs or NSs,[2] but soon recognized as spinning compact NSs,[3] the Kepler frequency of which in Newtonian gravity is

$$\nu_{\mathrm{Kepler}} = \sqrt{\frac{G}{3\pi}\bar{\rho}} \simeq 841\sqrt{\frac{\bar{\rho}}{10^{14}\mathrm{g/cm}^3}}\ \mathrm{Hz}.$$

The average densities of NSs or QSs, $\bar{\rho}$, are the order of $\mathrm{M}_\odot/(4\pi(10\ \mathrm{km})^3/3) \simeq 5\times 10^{14}\ \mathrm{g/cm}^3$, a few nuclear densities, which could be high enough to satisfy observational frequency $\nu < \nu_{\mathrm{Kepler}}$. More than 40 years later, can the NS model work all the way when more and more new phenomena of PSR-like stars are discovered?

2.1. *Isolated PSR-like stars: why non-atomic thermal spectra?*

Many theoretical calculations, first developed by Romani,[4] predicted the existence of atomic features in the thermal X-ray emission of NS (or crusted QS) atmospheres, and advanced facilities of *Chandra* and *XMM-Newton* were then proposed to be built for detecting those lines in order to constrain stellar mass and radius by spectral redshift and pressure broadening. However, unfortunately, none of the expected spectral features has been detected with certainty up till now, and this negative test may hint a fundamental weakness of the NS models. Though conventional NS models cannot be ruled out by only non-atomic thermal spectra since modified NS atmospheric models with very strong surface magnetic fields[5,6] might reproduce a featureless spectrum too, a natural suggestion to understand the general observation is that pulsars are actually bare QSs[1] because of the absence of an atom on the surfaces.

More observations, however, did show absorption lines of PSR-like stars, particularly from an interesting one, 1E 1207, at ~ 0.7 keV and ~ 1.4 keV. When discovered, these lines were suggested to be associated with the atomic transitions of once-ionized helium in an atmosphere with a strong magnetic field, but thought to require artificial assumptions as cyclotron lines.[7] This view was soon criticized by Xu, Wang and Qiao,[8] who addressed that all the four criticisms[7] about the cyclotron mechanism can be circumvented, and emphasized that 1E 1207 could be a bare QS with surface field of $\sim 10^{11}$ G. Further observations of both spectra feature[9] and precise timing[10] favor the electron–cyclotron model of 1E 1207. The bare QS idea may survive finally if other absorption features (e.g., of the spectra of soft gamma-ray repeaters and anomalous X-ray pulsars) are also cyclotron-originated.

2.2. *Isolated PSR-like stars: real small X-ray radiation radii?*

One of the key differences between NSs and (bare) QSs lies in the fact that NSs are gravitationally bound while QSs are bound not only by gravity but also by additional strong interaction, due to the strong confinement between quarks. This fact results in an important astrophysical consequence that bare QSs can be very low mass with small radii (and thus spinning very rapidly, even at sub-millisecond periods[11,12]), while NSs cannot. We see in Fig. 1 that the radii of gravitationally bound QSs are smaller than that of QSs in flat space–time. The radius difference between QSs without and with gravity represents the power of gravitational interaction, which is certainly strong as stellar mass (M) increases. It is evident from Fig. 1 that gravity cannot be negligible when QS's mass $M \gtrsim (10^{-3} \sim 10^{-2})\mathrm{M}_\odot$ in phenomenological models[13] of quark matter.

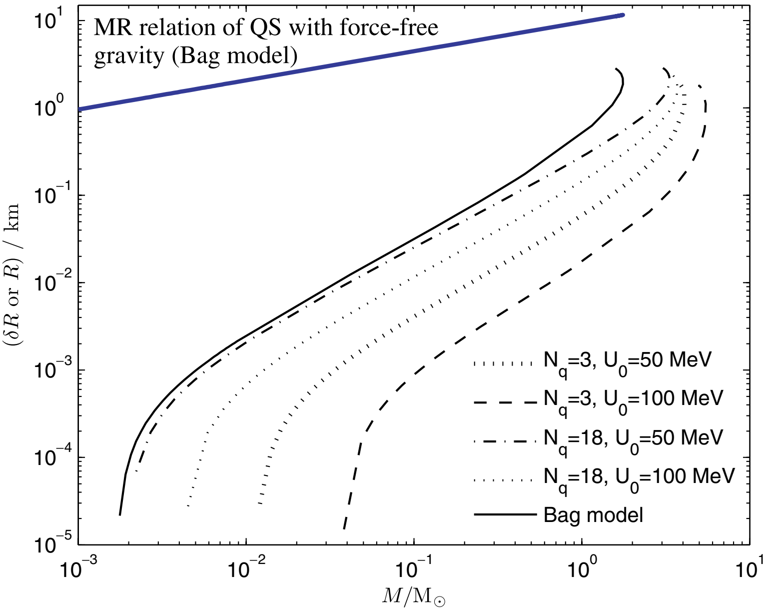

Fig. 1. The radius difference (δR) between QSs, without and with gravity interaction, as a function of stellar mass. This differences are correlated with the gravity in QSs. The mass (M)–radius (R) relation of quark star in flat space–time is of $M \propto R^3$, that is the straight thick line at the top of the figure. The curves of M–δR are for different models: solid line in a simple bag model while others in Lennard–Jones quark matter models. The baryon number density on the surface is chosen as two times of nuclear density here. (*Data provided by X. Lai.*)

Are there any observational hints of low-mass QSs? Thermal radiation components from some PSR-like stars are detected, the radii of which are usually much smaller than 10 km in blackbody models where one fits spectral data by the Planck spectrum.[14] Recently, Pavlov and Luna[15] find no pulsation with period longer than $\sim 0.68\,\mathrm{s}$ in the central compact object (CCO) of Cas A, and constrain stellar radius and mass to be $\{R = (4 \sim 5.5)$ km, $M \lesssim 0.8\mathrm{M}_\odot\}$ in hydrogen NS atmosphere models. Two types of efforts are made toward an understanding of the fact in conventional NS models. (1) The emissivity of NS's surface is not of blackbody or of hydrogen-like atmospheres. The CCO in Cas A is suggested to covered by a carbon atmosphere.[16] However, the spectra from some sources (e.g., RX J1856) are still puzzling, being well-fitted by blackbody, especially with high-energy tails surprisingly close to Wien's Formula, that it decreasing exponentially ($\propto e^{-\nu}$). (2) The small emission areas would represent hot spots on NS's surfaces, i.e., to fit the X-ray spectra with at least two blackbodies, but this has three points of weakness in NS models. (a) About P and $\dot{P}$. No pulsation is detected in any of thermal component-dominated sources (e.g., the Cas A CCO[15]), and the inferred magnetic field from $\dot{P}$ seems to be inconsistent with the atmosphere models at least for RX J1856.[17] (b) The fitting of thermal X-ray spectra (e.g., PSR J1852+0040) with two blackbodies finds two small emitting radii (significantly smaller than 10 km), which are not yet understood.[18] (c) The blackbody temperature of the entire surface of some PSR-like stars are much lower than those predicted by the standard NS cooling models,[19] even when hot spots exist. Nevertheless, besides these two above, a *natural* idea could be that the detected small thermal regions (*if* being global) of CCOs and others may reflect their small radii (and thus low masses in QS scenario[20]).

How can low-mass QSs be created? Low-mass QSs are supposed to form during accretion-induced collapse (AIC) of white dwarfs (WD).[20] For a WD approaching the Chandrasekhar limit, with mass of $M_{\mathrm{wd}} \sim 1.4\mathrm{M}_\odot$ and radius of $R_{\mathrm{wd}} \sim 10^8$ cm, its gravitational energy is $E_{\mathrm{g}} \sim (3/5)GM_{\mathrm{wd}}^2/R_{\mathrm{wd}} \simeq 3 \times 10^{51}$ ergs. If the energy released during the detonation combustion of hadronic matter to strange quark matter, starting from near the stellar center, is responsible for the WD exploding, a necessary for mass QS ($M_{\mathrm{qs,min}}$) should satisfy $0.1M_{\mathrm{qs,min}}c^2 \simeq E_{\mathrm{g}}$, where 10% of rest mass is liberated, corresponding to ~ 100 MeV per baryon. We then have $M_{\mathrm{qs,min}} \simeq 2 \times 10^{-2}\mathrm{M}_\odot$ (i.e., for a QS with radius of ~ 2 km). Certainly such a QS should be bare after photon-driven explosion, and should be kept bare if it does not have a history of Super-Eddington accretion.[1,21] An accreted ion (e.g., a proton) should have enough kinematic energy to penetrate the Coulomb barrier of a QS with mass M_{qs} and radius R_{qs}, as long as $GM_{\mathrm{qs}}m_p/R_{\mathrm{qs}} > V_q$. The Coulomb barrier, V_q, is model-dependent, which varies from $\sim 20\,\mathrm{MeV}$ to even $\sim 0.2\,\mathrm{MeV}$. Approximating $M_{\mathrm{qs}} = (4/3)\pi R_{\mathrm{qs}}^3\rho$ for low-mass QSs, we have a necessary condition of $M_{\mathrm{qs}} > \sqrt{3V_q^3/4\pi G^3m_p^3\rho} \simeq 6 \times 10^{-4}V_{q1}^{3/2}\rho_2^{-1/2}\mathrm{M}_\odot$, where the density $\rho = \rho_2 \times (2\rho_0)$, with ρ_0 the nuclear density, and $V_q = V_{q1}\,\mathrm{MeV}$. In a word, strange QSs with mass as low as $\sim 10^{-2}\mathrm{M}_\odot$ could form and would keep them bare if they are without strong accretion history.

2.3. *Radio pulsars: how to reproduce drifting sub-pulses in pulsar magnetospheres?*

Although PSR-like stars have many different manifestations, they are populated by radio pulsars. Abundant radio pulses are not applied to constrain the state of dense matter until Xu *et al.*[22,23] addressed that radio pulsars could be bare QSs and that the bare quark surface provides peculiar boundary conditions for pulsar's magnetosphere electrodynamics. Additionally, this certainly opens a new window to distinguish QSs from conventional NSs via their magnetospheric activities.

Among the magnetospheric emission models for pulsar radio radiative process, the user-friendly nature of the Ruderman–Sutherland[24] model is a virtue unshared by others, and clear drifting sub-pulses (especially bi-drifting) suggest the existence of gap-sparking in the model. However, that model can only work in strict conditions: strong magnetic field and low temperature on surfaces of pulsars with $\mathbf{\Omega}\cdot\mathbf{B} < 0$, while calculations showed, unfortunately, that these conditions usually cannot be satisfied there. This problem might be alleviated within a partially screened model[25] for NSs with $\mathbf{\Omega}\cdot\mathbf{B} < 0$, but could be naturally solved for any $\mathbf{\Omega}\cdot\mathbf{B}$ in the bare QSs scenario.

2.4. *Birth of PSR-like stars: can supernova be successful?*

It is still an unsolved problem to simulate supernovae successfully in the neutrino-driven explosion models of NSs. Nevertheless, in the QS scenario, the *bare* quark surfaces could be essential for successful explosions of both core and accretion-induced collapses.[20] The reason is that, because of the strong binding of baryons, the photon luminosity of a quark surface is not limited by the Eddington limit, and it is thus possible that the prompt reverse shock could be revived by photons,[26,27] rather than by neutrinos.

3. What if Pulsars are Quark Stars?

Although it could be an attractive idea to solve the problems listed in Sec. 2 in the QS scenario, can we understand all of the different manifestations in QS models? The answer could be "yes". In principle, the discrepancies between observations and expectations in previous QS models (e.g., the bag model) could be explained if we conjecture a *new* solid state of cold quark matter in compact stars. I will summarize those issues in this section, demonstrating that the solid state is very necessary.

3.1. *Thermal spectra: why Planck-like?*

There is certainly no atomic absorption in a bare QS's thermal spectrum, but can the spectrum be well described by Planck's radiation law? In bag models where quarks are nonlocal, one limitation is that bare QSs are generally supposed to be poor radiators in thermal X-ray because of their high plasma frequency, $\sim 10\,\mathrm{MeV}$. Nonetheless, if quarks are localized to form quark-clusters in cold quark matter due to very strong interactions, a regular lattice of the clusters (i.e., similar to a classical *solid* state) emerges as a consequence of the residual interaction between clusters.[28] In this latter case, the metal-like solid quark matter would induce a metal-like radiative spectrum, with which the observed thermal X-ray data of RX J1856 can be fitted.[29] Exact emissivity of such solid quark matter cannot be calculated now because of non-perturbative QCD, but that does not imply one should not pursue this idea before finishing a QCD-based calculation. Alternatively, other radiative mechanism in the electrosphere (e.g., electron *bremsstrahlung* in the strong electric field[30]) may also reproduce a Planck-like spectrum.

3.2. *Radio pulsars: normal and slow glitches*

A big disadvantage that one believes pulsars are QSs lies in the fact that the observation of pulsar glitches conflicts with the hypothesis of conventional QSs in fluid states[31,32] (e.g., in MIT bag models). The problem could be solved in a solid QS model since a solid stellar object would inevitably result in star-quakes when strain energy develops to a critical value. Huge energy are released (and thus large spin-change occurs) after a quake of a solid quark star because of the almost homogeneous distribution of density. Star-quakes could then be a simple and intuitional mechanism for pulsars to have glitches frequently with large amplitudes. In the regime of QSs, by extending the model for normal glitches,[33] one can also model pulsar's slow glitches[34] not to be well understood in NS models.

3.3. *Exploding events: AXPs/SGRs and GRBs*

Solid QSs can have substantial free energy, both elastic and gravitational, to be released after star-quakes, which would power some extreme events detected in anomalous X-ray pulsars (AXPs) and soft γ-ray repeaters (SGRs) and during γ-ray bursts (GRBs). Besides persistent pulsed X-ray emission with luminosity well in excess of the spin-down power, AXPs/SGRs show occasional bursts (associated possibly with glitches), even superflares with isotropic energy $\sim 10^{44-46}$ erg and initial peak luminosity $\sim 10^{6-9}$ times of the Eddington one. They are speculated to be *magnetars*, with the energy reservoir of magnetic fields $\gtrsim 10^{14}$ G (still the origin is a matter of debate[35] since the dynamo action might not be so effective and the strong magnetic field could decay effectively), but could be solid quark stars with surface magnetic fields similar to that of radio pulsars. Star-quakes are responsible to both bursts/flares and glitches in the latter scenario.[36] The most conspicuous asteroseismic manifest of solid phase of quark stars is their capability of sustaining torsional shear oscillations induced by SGR's starquake.[37] In addition, there are more and more authors who are trying to connect the GRB central engines to SGRs' flares in order to understand different GRB light curves observed, especially the internal-plateau X-ray emission.[38] Besides the energy released during deconfinement phase transition,[39] extra ones are liberated after quakes.

3.4. *Free or torque-induced precession*

Rigid body precesses naturally, but one that is fluid can hardly. The observation of a few precession pulsars may suggest a totally solid state of matter. As is shown in Fig. 1, low-mass QSs with masses of $\lesssim 10^{-2}\mathrm{M}_\odot$ and radii of a few kilometers are gravitationally force-free, and their surfaces could then be irregular, asteroid-like. Therefore, free or torque-induced precession may easily be excited and expected with larger amplitude in low-mass QSs. The masses of AXPs/SGRs approach the mass-limit ($> \mathrm{M}_\odot$) in the AIQ model[36]; they could then manifest no or weak precession as observed, though they are more likely than CCOs/DTNs (e.g., RX J1856) to be surrounded by dust disks because of their higher masses (and thus stronger gravity).

4. Could Cold Quark Matter be Solid?

Due to QCD's asymptotic freedom, cold dense quark matter would certainly be of Fermi gas or liquid if the baryon density is extremely high, with a quark chemical potential ~ 0.4 GeV for typical QSs (mass $\sim 1.4\mathrm{M}_\odot$ and radius $\sim 10\,\mathrm{km}$). Most physicists then base their research on this Fermi matter. However, the problem is: "Can the potentials be high enough so that the interaction between quarks is negligible?" We may have a negative answer presented in this section, and previous researches show also that pQCD would work reasonably well only for quark chemical potentials above 1 GeV to the least.

We note that the strong interaction between quarks in compact stars may result in the formation of quark clusters, with a length scale l_q and an interaction energy E_q. An estimate from Heisenberg's relation gives that if quarks are dressed,[40] with mass $m_q \simeq 300$ MeV, then

$$l_q \sim \frac{1}{\alpha_s}\frac{\hbar c}{m_q c^2} \simeq \frac{1}{\alpha_s}\ \mathrm{fm}, \quad E_q \sim \alpha_s^2 m_q c^2 \simeq 300\alpha_s^2\ \mathrm{MeV}.$$

This is dangerous for the Fermi state of matter since E_q is approaching and is even greater than the potential $\sim$ 400 MeV if the running coupling constant $\alpha_s > 1$. With the estimation about α_s from recent work on perturbative[41] and non-perturbative[42,43] QCD, we can draw a numerical coupling as a function of baryon number density as shown in Fig. 2, assuming the energy scale likely to be of the order of the chemical potential $\sim \hbar c(3\pi^2)^{1/3} \cdot n^{1/3}$ MeV (n is the quark number density). At a few nuclear density in compact stars, the color coupling should be very

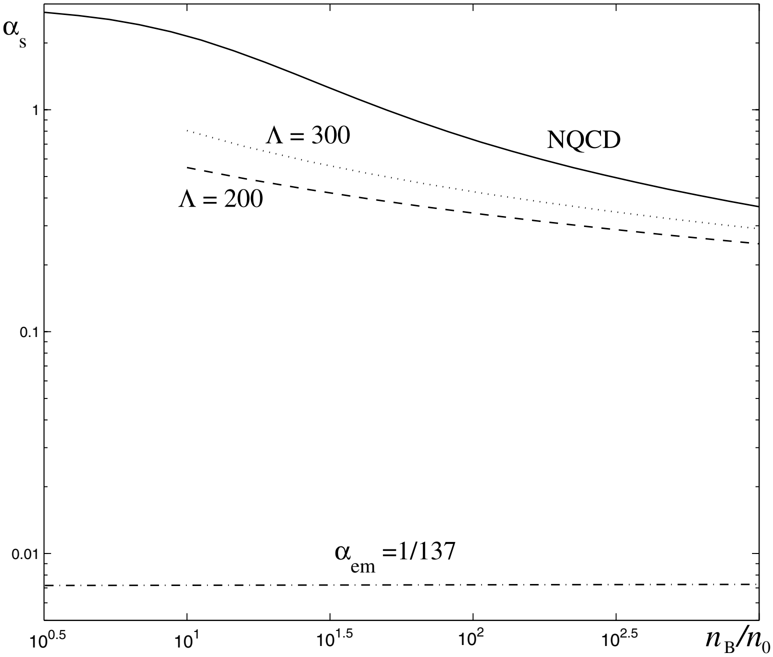

Fig. 2. The running coupling, α_s, in cold quark matter as a function of baryon density, n_B. Both perturbative (for cutoff parameter $\Lambda = 200$ and 300) and non-perturbative QCD (solid line, "NQCD") calculations are presented, respectively. For comparison, the electromagnetic coupling of α_{em} is also drawn. The coupling would be $\alpha_s \gtrsim 2$ in cold quark matter at a realistic baryon density ($\sim$ a few nuclear density, n_0).

strong rather weak and we may have $\alpha_s \gtrsim 2$ if non-perturbative QCD effects are included. This surely means that a weakly coupling treatment could be dangerous for realistic cold quark matter, and quarks would be clustered and localized there.

In the QCD phase diagram, at extremely unrealistic high density, cold quark matter would be of Fermi gas, and condensation in momentum space may occur near the Fermi surface due to color interaction (a BCS-like color superconducting state). However, as density decreases, various interesting phases of quark matter may appear. Firstly, as interaction strength increases, quarks may condense in position space to form different kinds of bosons, and bosons may condense (a BEC state) at low temperature. This is called as BCS–BEC crossover. Secondly, a much stronger coupling between quarks may favor bosons to condensate in position space and quark clusters form. This quark cluster matter could be in a liquid (solid) state at high (low) temperature.

5. Conclusions and Discussions

The nature of PSR-like stars depends on the physics of cold matter at supranuclear density, which is related to one of the challenging problems nowadays: the non-perturbative QCD. Besides efforts in QCD or QCD-based models from the first principles, terrestrial experiments and astronomical observations can also provide valuable information on cold dense matter. It is conjectured from an astrophysical point of view that cold quark matter in compact star is in a solid state and that PSR-like stars are actually solid QSs. We find that this conjecture would be correct if color interaction between dresses quarks is still very strong, with a coupling constant $\gtrsim 1$, in realistic cold quark matter.

That conjecture may have significant implications for the fundamental strong interaction. An essential point we proposed is that quarks should be dressed (i.e., the chiral symmetry is broken) when density and temperature are marginally high enough that the hadronic degree of freedom freezes while the quark degree begins to free. This means that quarks have QCD masses, and not only Higgs masses, at an energy scale of $\sim 10^2$ MeV. Hadronization in the early universe would accordingly be impossible due to the strong color interaction *if* the electromagnetic interaction is not included (i.e., the charge of quark could be negligible). Nucleon is the lightest, but electrons with typical energy $\mu_e \sim 10^2$ MeV have to participate in nuclear matter. Such nuclear matter would be unstable, to evaporate into a nucleon gas with electron's kinetic energy $\ll \mu_e$. Big bang nucleosynthesis occurs then, when the temperature of nucleon gas cools. Nevertheless, strange quark nuggets should form during cosmic QCD phase transitions because of a very low charge–mass ratio and a high binding energy per baryon. Additionally, multi-quark clusters may temporarily form in nuclei in order to understand the puzzling EMC effect.[44,45]

We try to raise the possibility of quark matter in a solid state, but never intending to present a general review. We regret neglecting many interesting and related references.

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