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Renxin Xu



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Possible evidence that pulsars are quark stars

Renxin Xu

Astronomy Department, School of Physics, Peking University, Beijing 100871, China

Abstract. It is a pity that the real state of matter in pulsar-like stars is still not determined confidently because of the uncertainty about cold matter at supranuclear density, even 40 years after the discovery of pulsar. Nuclear matter (related to neutron stars) is one of the speculations for the inner constitution of pulsars even from the Landau's time more than 70 years ago, but quark matter (related to quark stars) is an alternative due to the fact of asymptotic freedom of interaction between quarks as the standard model of particle physics develops since 1960s. Therefore, one has to focus on astrophysical observations in order to answer what the nature of pulsars is. In this presentation, I would like to summarize possible observational evidence/hints that pulsar-like stars could be quark stars, and to address achievable clear evidence for quark stars in the future experiments.

Keywords: Pulsars, Quark matter, Neutron stars

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1. Introduction: pulsars and cold quark matter

It is a puerile desire to know the fundamental constituents of matter and the interactions between them. Elemental fermions (quarks and leptons) are supposed to be the building blocks, between which fundamental interaction occurs via exchanging gauge bosons, in the *standard model of particle physics* that is one of most prominent achievements in the last century. QCD (quantum chromo-dynamics) is believed to be the underlying theory of the elementary strong interaction between quarks, which is relatively poorly understood compared with others (except for the planck-scale gravity). QCD has been precisely tested in the high energy limit due to the asymptotic freedom, while it becomes one of the daunting challenges nowadays to understand QCD in the low energy regime because of QCD's highly nonperturbative nature. The aspects of nonperturbative QCD include the argument of color confinement (would color states be really still single in astrophysics? [17]) and possible phases of quark matter (i.e., matter composed of quarks as building fermions).

It is a simple motivation idea to explore the Universe. One of the attractive questions is about stars: their formation, evolution, and death. Pulsars, discovered 40 years ago, are the residues of massive main sequent stars during supernovae, which were suggested to be normal neutron stars (the most original one was speculated by Landau more than 70 years ago) soon after the discovery, but were suspected to be quark stars (Qs) as the quark model for hadrons develops since 1960s. Pulsars are one kind of so-called compact stars, whose average density is beyond the nuclear density, ρ_{nuc} . Thanks to advanced facilities, very different manifestations of pulsar-like stars are observed recently, and much important astrophysics depends certainly on the real nature of pulsars.

Both particle physicists and astrophysicists meet together when trying to answer what the nature of matter at supranuclear density is. Neutron matter was proposed long before our recognizing the structure of hadrons, and could certainly exist if neutron (and

protons, etc.) could be treated as point-like particles at the energy scale of supranuclear density. Quark matter is a direct consequence and a prediction of asymptotic freedom, which could actually be classified into two kinds: temperature effect dominated (quark-gluon plasma, QGP) and density effect dominated. The latter is relevant to pulsars (the focus of this paper), the physics of which is illustrated in Fig.1 for a very simple composition of protons and electrons. It is evident that, as the density increases, various

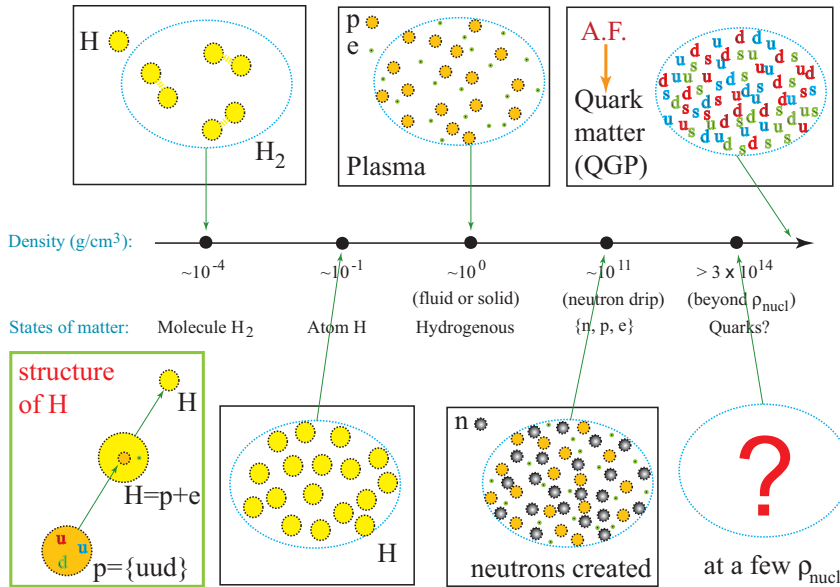


FIGURE 1. Density effect dominated phases of matter composed simply of electrons and protons. Temperature effect is negligible here. It is worth noting that one could know the microphysics by studying the states of matter at different densities. “A.F.”: asymptotic freedom, “ ρ_{nuc} ”: the nuclear density.

states of matter are identified. This is certainly an effective way to reveal the fundamental constitutions and their interactions as well.

The state of cold matter at a few ρ_{nuc} is still an unsolved problem in nonperturbative QCD. Is it of neutron matter or quark matter? What about cold quark matter? Two kinds of efforts are made to date for the latter question. (a) Phenomenological models: to focus on pulsar-like stars as astro-laboratories. Based on different manifestations of pulsars, a solid state for cold quark matter was conjectured by Xu [24], who also proposed more realistically that quark clusters could be essential for the state called as *normal-solid*. (b) Effective models: to construct theoretical frames qualitatively equipollent to QCD for specific problems. BCS-type quark pairs may form at a Fermi surface of cold quark matter, and the shear moduli of the rigid crystalline color superconducting quark matter (*super-solid state*) could be 20 to 1000 times larger than those of neutron star crusts [11]. It could be interesting to observationally distinguish between and search evidence for possible normal-solid and super-solid states although the latter might be more robust than the former from a theoretical point of view.

Possible evidence for Qs will be summarized. My related previous reviews [25, 26, 28, 31] could be readable for historical notes, backgrounds, and a few details.

2. Possible evidence for quark stars

Qs are conventionally thought as a special kind of neutron stars [22], but it is worth to distinguish them from other normal neutron stars because of no free neutron and a very exotic state in their interiors. Although Qs seem to be ‘easily’ ruled out from time to time in the literatures (similar to the case of one’s refraining from smoking), we would like to address possible evidence for them since this is still an unsolved physical and astrophysical problem mixed with a variety of research subjects.

Quark stars: to be bare? Radio pulsars were alternatively suggested to be crusted strange stars [2] until Xu & Qiao [32] argued the magnetospheric activity of *bare* strange stars (BSSs) and addressed three advantages for BSSs as the nature of pulsars: binding energy, spectral feature, and successful supernovae. The RS-type vacuum gap model [21], with an “user friendly” nature, is popular and successful in explaining the radiative behaviors of radio pulsars, which can only work in strict conditions: strong magnetic field and low temperature on surface of pulsars with $\Omega \cdot \mathbf{B} < 0$ (see, e.g., [20]). This binding energy could be completely solved for any $\Omega \cdot \mathbf{B}$ if radio pulsars are BSSs [32, 33]. Drifting subpulses [7] and microstructures could be strong evidence for RS-type sparking on polar caps, and further more, the bi-drifting phenomena [16, 3] could only be understood in BSS models.

Besides RS-type sparking, the bare quark surface could also help to explain a few other observations. Only a layer of degenerated electrons in strong magnetic fields on bare quark surface, which can naturally reproduce non-atomic spectra [23] though atomic features were predicted in normal neutron star models long before observations. The absorption lines of several X-ray sources (e.g., 1E1207 and SGR1806) could originate from transition between Landau levels of electrons [35]. Additionally, the quark surface may help to alleviate the current difficulties in reproducing two kinds of astronomical bursts which are challenging today’s astrophysicists to find realistic explosive mechanisms. Because of chromatic confinement (the photon luminosity of a quark surface is then not limited by the Eddington limit), BSSs could create a lepton-dominated fireball [27, 13] which could push the overlying matter away through photon-electron scattering with energy as much as $\sim 10^{51}$ erg for successful supernovae [5]. Asymmetric explosion in such a way may naturally result in long-soft γ -ray bursts and in kicks on Qs [4, 8, 6].

Mass-radius relation: low-mass Qs? The striking difference between the mass-radius relations [9] of normal neutron stars and (bare) Qs is thought to be useful for identifying Qs (e.g. [10]), and yet it is worth paying attention to *low-mass* Qs [27] since Qs and normal neutron stars with similar maximum mass can hardly be distinguished observationally. Specially, BSSs can be of very low mass (e.g., $\sim 10^{-4}M_{\odot}$, and radius < 1 km), while normal neutron stars cannot (the minimum mass $\sim 0.1M_{\odot}$, and radius ~ 160 km). In principle, the low limit of BSS’s mass could almost be zero because of self-confinement (quark nuggets, quark planets, and Qs). Solar-mass and low-mass Qs may form in different channels: core-collapse explosion for the former and AIC (accretion-induced collapse) of white dwarfs for the latter. The latter could also be possibly the residue of cosmic QCD phase separation in the early Universe. Note that

the astrophysical appearance of low-mass BSSs in both rotation- and accretion-powered phases is quite different to the standard scenarios [27].

Actually, there may be some observational hints of low-mass pulsar-like stars, which include the spin and polarization behaviors (PSR 1937+21) [36], the peculiar timing behavior (1E1207) [27], no-detection of gravitational waves from radio pulsars [29], and small polar cap area (PSR B0943+10) [37]. The detected small thermal area [14] (if being global) of central compact objects may reflect their low masses too.

Conjecture: solid quark matter? Based on a variety of observational features (Planck-like thermal spectra, precessional motion, glitches), a solid state of cold quark matter is conjectured [24], that could not be ruled out by first principles of QCD. Quark clustering is necessary if the solid is one kind of normal solid at low temperature. This idea could explain naturally the discrepancy between precession and glitch of radio pulsars.

As a solid QS evolves (initially cooling and solidification, spinning down, accreting matter), strain develops and a star-quake would occur if the stress increases to a critical value. Quakes of solid QSs may result in pulsar glitches [39] and bursts (even superflares) of anomalous X-ray pulsars/soft gamma-ray repeaters [34]. Actually there are two kinds of stress force inside solid stars: bulk-invariable and bulk-variable forces, both of which could result in decreases of moment of inertia, and thus in pulsar glitches. The total stellar volume may keep almost constant if the former dominates during quake (see Fig.2 for a demonstration), but not if the latter dominates. Small or slow glitches could

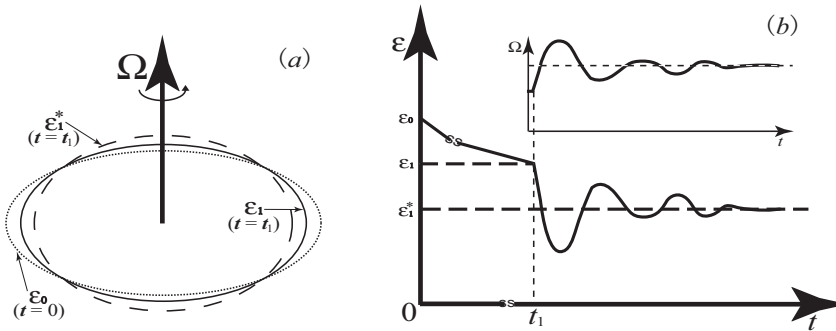


FIGURE 2. An illustration of bulk-invariable force induced quake of a solid quark star. The Maclaurin figure determines the eccentricities of ϵ_0 and ϵ_1^* . A star-quake with real eccentricity ϵ_1 occurs at time t_1 .

be relevant to bulk-invariable force, and numerical calculations show that the observed slow glitches could be reproduced for a certain parameter space [15].

3. Evidence in the future?

Searching for sub-millisecond pulsars. Among the likely ways to identify QSs, discovering sub-millisecond pulsars would model-independently be a clear evidence for QSs [30] because normal neutron stars are bound by gravitation while BSSs are chromatically confined. The smallest spin period is $\sim 0.5M_1^{-1/2}R_6^{3/2}$ ms for neutron stars with maximum mass M_1M_\odot and smallest radius R_610^6 cm, by which the spin of QSs are not limited. The low limit is higher if possible instabilities (e.g., the r -mode one) are considered. Recent observation may hint a discovery of QS [38], in fact.

There could be several ways to form sub-millisecond radio pulsars. *a*, A white dwarf is spun up to a high state of angular momentum in an accreting binary, and would collapsed to be a sum-millisecond pulsar after AIC. *b*, Merging quark nuggets soon after cosmic QCD phase transition may result in low-mass QSs with high spins. *c*, Orbital angular momentum is transferred into spin one of compact low-mass QSs during accretion phase of binaries. *d*, The mass of a BSS with mass of $\sim 10^{-4}M_{\odot}$ may increase to $\sim 10^{-3}M_{\odot}$ after $\sim 10^6$ -year's accretion with Eddington rate. These mean that BSSs with a few kilometers in radius and with sum-millisecond periods are possible after significant accretion in binaries. Should a sub-millisecond radio pulsar be a QS with very low mass, its emissivity would be weak because of small both moment of inertia and magnetic moment. We need large telescope (e.g., *FAST*) to find such radio pulsars in order to cool down the long heated debate on the nature of pulsars.

Others. It would be direct and important to measure certainly a small bolometric radius (e.g., < 5 km) of QS in X-ray (e.g., Constellation-X) and UV bands (to detect emission component at low energy). Is there any hint of QSs in both accretion and no-accretion binaries? It is worth searching observational QS-features in binaries with companies of white dwarfs, giants or super-giants (e.g., the symbiotic X-ray binaries), main-sequent stars, etc. Besides, QSs and normal neutron stars could be differentiated by their radiative features of gravitational waves, which has been studied diversely [12, 18, 19, 1]. It is worth noting no-detection may hint a low mass of QS since the gravitational wave behaviors should be mass-dependent [29]. Additionally, detecting strangelets as cosmic rays (e.g., in the future AMS02 experiment) could also be in-direct evidence for quark stars. A support [31] for solid quark matter could be through identifying quark clusters in strongly coupled QGP created in relativistic colliders (e.g., RHIC).

4. Conclusions

Low-mass solid bare strange quark stars could be the nature of pulsars, that are *not* ruled out and would probably be discovered in the future. I focused on the work of my group and feel sorry for neglecting many interesting references due to the page limit.

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