RESEARCH PAPERS

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

To cite this article: Xiao-Yu Lai and Ren-Xin Xu 2011 *Res. Astron. Astrophys.* **11** 687

View the article online for updates and enhancements.

Related content

- A new parametric equation of state and quark stars
  Na Xue-Sen and Xu Ren-Xin

- Quark-clustering in cold quark matter
  Lai Xiao-Yu and Xu Ren-Xin

- Strange quark stars: observations and speculations
  Renxin Xu

Recent citations

- Uniformly rotating, axisymmetric, and triaxial quark stars in general relativity
  Enping Zhou *et al*

- Calvera: A Low-mass Strangeon Star Torqued by Debris Disk?
  Yunyang Li *et al.*

- Isovector properties of quark matter and quark stars in an isospin-dependent confining model
  Peng-Cheng Chu and Lie-Wen Chen

*R*esearch in
*A*stronomy and
*A*strophysics

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

Xiao-Yu Lai and Ren-Xin Xu

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China; *laixy@pku.edu.cn*

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 pulsars unlikely to be quark stars. 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 in compact stars. It can be argued that the state equation of clustered quark matter stiffens to support compact stars with maximum mass $M_{\mathrm{max}} > 2M_\odot$. In this brief note, it is demonstrated that large parameter space ranges are allowed for $M_{\mathrm{max}} > 2M_\odot$ in a Lennard-Jones model of clustered quark matter and the newly measured highest mass of PSR J1614–2230 would be meaningful for constraining the number of quarks inside a single quark-cluster to be $N_{\mathrm{q}} \lesssim 10^3$.

Key words: 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 the energy scale increases, 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, weakly-interacting particles which are confined inside the star by an additional pressure denoted by the bag constant (e.g., Alcock et al. 1986).

Recently, radio observations of a binary millisecond pulsar PSR J1614–2230, which show a strong Shapiro delay signature, imply that the pulsar's mass is $1.97\pm0.04\,M_\odot$ (Demorest et al. 2010). Although this high mass could rule out conventional quark star models (whose equations of state are soft), some other models of pulsar-like stars with quark matter could be consistent with the observation of the high mass pulsar. For example, quark stars made of color-superconducting quark matter could have maximum mass higher than $2M_\odot$ if the gap parameter and coupling constant are large enough (Rüster & Rischke 2004). The maximum mass of hybrid stars could marginally reach $2M_\odot$, if the quark matter phase is described by the Nambu-Jona-Lasinio (NJL) model including diquark condensates (Baldo et al. 2003), the MIT bag model if the interaction between quarks is strong enough (Alford et al. 2005), and the matter exists in the color-superconducting phase under some suitable parameters (Alford & Reddy 2003).

In cold quark matter at realistic baryon densities of compact stars (with an average value of $\sim 2-10\rho_0$), however, 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 a Fermi gas (see a discussion given by Xu 2009, 2010).

The interaction between quarks inside a quark star could make quarks condense in position space to form quark clusters (Xu 2003) and at low enough temperature the quark-clusters could even crystallize 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 et al. 2007).

It is a really 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 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 interaction in quark stars. Both of the models are very different from the conventional ones (e.g., the MIT bag model), since the quark-clusters are non-relativistic particles.

Consequently, the equations of state in our two phenomenological models could be stiffer than that in conventional quark star models, which could then lead to larger maximum masses for quark stars. Under some reasonable parameters, the maximum mass could be higher than $2M_\odot$. 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 $2M_\odot$.

Although the newly measured mass of PSR J1614–2230 is as high as $2M_\odot$, the solid quark star model still cannot be ruled out, because a solid quark star could reach such high mass without suffering from gravitational instability. Certainly, besides the equation of state, the highest mass would also be meaningful for researches about γ-ray bursts (GRBs) and gravitational waves (Özel 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 mass of the newly discovered pulsar, we take the Lennard-Jones model to describe the state of cold quark matter in quark stars (Lai & Xu 2009b) and present the parameter space which could 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 $N_q \lesssim 10^3$, then there is a large enough allowable range in the parameter space for the existence of quark stars with masses higher than $2M_\odot$.

We also find that the results are consistent with the constraint imposed by the 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 related to the strong interaction between quarks. Deriving the properties of cold quark matter from QCD calculations is very difficult; however, the astrophysical observations of pulsar-like compact stars provide us with effective tools to give constraints on the phenomenological models of cold quark matter. The constraints by the 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 in 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 the MIT bag model, the number of electrons per baryon N_e/A is found for different values of strange quark mass m_s and coupling constant α_s (Farhi & Jaffe 1984a). 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 number of electrons per baryon required to guarantee the neutrality should also be very small. Although at the present stage we have not derived the exact 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 and nuclei, the non-atomic spectrum of pulsar-like compact stars can give us some insight about the positive electric charge of a 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 charges in the nucleus. Similarly, taking Z as the number of positive charges of one quark-cluster, from the above equation we can calculate the energy needed for quark-clusters to emit the K_α line. When the temperature of a quark star is about $100{\sim}1000\,\text{eV}$, the condition $Z \lesssim 10$ should be satisfied, otherwise there could be a 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 a function of their distance r is assumed to be described by the Lennard-Jones potential (Lennard-Jones 1924)

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

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 the 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 Equation (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 obtain the equation of state, including the contribution of the lattice vibration inside solid quark stars and then derive the mass-radius curves by numerically integrating 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 $E_k \sim 1\,\text{MeV} \left(\frac{\rho}{\rho_0} \right)^{\frac{2}{3}} \left(\frac{N_q}{10} \right)^{-\frac{5}{3}}$, where ρ_0 is the nuclear matter density. To get the quark-clusters trapped in the potential wells to form a lattice structure, U_0 should be larger than the kinetic energy of quarks. Because of the strong interaction between quarks, we adopt U_0 to be in the range between 10 and
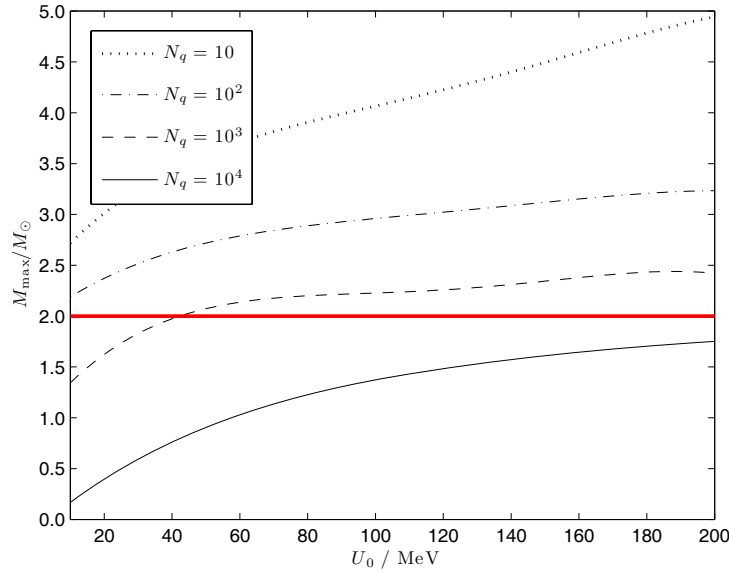
Fig. 1 Dependence of maximum mass M_{max} on U_0 (depth of potential well), for some different values of N_{q} (number of quarks inside one quark-cluster), in the Lennard-Jones cold quark matter model. The surface density ρ_{s} is chosen to be two times ρ_0 (the nuclear matter density). If $N_{\mathrm{q}} \lesssim 10^3$, there is a large enough allowable range in parameter space for the existence of quark stars with mass larger than $2M_{\odot}$.

200 MeV for 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 $\rho_{\mathrm{s}} = 2\rho_0$ in the calculations. A minor change in ρ_{s} would not qualitatively change the results.

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 the relation between the maximum mass of quark stars (M_{max}) and the depth of potential (U_0) when $\rho_{\mathrm{s}} = 2\rho_0$, for some different values of N_{q}, in Figure 1.

We can see that if $N_{\mathrm{q}} \lesssim 10^3$, there is a large enough allowable range in parameter space for the existence of quark stars with mass larger than $2M_{\odot}$. A high maximum mass for pulsar-like compact stars might be helpful for us to understand the mass gap between the most massive neutron stars (well below $3M_{\odot}$) and the least massive black holes (Bailyn et al. 1998; Farr & Sravan 2010), since a quark star with a high mass (e.g. $\sim 5M_{\odot}$) could still be gravitationally stable in our present model. The case $N_{\mathrm{q}} > 10^4$ should be ruled out by the discovery of PSR J1614–2230. This constraint of N_{q} by the maximum mass of pulsars is consistent with that given by the non-atomic spectrum of pulsars ($N_{\mathrm{q}} < 10^5$).

Figure 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 the most inner part of a quark star, and U_0 only reacts near the star's surface where the density is low enough for one cluster to feel 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 a short distance.

3 CONCLUSIONS AND DISCUSSIONS

The newly discovered high mass pulsar PSR J1614–2230 with mass $\sim 2M_\odot$ still cannot rule out the existence of quark stars, because quarks could be clustered in realistic cold quark matter at supra-nuclear density and 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 $N_q \lesssim 10^3$, there is a large enough range in parameter space for the existence of quark stars with masses higher than $2M_\odot$. Moreover, this constraint on N_q could generally be true for clustered quark matter, insensitive to the form of inter-cluster potential.

We still do not exactly know how strong the interaction between quarks could be when the density is a few times the nuclear matter density. Actually, the particles inside pulsar-like compact stars should be very different from free particles. If the interaction between quarks is so strong that it could make quarks form groups of clusters, then the equation of state could be even stiffer than that of nuclear matter. From this point of view, the newly discovered high mass pulsar could give support to the existence of quark-clustering in cold matter.

References

Alcock, C., Farhi, E., & Olinto, A. 1986, ApJ, 310, 261
Alford, M., Braby, M., Paris, M., & Reddy, S. 2005, ApJ, 629, 969
Alford, M., & Reddy, S. 2003, Phys. Rev. D, 67, 074024
Bailyn, C. D., Jain, R. K., Coppi, P., & Orosz, J. A. 1998, ApJ, 499, 367
Baldo, M., Buballa, M., Burgio, G. F., et al. 2003, Physics Letters B, 562, 153
Dai, Z. G., Wang, X. Y., Wu, X. F., & Zhang, B. 2006, Science, 311, 1127
Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, Nature, 467, 1081
Farhi, E., & Jaffe, R. L. 1984a, Phys. Rev. D, 30, 2379
Farr, W. M., Sravn, N., Cantrell, A., Kreidberg, L., Bailyn, C. D., Mandel, I., & Kalogera, V., arXiv: 1011. 1459
Horvath, J. 2005, Mod. Phys. Lett. A, 20, 2799
Lai, X. Y., & Xu, R. X. 2009a, Astroparticle Physics, 31, 128
Lai, X. Y., & Xu, R. X. 2009b, MNRAS, 398, L31
Lennard-Jones, J. E. 1924, Proc. Roy. Soc. London, Ser. A, 106, 463
Mannarelli, M., Rajagopal, K., & Sharma, R. 2007, Phys. Rev. D, 76, 4026
Na, X. S., & Xu, R. X. 2010, arXiv: 1009.4247
Owen, B. J. 2005, Phys. Rev. Lett., 95, 211101
Özel, F., Psaltis, D., Ransom, S., Demorest, P., & Alford, M. 2010, ApJ, 724, L199
Rüster, S. B., & Rischke, D. H. 2004, Phys. Rev. D, 69, 045011
Xu, R. X. 2003, ApJ, 596, L59
Xu, R. 2009, J. Phys. G: Nuclear Physics, 36, 064010
Xu, R. 2010, International Journal of Modern Physics D, 19, 1437