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QUARK-CLUSTER STARS: HINTS FROM THE SURFACE

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The matter inside pulsar-like compact stars could be in a quark-cluster phase since in cold dense matter at a few nuclear densities ($\rho \sim 2 - 10\rho_0$), quarks could be coupled still very strongly and condensate in position space to form quark clusters. Quark-cluster stars are chromatically confined and could initially be bare, therefore the surface properties of quark-cluster stars would be quite different from that of conventional neutron stars. Some facts indicate that a bare and self-confined surface of pulsar-like compact stars might be necessary in order to naturally understand different observational manifestations. On one hand, as for explaining the drifting sub-pulse phenomena, the binding energy of particles on pulsar surface should be high enough to produce vacuum gaps, which indicates that pulsar's surface might be strongly self-confined. On the other hand, a bare surface of quark-cluster star can overcome the baryon contamination problem of γ-ray burst as well as promote a successful core-collapse supernova. What is more, the non-atomic thermal spectra of dead pulsars may indicate also a bare surface without atmosphere, and the hydro-cyclotron oscillation of the electron sea above the quark-cluster star surface could be responsible for those absorption features detected. These hints could reflect the property of compact star's surface and possibly the state of condensed matter inside, and then might finally result in identifying quark-cluster stars.

Keywords: Pulsars; dense matter; quark matter.

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1. Introduction

Pulsar-like compact stars as the densest observable objects in the universe, are not only important in understanding diverse phenomena in astronomy, but also significant in fundamental physics. The answer to the question whether they are neutron or quark stars would have profound implications on the physics of condensed matter, the nature of strong interaction as well as the QCD phase diagram.[1,2,3]

Investigating the state of condensed matter inside pulsar-like compact stars by first principles is extremely difficult. However, it is meaningful to consider some phenomenological models to understand observational properties of pulsar-like compact stars. We conjectured that pulsar-like compact stars could be "quark-cluster stars" which are composed of quark-clusters with almost equal numbers of up, down and strange quarks, and could be in a solid state if the kinetic energy of quark clusters (order of kT, with temperature T) is lower than the interaction energy between the clusters. From a physical point of view, we knew that strong coupling between quarks is still very strong even in the hot quark-gluon plasma,[4] so in cold quark matter at realistic baryon densities ($\rho \sim 2 - 10\rho_0$), quarks would be expected to be also coupled strongly and to condensate in position space, rather than only in momentum space, to form quark clusters. From an astronomical point of view, the stiff equation of state of quark-cluster matter could naturally explain the ~ 2 solar mass neutron star,[5] and the solid state star could provide gravitational, phase transition and elastic energies to understand bursts of anomalous X-ray pulsars, soft gamma-ray repeaters and even the shallow decay of gamma-ray burst afterglow.[6]

More observational hints come from the surface, since the surface of quark-cluster stars could be bare and is chromatic confined, which is quite different from that of conventional neutron stars. One important surface hint is the drifting[7,8,9] and bidrifting[10] subpulses. The vacuum gap model can explain drifting subpulses naturally,[11] but for conventional neutron star, the binding energy is too low to form such a vacuum gap.[12,13] However, for quark-cluster stars, the surface is chromatic confined and the potential barrier built by the electric field in the vacuum gap above the polar cap can prevent electrons from streaming into the magnetosphere, therefore a vacuum gap can be formed.[14] Other important surface hints are associated with the bare surface of quark-cluster stars. As discussed in Xu (2002), a quark star could be born to be bare. Such a bare quark-cluster star can not only provide a clean fireball for supernovae and gamma-ray bursts, but also explain the thermal featureless spectrum of neutron stars.[15] What is more, quark-cluster stars are enveloped in thin electron layers and vortex hydrodynamical oscillations may be invoked in those electron seas, which could explain the absorption features detected in the spectra of some pulsar-like compact stars.[16]

The outline of the paper is as following. In §2, we briefly review the quark-cluster star model. In §3, we summarize different hints from the surface of quark-cluster stars. In §4, conclusions are presented.

2. A Brief Introduction to Quark-Cluster Stars

Although pulsars have been discovered for more than 40 years, the inner structure of pulsar-like compact stars is still in controversy. Conventional neutron stars and quark stars are two main types of models. While conventional neutron stars are composed mainly of hadrons, the equation of supra-nuclear matter should be understood essentially in the level of quarks.

Previously it is supposed that a perturbative strong interaction inside quark stars could make quarks to be almost free if the coupling is weak, whereas for the conventional neutron stars, the highly non-perturbative strong interaction makes quarks grouped into neutrons. However, results of relativistic heavy ion collision experiments have shown that the interaction between quarks is very strong in hot quark-gluon plasma.[4] Therefore, in cold quark matter at realistic baryon densities

($\rho \sim 2 - 10\rho_0$), quarks could also be coupled strongly and the strong interaction could make quarks to condensate in position space to form quark clusters. We may then expect that quark matter inside compact stars could be in a "quark clustering phase", where the energy scale would be high enough to allow the restoration of 3-light-favor symmetry, but may not be high enough to make the quarks really deconfined. For a realistic pulsar-like compact star whose temperature is low, the kinetic energy of quark clusters should be much lower than the interaction energy between the clusters, and the stars should in a solid state.

The peculiar inner structure of quark-cluster stars which are very different from conventional neutron stars would result in special global and surface properties. These properties are not only instructive for us to understand astrophysical phenomena, but also helpful to identify quark-cluster stars. Globally speaking, quark-cluster stars have stiff equation of state with which a compact star could have a maximum mass even to be > 3 solar mass.[5] The heat capacity of quark-cluster matter is negligible, therefore the cooling behavior would be different from conventional neutron stars,[17] and the missing compact star of SN1987A could be a quark-cluster star.[18] Gravitational and elastic energies of solid quark-cluster stars could explain bursts of anomalous X-ray pulsars and soft gamma-ray repeaters;[19] the latent heat of phase transition of quark-cluster matter from liquid to solid could explain the shallow decay phase of gamma-ray bursts.[6] As for the surface of quark-cluster stars, it could be bare and is chromatic confined, and would be directly associated with the broadband radiation of pulsar-like compact stars. In the next section, we may discuss the details about hints from the surface.

In addition, the conjectured quark-cluster matter with 3-flavor symmetry may also have profound implication to the research of cosmic rays. Strangelets composed by quark clusters would exist and propagate in interstellar space if the gravitational energy is not significant to form stable quark clusters with strangeness. It is well know that the most stable hadrons are nucleons (protons and neutrons), with mass of ~ 940 MeV. The simplest particle in 3-flavor symmetry is Λ^0 (~ 1116 MeV), but the interaction between Λ's is attractive.[20] Therefore the simplest quark clusters in compact stars would be Λ-Λ dibaryon, the so-called H-particle.[21] A strangelet with mass per baryon < 940 MeV (i.e., binding energy per baryon $\gtrsim 200$ MeV) could be stable in cosmic rays, and would decay finally into nucleons when collision-induced decrease of baryon number make it unstable due to the increase of surface energy. When a stable strangelet with probably a few (or decades of) quark clusters bombard the atmosphere of the Earth, its fragmented nuggets may decay quickly into Λ's by strong interaction and further into nucleons by weak interaction.

3. Hints from the Surface

Quark-cluster stars could be bare, since proto-quark-cluster stars may be bare owing to strong mass ejection and high temperature,[22] and accretion of supernova fall-back and the debris disk are unlikely to cover the star with a crust.[15] For bare quark-cluster stars, surface clusters are confined by strong colour interaction while the huge potential barrier built by the electric field can usually prevent electrons from streaming freely into the magnetosphere.[14]

Several observational facts have indicated that such a bare, self-confined surface could be necessary for us to understand different phenomena. These hints from the surface of pulsar-like compact stars may help us identify quark-cluster stars too.

3.1. *Drifting subpulses*

Drifting subpulses were first explained by Ruderman & Sutherland (1975). In the seminal paper, a vacuum gap was first suggested above the polar cap of a pulsar. The sparks produced by the inner-gap breakdown result in the subpulses, and the $E \times B$ drift which is due to the lack of charges within the gap, causes the observed drifting features. However, the above model encounters the so-called "binding energy problem". Calculations have shown that the binding energy of Fe at the neutron star surface is < 1 keV,[12,13] which is not sufficient to reproduce the vacuum gap. One way to solve this binding energy problem is the a partially screened inner gap model,[23,24] but a simple way would be in the bare quark-cluster star model.[14]

In Yu & Xu (2011), the magnetospheric activity of bare quark-cluster star was investigated in quantitative details. Since quarks on the surface are confined by strong color interaction, the binding energy of quarks can be considered as infinity compared to electromagnetic interaction. As for electrons on the surface, on one hand the potential barrier of the vacuum gap prevents electrons from streaming into the magnetosphere, on the other hand the total energy of electrons on the Fermi surface is none zero. Therefore, the binding energy of electrons is determined by the difference between the height of the potential barrier in the vacuum gap and the total energy of electrons. Calculations have shown that the huge potential barrier built by the electric field in the vacuum gap above the polar cap can usually prevent electrons from streaming into the magnetosphere, unless the electric potential of a pulsar is sufficiently lower than that at the infinite interstellar medium. Figure 1 shows a potential barrier of electrons on the stellar surface of a typical pulsar.[14]

We conclude that in the bare quark-cluster star model, both positive and negative particles on the surface are usually bound strongly enough to form a vacuum gap above its polar cap, and the drifting subpulses can be understood naturally.

3.2. *A clean fireball for both supernova and γ-ray burst*

It is well known that the radiation fireballs of gamma-ray bursts and supernovae as a whole move towards the observer with a high Lorentz factor.[25] The bulk Lorentz factor of the ultrarelativistic fireball of GRBs is estimated to be order of $\Gamma \sim 10^2 - 10^3$.[26] For such an ultrarelativistic fireball, the total mass of baryons can not be too high, otherwise baryons would carry out too much energy of the central engine energy, and this is the so-called "baryon contamination". For conventional neutron stars as the central engine, the number of baryons loaded with the fireball

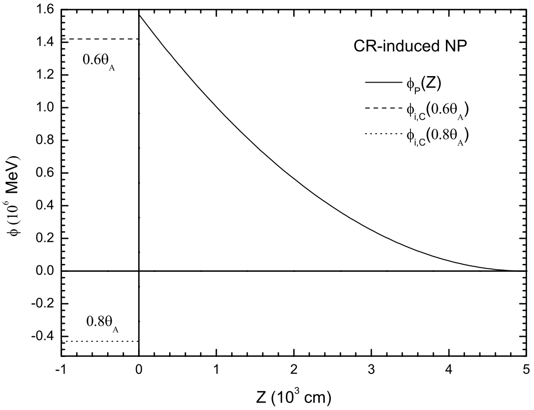

Fig. 1. A potential barrier of electrons in the curvature-radiation (CR) induced vacuum gap of a typical normal pulsar (NP, period $P = 1$ s and magnetic field $B = 10^{12}$ G). The potential energy of electrons at the stellar surface, $\phi_{\mathrm{i,C}}(\theta)$, is illustrated with fixed polar angles (e.g. at $0.6\theta_{\mathrm{A}}$ and $0.6\theta_{\mathrm{A}}$), where θ_{A} is the polar angle of the feet of the last open field lines (Yu & Xu 2011).

is unlikely to be small, since neutron stars are gravity-confined and the luminosity of fireball is extremely high. However, the baryon contamination problem can be solved naturally if the central compact objects are quark-cluster stars. The bare and chromatic confined surface of quark-cluster stars separate baryonic matter from the photon and lepton dominated fireball. Inside the star, baryons are in quark-cluster phase and can not escape due to strong color interaction, but $e^{\pm}$-pairs, photons, neutrino pairs and magnetic fields can escape from the surface. Thus, the surface of quark-cluster stars automatically generates a low baryon condition for GRBs as well as supernovae.[27,28]

A nascent quark-cluster star born in the center of GRB or supernova would radiate Planck-like thermal emission due to its ultrahigh surface temperature,[29] and the photon luminosity is not constrained by the Eddington limit since the surface of quark-cluster stars could be bare and is chromatic confined. Therefore, the strong radiation pressure caused by enormous thermal emissions from quark-cluster stars might play an important role in promoting core-collapse supernovae.[30] Calculations have shown that the radiation pressure due to such strong thermal emission can push the overlying mantle away through photon-electron scattering with energy as much as $\sim 10^{51}$ ergs. Such photon-driven mechanism in core-collapse supernovae by forming a quark-cluster star inside the collapsing core is promising to alleviate the current difficulty in core-collapse supernovae. An illustration of the photon-driven mechanism is shown in Figure 2.[30]

The nascent quark star could be in a fluid state, but according to Xu & Liang (2009), a phase transition of the quark star from liquid to solid could occur about

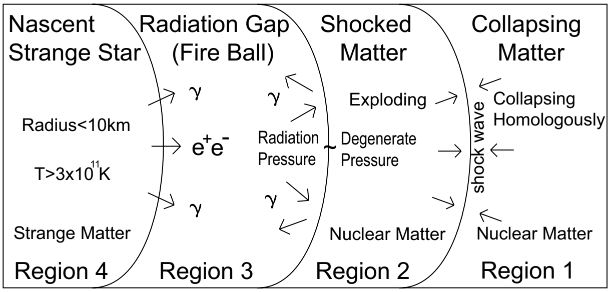

Fig. 2. An illustration of the photon-driven mechanism for core-collapse supernova (Chen et al. 2007). The outermost region 1 consists of the unshocked normal matter which is still in-falling, assembled to the homologous solution. Behind the shock front which serves as the border and increases in thickness, region 2 comprises the shocked nuclear matter whose motion has been reversed by the shock. Between the nascent strange quark-cluster star in the center of the original collapsing core and region 2 is a fireball (region 3), a gap filled up with high energy photons and e^+e^- pair plasma, similar to the fireball of gamma-ray bursts.

$10^3 - 10^6$ s later after its birth. Since the quark-cluster star in phase transition would emit thermal radiation at almost constant temperature and a solid quark star would cool very fast due to its extremely low heat capacity,[17] the latent heat of this phase transition not only provides a long-term steady central engine, but also shows an abrupt cutoff of energy injection when the phase transition ends. Such kind of energy injection may explain the long-lived plateau followed by an abrupt falloff observed in some afterglows.[6] A schematic cooling behavior of a new-born quark star is shown in Figure 3.[6] After the central quark-cluster star is solidified, star-quake would occur when strains accumulate to a critical value. The star-quake induced energy ejection would then results in the observed X-ray flares of bursts.[31]

3.3. *Non-atomic thermal spectra*

In conventional neutron star/crusted quark stars models, an atmosphere exists above the surface of central star. The spectrum determined by the radiative transfer in atmosphere should differ substantially from Planck-like one, depending on the chemical composition, magnetic field, etc.[32] Many calculations (e.g., Romani (1987); Zavlin, Pavlov, & Shibanov 1996) show that spectral lines should be detectable with the spectrographs on board Chandra and XMM-Newton. One expects to know the chemical composition, magnetic field of the atmosphere through such observations, and eventually to determine the mass of the compact star according to the redshift and pressure broadening of an absorption spectrum.

However, up to now, no atomic line has been observed with certainty. Although this discrepancy could be explained for some of the sources by assuming a low-Z element (hydrogen or helium) photosphere or by adjusting the magnetic field, we address that the featureless thermal spectrum can be understood naturally in the bare quark-cluster star scenario.[15] The best example is the detailed spectral analysis

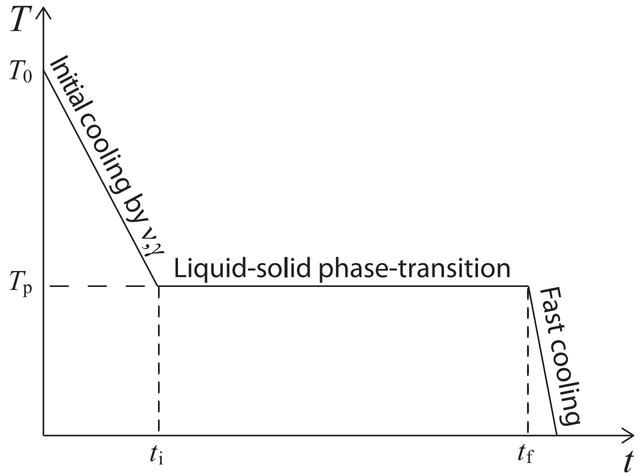

Fig. 3. A schematic cooling behavior of a new-born quark-cluster star (Dai et al. 2011). Three stages are shown: an initial cooling stage due to the emission of neutrinos and photons at the very beginning of a quark-cluster star with initial temperature T_0, a liquid to solid phase transition stage from time t_i to t_f with constant temperature T_p, and, after solidification, a fast cooling stage because of solid quark star's low heat capacity. The long-lived plateau followed by an abrupt falloff observed in some GRB afterglows could be be understood under this scenario.

of the combined X-ray and optical data of RX J1856.5-3754, which have shown that no atmosphere model can fit the data well.[34]

Nevertheless, the best absorption features were detected for the central compact object (CCO) 1E 1207.4-5209 in the center of supernova remnant PKS 1209-51/52 at $\sim$ 0.7 keV and $\sim$ 1.4 keV.[35,36,37] Although initially these features were thought to be due to atomic transitions of ionized helium, soon thereafter it was noted that these lines might be of electron-cyclotron origin.[38] Recent timing results seems to agree with the electron-cyclotron interpretation.[39,40] But this simple single particle approximation might not be reliable due to high electron density on strange stars, and Xu et al. (2012) investigated the global motion of the electron seas on the magnetized surfaces. It is found that hydrodynamic surface fluctuations of the electron sea would be greatly affected by the magnetic field, and an analysis shows that the seas may undergo hydrocyclotron oscillations whose frequencies are given by $\omega(l) = \omega_c/[l(l+1)]$, where $l = 1, 2, 3, ...$ and $\omega_c = eB/mc$ is the cyclotron frequency. The fact that the absorption feature of 1E 1207.4-5209 at 0.7 keV is not much stronger than that at 1.4 keV could be understood in this hydrocyclotron oscillations model, because these two lines with l and $l+1$ could have nearly equal intensity, while the strength of the first harmonic is much smaller than that of the fundamental in the electron-cyclotron model. Besides the absorption in 1E 1207.4-5209, the detected lines around $(17.5, 11.2, 7.5, 5.0)$ keV in the burst spectrum of

SGR 1806-20 and those in other dead pulsars (e.g., radio quiet compact objects) would also be of hydrocyclotron origin.[16]

4. Conclusions

The nature of pulsar-like compact stars is closely related to the physics of condensed matter and the elementary strong interaction. According to the results of relativistic heavy ion collision experiments and various properties of pulsar-like compact stars, we conjecture that quarks could be coupled strongly and condensate in position space to form quark clusters in cold dense matter at realistic baryon densities ($\rho \sim 2 - 10\rho_0$). Under this scenario, pulsars could be "quark-cluster stars" which are composed of quark-clusters with almost equal numbers of up, down and strange quarks, and could be in a solid state during almost all of their lives.

Both global and surface properties of quark-cluster stars are different from conventional neutron stars. Globally speaking, the equation of state of quark-cluster stars is stiffer to support higher mass, while the heat capacity of quark-cluster stars is low, and solid quark-cluster stars could provide gravitational, phase transition and elastic energies to various bursts phenomena. However, more direct hints come from the surface of quark-cluster stars. Drifting subpulses phenomena may comfortably be understood with the vacuum gap above the polar cap, and we have noted that such as vacuum gap can easily formed above a quark-cluster star surface, while the binding energy of conventional neutron stars is too low to form vacuum gap. The bare and chromatic confined surface of quark-cluster star could naturally overcome the baryon contamination problem in gamma-ray burst and supernova fireball, and the strong thermal radiation from quark-cluster star could promote core-collapse supernovae. The non-atomic thermal spectra of some pulsar-like compact stars could also be explained by the bare surface of quark-cluster star, and we have shown that the hydro-cyclotron oscillation of the electron sea could reproduce observational frequencies of the absorption features.

All these hints indicate that the surface of pulsar-like compact star should be bare and self-confined, which is different from conventional neutron stars. Together with stiff equation of state, we think that the quark-cluster star model is reasonable to describe pulsar-like stars. We also expect future astrophysical observations would identify quark-cluster stars along this line.

Finally, it is worth noting that a high binding (> 200 MeV per baryon) between quark clusters not only results in the large maximum mass of quark-cluster stars,[21] but also favors one to conjecture that bulk quark-cluster matter in 3-flavor symmetry could be absolutely stable. Compared with nuclear matter (binding energy of ~ 10 MeV per baryon), strange quark-cluster matter is bound strongly, indicating that the color interaction is still very strong for cold matter at a few nuclear densities. No-detection of stellar-mass black holes with mass $< 5M_\odot$ may hint that the maximum mass for quark-cluster stars is really large.

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