A note on the discovery of a $2M_\odot$ pulsar

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ABSTRACT

It is conventionally thought that the state equation of dense matter softens and thus cannot result in high maximum mass if pulsars are quark stars, and that a recently discovered $2M_\odot$ pulsar (PSR J1614-2230) may make quark stars to be unlikely. However, this standard point of view would be revisited and updated if quark clustering could occur in cold quark matter because of the strong coupling between quarks at realistic baryon densities of compact stars, and it is addressed that the state equation of clustering quark matter stiffs to support compact stars with maximum mass $M_{\rm max} > 2M_\odot$. In this brief note, it is demonstrated that large parameter spaces are allowed for $M_{\rm max} > 2M_\odot$ in a Lennard-Jones model of clustered quark matter, and the newly measured highest mass of PSR J1614-2230 would be meaningful to constrain the number of quarks inside single quark-cluster, to be $N_q <\sim 10^3$.

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

1. Introduction

Quark stars have been characterized by soft equations of state, since the asymptotic freedom of quantum chromo-dynamics (QCD) tells us that as energy scale goes higher, the interaction between quarks will become weaker. In fact, the simplest and most widely used model for quark stars, the MIT bag model, treats the quarks inside a quark star as relativistic and weak-interaction particles which are confined inside the star by an additional pressure denoted by the bag constant (e.g., Alcock et al. 1986).

However, in cold quark matter at realistic baryon densities of compact stars (with an average value of $\sim 2-10\rho_0$), the energy scale is far from the region where the asymptotic freedom approximation could apply, so the the ground state of realistic quark matter might not be that of Fermi gas (see a discussion given by Xu 2009, 2010). The interaction between quarks inside a quark star could make quarks to condensate in position space to form quark clusters (Xu 2003), and at low enough temperature the quark-clusters could crystallize even to form a solid state of quark stars. Solid quark stars still cannot be ruled out in both astrophysics and particle physics (e.g., Horvath 2005; Owen 2005; Mannarelli 2007).

It is really a difficult task to obtain a realistic state equation of cold quark matter at a few nuclear densities, because of (i) the non-perturbative effect of the strong interaction between quarks at low energy scale and (ii) the many-body problem of vast assemblies of interacting particles. However, it is still meaningful for us to consider some phenomenological models to explore the properties of quarks at the low energy scale. In the earlier work, we tried two models; one is the polytropic quark star model (Lai & Xu 2009a) which establishes a general framework for modeling quark stars, and the other one is the Lennard-Jones quark matter model (Lai & Xu 2009b) which introduces a specific kind of interactions in quark stars. Both of the models are much different from the conventional ones (e.g., MIT bag model). In the former case the quark-clusters are non-relativistic particles, whereas in the the latter case quarks are relativistic particles. Consequently, the equations of state in our two phenomenological models could be stiffer than that in conventional quark star models, and then lead to larger maximum masses for quark stars. Under some reasonable parameters, the maximum mass could be higher than 2 $M_{\odot}$. There could be some other models for the clustered cold quark matter. Na & Xu (2010) adopted a two-Gaussian component soft-core potential and also found the parameter space in which the maximum mass could be higher than 2 $M_{\odot}$.

Recently, radio observations of a binary millisecond pulsar PSR J1614-2230, which show a strong Shapiro delay signature, imply that the pulsar mass is $1.97{\pm}0.04\ M_{\odot}$ (Demorest et al. 2010). Although this high mass could rule out conventional quark star models (whose equations of state are soft) and normal neutron stars with hyperon or boson condensation cores, the solid quark star model still cannot be ruled out, because a solid quark star could reach such high mass without suffering the gravitational instability. Certainly, besides equation of state, the highest mass would also be meaningful for researches of γ-ray bursts (GRBs) and gravitational waves (Ozel et al. 2010) since GRB X-ray Flares may originate from massive millisecond pulsars produced by compact star mergers (Dai et al. 2006).

In this note, to constrain the parameters in solid quark stars by the newly discovered high mass pulsar, we take the Lennard-Jones model to describe the state of could quark matter in quark stars (Lai & Xu 2009b), and present the parameter space which can be allowed by pulsars with mass higher than $2M_{\odot}$. We find that if the number of quarks in one quark-cluster N_q satisfies $N_q <\sim 10^3$, then there is enough parameter space for the existence of quark stars with masses to be higher than $2M_\odot$. We also find that the results are consistent with the constraint imposed by non-atomic spectrum of pulsars.

2. Constraint on the number of quarks N_q in one quark-cluster

Quark clustering could occur in cold quark matter because of the strong coupling between quarks at realistic baryon densities of compact stars. The number of quarks in one quark-cluster, N_q, is an important parameter, because it is closely relevant to the strong interaction between quarks. To derive the properties of cold quark matter from QCD calculations is very difficult; however, on the other hand, the astrophysical observations of pulsar-like compact stars provide us effective tools to give constrains on the phenomenological models of cold quark matter. The constrains by non-atomic spectrum of X-ray observations of pulsar-like compact stars and by the $2M_\odot$ PSR J1614-2230 can give us consistent results on the allowed range of N_q.

2.1. Constraint by the non-atomic spectrum

Strange quark matter is composed of up, down and strange quarks, as well as electrons to maintain the charge-neutrality. In MIT bag model, the number of electrons per baryon N_e/A is found for different strange quarks mass m_s and coupling constant α_s (Farhi & Jaffe 1984). In their results, when $\alpha_s = 0.3$, N_e/A is less than 10^{-4}; a larger α_s means a smaller N_e/A at fixed m_s, because the interaction between quarks will lead to more strange quarks and consequently less electrons. In our model, we also consider the strong interaction between quarks as well as between quark-clusters, and consequently the required number of electrons per baryon to guarantee the neutrality should be also be very small. Although at the present stage we have not got the exactly value for the number density of electrons, it is reasonable to assume that N_e/A is less than 10^{-4}.

Making an analogy between quark-clusters to nuclei, the non-atomic spectrum of pulsar-like compact stars can give us some implies about the positive electric charge of an quark-cluster. The K_α line is the strongest line among all the emission lines of an atom, whose energy is written as

$$E_n \simeq -10.2 \; Z^2 \;\; \text{eV}, \tag{1}$$

where Z is the number of positive charge of the nucleus. Similarly, taking Z as the number of positive charge of one quark-cluster, from above equation we can get the energy needed for quark-clusters to emit K_α line. The temperature of a quark star is about 100∼1000 ev, then $Z <\sim 10$ should be satisfied, otherwise there could be K_α line which is thermally produced. Consequently, if $N_e/A \sim 10^{-4}$ for each quark-cluster (note that the baryon number of one quark is 1/3), then $N_q < 10^5$ is required.

2.2. Constraint by the $2M_\odot$ PSR J1614-2230

In the Lennard-Jones quark matter model (Lai & Xu 2009b), 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 (Lennard-Jones 1924)

$$u(r) = 4U_0[(\frac{r_0}{r})^{12} - (\frac{r_0}{r})^6], \quad (2)$$

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. Although the form of interaction between quark-clusters is difficult for us to derive due to the non-perturbative effect of QCD, we could adopt the potential in Eq.(2) because of its general features. Like the classical solid, if the inter-cluster potential is deep enough to trap the clusters in the potential wells, the quark matter would crystallize and form solid quark stars.

Under such potential, we can get the equation of state, including the contribution of the lattice vibration inside solid quark stars, and then derive the mass-radius curves by integrate numerically from the center to the surface of the star (Lai & Xu 2009b). In addition, because of the strong interaction, the surface density ρ_s should be non-zero. The maximum mass of quark stars depends on parameters U_0, r_0, ρ_s and the number of quarks inside one quark-cluster N_q.

Given the density of quark matter ρ and the mass of each individual quark, from Heisenberg's uncertainty relation we can approximate the kinetic energy of one cluster as $E_{\rm k} \sim 1\ {\rm MeV}(\frac{\rho}{\rho_0})^{\frac{2}{3}}(\frac{N_q}{10})^{-\frac{5}{3}}$, where ρ_0 is the nuclear matter density. To get the quark-clusters trapped in the potential wells to form lattice structure, U_0 should be larger than the kinetic energy of quarks. Because of the strong interaction between quarks, we adopt U_0=10 MeV and 200 MeV to do the calculations. The surface density r_0 should be between 1 to 3 ρ_0, to ensure quark-deconfinement without exceeding the average density for a typical pulsar. We choose $\rho_s = 2\rho_0$ in the calculations. The minor chance of ρ_s would not chace the results qualitatively. In addition, we note that for a given ρ_s, we can get r_0 at the surface where the pressure is zero, so there are only three independent parameters, U_0, ρ_s and N_q, which determine the maximum mass of quark stars.

We show relation between the maximum mass of quark stars ($M_{\max}$) and the depth of potential (U_0) when $\rho_s = 2\rho_0$, for some different cases of N_q, in Fig.1. We can see that if

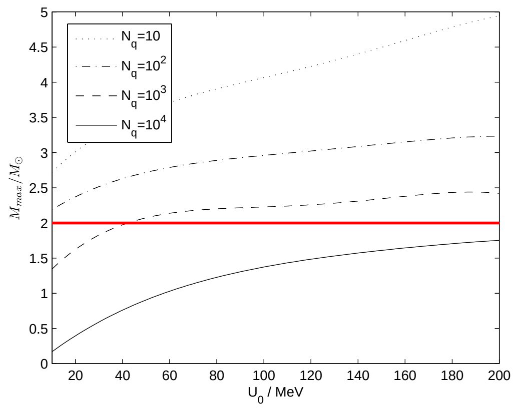

Fig. 1.— The dependence of maximum mass $M_{\max}$ on U_0 (depth of potential well), for some different cases of N_q (number of quarks inside one quark-cluster), in Lennard-Jones cold quark matter model. The surface density ρ_s is chosen to be 2 times of ρ_0 (the nuclear matter density). If $N_q <\sim 10^3$, there is enough parameter space for the existence of quark stars with mass larger than 2 $M_\odot$.

$N_q <\sim 10^3$, there is enough parameter space for the existence of quark stars with mass larger than 2 $M_\odot$. The case $N_q > 10^4$ should be ruled out by the discovery of PSR J1614-2230. This constrain of N_q by the maximum mass of pulsars is consistent with that by the non-atomic spectrum of pulsars ($N_q < 10^5$).

Fig.1 also shows that $M_{\max}$ is insensitive to U_0. This is understandable, because the repulsive core of the inter-cluster potential reacts in most part of the dense cold quark matter inside a quark star, and U_0 only reacts near the star's surface where the density is low enough for one cluster to fell the depth of the potential well of a nearby cluster. Furthermore, it could imply that the constraint of $M_{\max}$ on N_q is insensitive to the form of inter-cluster potential, as long as the potential has a strong repulsive core at short distance.

3. Conclusions

The newly discovered high mass pulsar PSR J1614-2230 with mass $\sim 2M_\odot$ still cannot rule out the existence of quark stars, because quark could be clustered in realistic cold quark matter at supra-nuclear density and then stiff equations of state are possible. We take the Lennard-Jones quark matter model to calculate the maximum masses of quark stars, finding that if $N_q <\sim 10^3$, there is enough parameter space for the existence of quark stars with masses to be higher than 2 $M_\odot$. Moreover, this constraint on N_q could shows generality for clustered quark matter, insensitive to the form of inter-cluster potential.

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