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Quark-cluster Stars: the structure

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The nature of pulsar-like compact stars is still in controversy although the first pulsar was found more than 40 years ago. Generally speaking, conventional neutron stars and non-mainstream quark stars are two types of models to describe the inner structure of pulsars, with the former composed mainly of hadrons and the latter of a peculiar kind of matter whose state equation should be understood in the level of quarks rather than hadrons. To construct a more realistic model from both theoretical and observational points of view, we conjecture that pulsars could be "quark-cluster stars" which are composed of quark-clusters with almost equal numbers of up, down and strange quarks. Clustering quark matter could be the result of strong coupling between quarks inside realistic compact stars. The lightest quark clusters could be of H-dibaryons, while quark clusters could also be heavier with more quarks. Being essentially related to the non-perturbative quantum-chromo dynamics (QCD), the state of supra-nuclear condensed matter is really difficult to obtain strictly by only theoretical QCD-calculations, and we expect, nevertheless, that astrophysical observations could help us to have a final solution.

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1. Introduction

The subjects which are attractive and of great importance are usually those ones that are beyond our comprehension, and the nature of pulsar-like compact stars is of such a kind. Our understanding towards pulsars is still developing, thanks to the developments both theoretical and observational, but the real state of matter is still uncertain. Neutron stars and quark stars, as two types of models for the nature of pulsar, have been debated for a very long time, but which model is more realistic remains to be seen.

The research history of extremely dense matter goes back to the very early time of stellar compact objects. Astronomers were not be able to understand the compactness of white dwarfs until the British physicist Ralph Howard Fowler (1889−1944) recognized the quantum pressure of degenerate electrons there, who for the first time discussed also dense matter at his maximum possible density in the same seminal paper (1926) [1] as "*The density of such 'energetic' matter is then only limited a priori by the 'sizes' of electrons and atomic nuclei. The 'volumes' of these are perhaps* 10^{-14} *times of the volume of the corresponding atoms, so that densities up to* 10^{14} *times that of terrestrial materials may not be impossible*" after Ernest Rutherford constructed the nucleus model of atom in 1911. What if the matter density becomes so high?

The year 1932 was special. (1) Neutron (or "neutral doublet" in Rutherford's words) was experimentally discoveries by James Chadwick although it had been speculated to exist for a long time and for a variety of reasons. (2) Landau [2] conjectured a condensed core with nuclear matter densities inside a star where protons and electrons combined tightly forming the "neutronic" state in order to explain the origin of stellar energy. In addition to advanced and detailed calculations, authors are modeling normal neutron stars generally along Landau's line although Landau did make two mistakes [3] 80 years ago because of the historical limitations.

The inner structure of quark stars which are totally composed of quark matter (with u, d and s quarks) was first calculated by Itoh [4] in 1970, because it was realized previously that there could be deconfined quarks inside neutron stars. From then on, neutron stars are defined as such a kind of compact objects that mainly composed of neutrons, with hyperons or even quark matter in their innermost cores, and quark stars as a kind of compact objects composed of pure (strange) quark matter. It is worth mentioning that, quark stars are characterized by soft equations of state, because the asymptotic freedom of QCD tells us that as energy scale goes higher, the interaction between quarks becomes weaker. The recent discovery [5] of a $\sim 2M_\odot$ neutron star seems to be evidence against quark stars unless the coupling between deconfined quarks is still very strong. [6] Anyway, a working model with the coupling parameter as high as $\alpha_s \gtrsim 0.6-0.7$ could be possible in principle, [7] but such a strong interaction may also favour a kind of condensation in position space rather than in momentum space as was already noted in 2003. [8]

Neutron stars and quark stars respectively correspond to two distinct regions in the QCD phase diagram, the hadron phase in the low density region and the quark-gluon plasma phase in the high density region. In other words, inside neutron stars the highly non-perturbative strong interaction makes quarks grouped into neutrons, whereas inside quark stars the perturbative strong interaction makes quarks to be almost free if the coupling is weak. At a few nuclear matter densities and extremely low temperature, the quark degrees of freedom should be significant, and there is possible observational evidence that pulsars could be quark stars (see reviews, e.g. Ref 9, 10, 11). However, in cold quark matter at realistic baryon densities of compact stars ($\rho \sim 2-10\rho_0$), the energy scale is far from the region where the asymptotic freedom approximation could apply. The strong coupling between quarks even exists in the hot quark-gluon plasma [12], then it is reasonable to infer that quarks could be coupled strongly also in the interior of quark stars, which could make quarks to condensate in position space to form quark clusters. The quark matter inside compact stars could in the "quark-clustering phase", where the energy scale could be high enough to allow the *restoration* of light flavor symmetry, but may not be high enough to make the quarks really deconfined. Quark-cluster stars are treated here to assort with the type of quark stars since (1) they manifest in a similar way of quark star with self-bound rather gravity-bound of neutron stars, (2) their equation of state should be understood in the level of quarks rather than hadrons (i.e., the quark degree of freedom would play a significant role in determining the equation of state and during the formation of quark-cluster stars), and (3) the term of "quark-cluster star" might be abbreviated simply as "quark star".

The observational tests from polarization, pulsar timing and asteroseismology have been discussed, [8] and it is found that the idea of clustering quark matter could provide us a way to understand different manifestations of pulsars. The realistic quark stars could then be actually "quark-cluster stars". An interesting suggestion is that quark matter could be in a solid state [13,14,15], and for quark-cluster stars, solidification could be a natural result if the kinetic energy of quark clusters is lower than the interaction energy between the clusters. To calculate the interaction between quarks and to predict the state of matter for quark stars by QCD calculations is a difficult task; however, it is still meaningful for us to consider phenomenologically some models to explore the properties of quarks at the low energy scale. In this paper we show two models for clustering quark matter. In the Lennard-Jones model [16] we take the number of quarks inside each quark-cluster N_q to be a free parameter, and in the H-stars model [17] we take H-cluster as a specific kind of quark-clusters. Under a wide range of parameter-space, the maximum mass of quark-cluster stars could be well above $2M_\odot$.

The asymptotic freedom of QCD makes the perturbative theory applicable to study the systems under strong interaction, but it cannot describe the systems with vast assemblies of particles under strong interaction that exist in the Universe. Quark matter at high density and low temperature is difficult to be created in laboratories as well as difficult to be study along with QCD calculations, and the observational tests should play an important role to constrain the properties of QCD at low energy scales.

2. Clustering Quark Matter

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. However, perturbative QCD would work reasonably well only for quark chemical potentials above 1 GeV, while the quark chemical potential for a typical quark stars is about 0.4 GeV. We can make an estimate on the chemical potential and the interaction energy of quarks inside quark stars.

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, if quarks are dressed with mass $m_q \simeq 300$ MeV, gives $l_q \sim \frac{1}{\alpha}\hbar c\ m_q c^2 \simeq \frac{1}{\alpha}$ fm, and $E_q \sim \alpha^2 mc^2 \simeq 300\alpha_s^2$ MeV. The strong coupling constant α can be estimated from non-perturbative QCD as a function of baryon number density, and at a few nuclear density in compact stars, the coupling could be very strong rather than weak, with $\alpha \simeq 2$ [18]. This means that a weakly coupling treatment could be dangerous for realistic cold quark matter, and quarks would be clustered.

Quark-clusters could emerge in cold dense matter because of the strong coupling between quarks. The quark-clustering phase has high density and the strong interaction is still dominant, so it is different from the usual hadron phase, and on the other hand, the quark-clustering phase is also different from the conventional quark matter phase which is composed of relativistic and weakly interacting quarks. The quark-clustering phase could be considered as an intermediate state between hadron phase and free-quark phase, with deconfined quarks grouped into quark-clusters, and that is another reason why we take quark-cluster stars as a special kind of quark stars. It is worth noting that, whether the chiral symmetry broken and confinement phase transition happen simultaneously inside compact stars is a matter of debate (see [19] and references therein), but here we assume that the chiral symmetry is broken in quark-clustering phase.

What are quark-clusters explicitly? There is no clear answer, and we could only have some candidates. A 18-quark cluster, called quark-alpha [20], could be completely symmetric in spin, light flavor and color space. Λ particles, with structure *uds*, is the light particle with light flavor symmetry. There could probably attraction between two Λs [21,22], so H-clusters with structure *uuddss* could emerge. If the light flavor symmetry is ensured, then the dominant components inside the stars is very likely to be H-clusters. In the following, we will show that the degree of light flavor symmetry breaking could be small in the macroscopic strange quark matter.

About light flavor symmetry. It is well know that there is an asymmetry term to account for the observed tendency to have equal numbers of protons (Z) and neutrons (N) in the liquid drop model of the nucleus. This nuclear symmetry energy (or the isospin one) represents a symmetry between proton and neutron in the nucleon degree of freedom, and is actually that of up and down quarks in the quark degree [23]. The possibility of electrons inside a nucleus is negligible because its radius is much smaller than the Compton wavelength $\lambda_c = h/m_e c = 0.24\mathring{A}$. The lepton degree of freedom would then be not significant for nucleus, but electrons are inside a large or gigantic nucleus, which is the case of compact stars. Now there is a competition: isospin symmetry favors $Z = N$ while lepton chemical equilibrium tends to have $Z \ll N$. The nuclear symmetry energy $\sim 100(Z-N)^2/A$ MeV, where $A = Z + N$, could be around 100 MeV per baryon if $N \gg Z$. Interesting, the kinematic energy of an electron is also ~ 100 MeV if the isospin symmetry keeps in nuclear matter. However, the situation becomes different if strangeness is included: no electrons exist if the matter is composed by equal numbers of light quarks of u, d, and s with chemical equilibrium. In this case, the 3-flavor symmetry, an analogy of the symmetry of u and d in nucleus, may results in a ground state of matter for gigantic nuclei. Certainly the mass different between u, d and s quarks would also break the symmetry, but the interaction between quarks could lower the effect of mass differences and try to restore the symmetry. Although it is hard for us to calculate how strong the interaction between quarks is, the non-perturbative nature and the energy scale of the system make it reasonable to assume that the degree of the light flavor symmetry breaking is small, and there is a few electrons (with energy ~ 10 MeV).

The above argument could be considered as an extension of the Bodmer-Witten's conjecture. Possibly it doesn't matter whether three flavors of quarks are free or bound. We may thus re-define *strange matter* as cold dense matter with light flavor symmetry of three flavors of u, d, and s quarks.

3. The Global Structure of Quark-cluster Stars

We propose that pulsar-like compact stars could be quark-cluster stars which are totally composed of quark clusters. Quark-cluster stars could have different properties from neutron stars and conventional quark stars, such as the radiation properties, cooling behavior and global structure. In this paper, we only focus on the global structure of quark-cluster stars, deriving the mass-radius relation based on the equation of state, under the Lennard-Jones model and H star model respectively.

3.1. *Lennard-Jones quark matter model*

In the Lennard-Jones quark matter model, the interaction potential u between two quark-clusters as the function of their distance r is assumed to be described by the Lennard-Jones potential, similar to that between inert molecules,

$$u(r) = 4U_0[(\frac{r_0}{r})^{12} - (\frac{r_0}{r})^6], \tag{1}$$

where U_0 is the depth of the potential and r_0 can be considered as the range of interaction. It is worth noting that the property of short-distance repulsion and long-distance attraction presented by Lennard-Jones potential is also a characteristic of the interaction between nuclei.

Under the interaction, quark-clusters could be localized and behave like classical particles, and in this case the tatal interaction potential of one quark-cluster could be written as

$$U(R) = 2U_0[A_{12}(\frac{r_0}{R})^{12} - A_6(\frac{r_0}{R})^6], \tag{2}$$

where R is the nearest distance between two quark-clusters, and A_{12} and A_6 are the coefficients depending on the lattice structure. The localization is natural for clustering quark matter, with the following reasons. One quark-cluster with mass m is under the composition of interaction from its neighbor quark-clusters, which forms a potential well. The energy fluctuation makes this quark-cluster oscillate about its equilibrium position with the deviation Δx, $\Delta E \simeq \hbar^2/(m\Delta x^2) \simeq k\Delta x^2$, where $k \simeq \partial^2 V(r)/\partial r^2$, and r is the distance of two neighbor H-clusters. We use the inter-cluster interaction in Eq(2), and estimate Δx at density $\rho = 10\rho_0$, $\Delta x \simeq (\hbar^2/mk)^{1/4} \simeq 0.2$ fm$(18/N_q)^{1/4}$, where N_q is the number of quarks inside each quark-cluster. On the other hand, the distance between two nearby quark-clusters at density $\rho = 10\rho_0$ is $d = n^{-1/3} \simeq 1.5$ fm $(N_q/18)^{1/3}$, with n the number density of quark-clusters. Consequently, the interaction would localize H-clusters in the potential well at the stellar center, since $\Delta x < d$. On the stellar surface, $\rho \simeq 2\rho_0$, we have $\Delta x = 0.4$ fm and $d \sim 2.6$ fm. Therefore, under the interaction, quark-clusters could be localized and behave like classical particles, and the quantum effect would be negligible.

Under such potential, we can get the equation of state for quark-cluster stars. Because of the strong interaction, the surface density ρ_s should be non-zero, and r_0 can be derived at the surface where the pressure vanishes. Choosing $\rho_s = 2\rho_0$ to ensure the deconfinement of quarks, we can derive the mass and radius of a quark star by combining the equation of state with the hydrostatic equilibrium condition. The dependence of maximum mass of quark stars on U_0 and N_q is shown in Figure 2 [24]. We can see that there is enough parameter space for the existence of quark stars with mass larger than $2M_\odot$. The case $N_q > 10^4$ should be ruled out by the discovery of PSR J1614-2230.

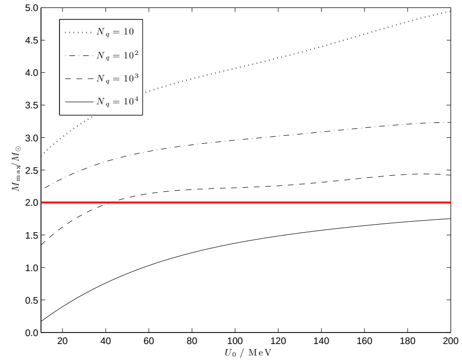

Fig. 1. The dependence of maximum mass $M_{\max}$ on U_0 (depth of potential well), for some different cases of N_q (number of quarks inside one quark-cluster), in Lennard-Jones cold quark matter model. The surface density ρ_s is chosen to be 2 times of ρ_0 (the nuclear matter density).

3.2. *H-cluster Stars*

In Lennard-Jones model, quark-clusters are analogized to electric neutral molecules; however, quark clusters may also be analogized to hadrons. A dihyperon with quantum numbers of $\Lambda\Lambda$ (H dibaryon) was predicted to be stable state or resonance [25], and recent lattice QCD simulations show some evidence that the H-dibaryons (with structure $uuddss$) are bound states [21,22]. Motivated by both the theoretical prediction and numerical simulations, we consider a possible kind of quark-clusters, H-particles, that could emerge inside quark stars during their cooling, as the dominant building blocks [17]. To study quark stars composed of H-matter, i.e. H stars, we assume that the interaction between H-particles is mediated by σ and ω mesons and introduce the Yukawa potential to describe the H-H interaction [26], and then derive the dependence of the maximum mass of H stars on the depth of potential well, taking into account the in-medium stiffening effect.

Using the similar argument as that in the Lennard-Jones model, H-clusters could be localized and behave like classical particles, and Bose condensate would not take place even though they are bosons. On the other hand, although H-clusters could be weakly bound particles which would decay to lighter baryons, such as the reaction of $H \to 2n + 2\pi$, the decay could hardly happen inside compact stars. At density ρ larger than $2\rho_0$, the fermi energy of neutrons is larger than 100 MeV, which makes H-clusters difficult to decay into neutrons and pions. Moreover, H-clusters could be safe under the high momentum fluctuation Δp at high densities inside compact stars, because the energy fluctuation ΔE is not so high due to their high mass. We can make the estimation of $\Delta E \sim \Delta p^2/2m_H \simeq 7\ \mathrm{MeV}(\rho/10\rho_0)^{2/3}(m_H/2210\ \mathrm{MeV})^{-5/3}$, where we set the mass of H-cluster, $m_H = 2m_\Lambda - 20$ MeV $= 2210$ MeV, and m_Λ the mass of Λ^0. The energy of ΔE could be not much lower than the binding energy of H-clusters and potential drop of interaction between H-clusters, but it could be reasonable to ensure the existence of H-clusters with large enough mass fraction of the star.

Compact stars composed of pure H-clusters are electric neutral, but in reality there could be some flavor symmetry breaking that leads to the non-equality among u, d and s, usually with less s than u and d. The positively charged quark matter is necessary because it allows the existence of electrons that is crucial for us to understand the radiative properties of pulsars. The pressure of degenerate electrons is negligible compared to the pressure of H-clusters, so the contribution of electrons to the equation of state is negligible.

We adopt the Yukawa potential with σ and ω coupling between H-particles [26],

$$V(r) = \frac{g_{\omega H}^2}{4\pi}\frac{e^{-m_\omega^* r}}{r} - \frac{g_{\sigma H}^2}{4\pi}\frac{e^{-m_\sigma^* r}}{r}, \tag{3}$$

where $g_{\omega H}$ and $g_{\sigma H}$ are the coupling constants of H-particles and meson fields. In dense nuclear matter, the in-medium stiffening effect, i.e., the Brown-Rho scaling effect, should be considered [27], and then the effective meson masses m_M^* satisfy the scaling law $m_M^* \simeq m_M(1 - \alpha_{BR} n/n_0)$, where α_{BR} is the coefficient of the scaling and m_M is the meson mass in free space. In the problem we are now considering, however, a quark star is at supra-nuclear density, and we then use a modified scaling law of

$$m_M^* = m_M \exp(-\alpha_{BR} n/n_0), \tag{4}$$

which also shows the in-medium effect that stiffens the inter-particle potential by reducing the meson effective masses, and approximately the same as the usual scaling law at the nuclear matter density.

From the potential, we can get the equation of state, and derive the total mass M and radius R of an H star by numerical integration. Figure 3 [17] shows the dependence of $M_{\max}$ on the depth of the potential well V_0 and the Brown-Rho scaling coefficient α_{BR}, in the case $\rho_s = 2\rho_0$. To make comparison, we also plot the result when $\alpha_{BR} = 0$, and the discrepancy between different values of non-zero α_{BR} is not very significant.

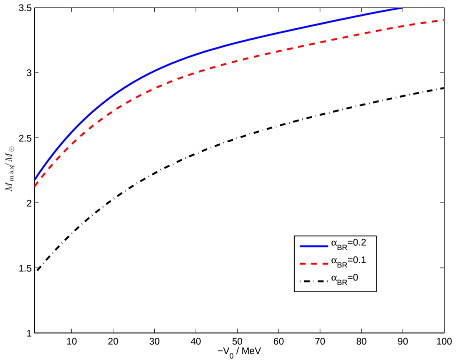

Fig. 2. The dependence of $M_{\max}$ on V_0 and α_{BR}, in the case $\rho_s = 2\rho_0$, including $\alpha_{BR} = 0.5$ (solid line), $\alpha_{BR} = 0.2$ (dashed line) and $\alpha_{BR} = 0$ (dotted line).

H stars could have stiff equation of state, and under a wide range of parameter-space, the maximum mass of H stars can be well above $2M_\odot$, providing a possible way to explain the observed high mass of the newly discovered pulsar PSR J1614-2230. Furthermore, if we know about the properties of pulsars from observations, we can get information on H-H interaction; for example, if a pulsar with mass larger than $3M_\odot$ is discovered, then we can constrain $-V_0$ to be larger than 60 MeV.

4. Conclusions and Discussions

Pulsars could be either neutron stars or quark stars. [a] Although the state of cold quark matter at a few nuclear densities is still an unsolved problem in low energy QCD, various pulsar phenomena would give us some hints about the properties of elemental strong interaction, complementary to the terrestrial experiments. Pulsar-like compact stars provide high density and relatively low temperature conditions where quark matter with quark-clusters could exist, and we have discussed some possible kinds of models to describe such kind of quark matter which could be tested by observations. We apply the Lennard-Jones model and H star model, where the

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[a] Strictly speaking, quark-cluster stars, where the degree of freedom is quark cluster, are *not* traditional quark stars if one thinks that the latter are composed by free quarks. Nonetheless, in this paper, we temporarily consider quark-cluster stars as a very special kind of quark stars. In astrophysics, it is evident that quark-cluster stars manifest themselves similar to quark stars rather than neutron stars.

quark-clusters are treated as molecules in the former and dibaryons in the latter. The $2M_\odot$ pulsar puts constraints on the number of quarks in one quark-cluster N_q to be less than 10^4 in the Lennard-Jones model. To put any constraint on the H-matter model with in-medium stiffening effect, some more massive pulsars (e.g. $M > 3M_\odot$) should be found in the future.

After addressing a lot about modeling quark-cluster stars, it could be interesting to compare Landau's "giant nucleus", neutron star and quark-cluster star. Landau conjectured a "neutronic" state core with nuclear matter densities inside a star in order to solve the origin problem of stellar energy. In Landau's scenario, the "neutronic" state core and the surrounding ordinary matter are in chemical equilibrium at the boundary, which is very similar to the neutron star picture where the inner and outer cores and the crust keep chemical equilibrium at each boundary. Landau's giant nucleus is then bound by gravity. The "neutronic" core should have a boundary and is in equilibrium with the ordinary matter because the star has a surface composed of ordinary matter. There is, however, no clear observational evidence for a neutron star's surface, although most of authors still take it for granted that there should be ordinary matter on surface, and consequently a neutron star has different components from inner to outer parts. Being similar to traditional quark stars, quark-cluster stars have almost the same composition from the center to the surface, and the quark matter surface could be natural for understanding some different observations. As an analog of neutrons, quark-clusters are bound states of several quarks, so to this point of view a quark-cluster star is more similar to a *real* giant nucleus of self-bound (not that of Landau), rather than "giant hadron" which describes traditional quark stars.

It is also worth noting that, although composed of quark-clusters, quark-cluster stars are self-bound. They are bound by the residual interaction between quark-clusters. This is different from but similar to the traditional MIT bag scenario. The interaction between quark-clusters could be strong enough to bind the star, and on the surface, the quark-clusters are just in the potential well of the interaction, leading to non-vanishing density but vanishing pressure.

It has been 80 years since Landau proposed the idea of "neutron" stars, and more than 40 years since the first pulsar was discovered, but the interior structure of pulsar-like compact stars is still in controversy. The nature of pulsars is essentially a non-perturbative QCD problem, corresponding the region between hadron phase and quark-gluon plasma phase in the QCD phase diagram. Although the state of cold quark matter at a few nuclear densities is still an unsolved problem in low energy QCD, various pulsar phenomena would give us some hints about the properties of elemental strong interaction, [18] complementary to the terrestrial experiments. Pulsar-like compact stars provide high density and relatively low temperature conditions where quarks may not be free but would be clustered to form quark-cluster matter. Whether this quark matter composed of quark-clusters could achieve at supra-nuclear density is still unknown, and on the other hand, the nature of pulsar-like stars also depends on the physics of condensed matter. These problems are essentially related to the non-perturbative QCD, and we hope that future astrophysical observations would test the existence of quark-cluster stars.

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