Compact Stars in the QCD Phase Diagram III (CSQCD III)
December 12-15, 2012, Guarujá, SP, Brazil
http://www.astro.iag.usp.br/~foton/CSQCD3

Compressed Baryonic Matter of Astrophysics

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Abstract

Baryonic matter in the core of a massive and evolved star is compressed significantly to form a supra-nuclear object, and compressed baryonic matter (CBM) is then produced after supernova. The state of cold matter at a few nuclear density is pedagogically reviewed, with significant attention paid to a possible quark-cluster state conjectured from an astrophysical point of view.

1 An introduction to CBM

It is well known from astrophysical observations that our universe is dominated by dark matter and dark energy, with a fraction of $\sim 23\%$ and $\sim 73\%$, respectively. Nevertheless, the most familiar composition we know best is the 4% atomic part—the baryons and leptons! In the standard model of particle physics, all of matter are composed of fundamental Fermions, 6 flavors of quarks and 6 flavors of leptons, between which elementary interactions are mediated by gauge bosons. Particles made of quarks are called baryon, and the baryonic number of a quark is 1/3. With Higgs boson, the origin of mass, discovered by LHC experiments at 5σ confidence level in July 2012, all 62 particles within the frame of standard model have been evidenced.

The most familiar and stable baryon are nucleon (proton and neutron), which is made of up and down quarks, the lightest two flavors of quarks easiest to be excited. At low energy scale, protons and neutrons are strongly coupled by residual forces of color interaction between quarks and form various kinds of atom nuclei. Nucleus with positive charge attracts electrons and then constitute atom combined by electromagnetic force, which is the building-block of ordinary substances. Although the nuclei contribute $> 99.9\%$ of the atomic mass, its length scale is only $\sim 10^{-13}$ cm $= 1$ fm, while that of atom is order of Å $= 10^{-8}$ cm; this means that there is plenty of empty space between atoms. Possible matter at the highest density, limited by the sizes of electrons and nuclei, was speculated by Fowler in 1926 [1]. If the space is squeezed out, one would then obtain the so-called compressed baryonic matter (CBM), which could be of extremely high density, even larger than the nuclear density, $\rho_{\rm nucl}$. Although it is almost impossible yet to squeeze the space out of normal matter in terrestrial laboratory, strong gravity inside the core of an evolved massive star could do this: the fascination of astrophysics! CBM could thus be in the heaven, and supernova could make CBM from atoms [2].

The outline of this paper is as follows. In §2, we will start with what we know about CBM, and what we do not know about CBM will be considered in §3. A possible state of CBM, quark-cluster, is discussed in §4. Then, in §5, observational hints for the nature of CBM are summarized. Finally, we make conclusions in §6.

2 What we do know about CBM

Let us put aside various speculations conceivable or not, and just think about what we are sure of CBM first.

For a pulsar-like compact star with a mass of $\sim M_\odot$, the baryon number of CBM inside can be roughly estimated to be $\sim M_\odot/m_{\rm p} \sim 10^{57}$ ($m_{\rm p}$ is the proton mass), which is so large that the medium effect would be significant. If nuclei are considered as gravity-free, the density of CBM would be larger than $\rho_{\rm nucl}$ as a consequence of gravitational compression. CBM is so dense that even a nugget of CBM not larger than a rubber could be as heavy as all of the world's population.

We can also estimate the energy scale of quarks in CBM via two simple ways. (i) In case of free quarks, the Fermi momentum is $p_F = (3\pi^2)^{1/3}\hbar n^{1/3}$, and a calculation of Fermi energy gives,

$$E_F^{NR} \approx \frac{\hbar^2}{2m_q}(3\pi^2)^{2/3} \cdot n^{2/3} = 380\mathrm{MeV} \tag{1}$$

if quarks are considered moving non-relativistically, or

$$E_F^{ER} \approx \hbar c(3\pi^2)^{1/3} \cdot n^{1/3} = 480\mathrm{MeV} \tag{2}$$

if quarks are considered moving extremely relativistically, where $n \simeq (3\times 0.16 = 0.48)$ fm^{-3} is the number density of each flavor of quark and the dressed quark mass $m_q \simeq 300$ MeV. (ii) In case of localized quarks, one could also estimate the zero-point momentum by Heisenberg's uncertainty relation, $p_0 \approx \hbar n^{1/3} \sim p_F$. Therefore, we have the energy scale $E_{\rm scale} \sim 400$ MeV by either Heisenberg's relation or Fermi energy.

Such a energy scale would have two implications.

(1) CBM should be *strange*. As $E_{\rm scale}$ would be much larger than the mass difference between strange and up/down quarks, $\Delta m \sim 100$ MeV, strange quark could be easily provoked and strangeness may play an important role

in determining the nature of CBM, while heavier quarks (c, t, b) are not likely to be excited.

(2) Non-perturbative QCD effects are significant for CBM because $E_{\rm scale} < 1$ GeV. The state of realistic CBM should be far from the region where the asymptotic freedom approximation could apply. It is worth noting that the the strong coupling between quarks might render quarks grouped, although this hypothetical quark-cluster [3] in CBM has not been confirmed due to the lack of both theoretical and experimental evidence. For a quark-cluster with length scale l, from Heisenberg's relation, the kinetic energy would be of $\sim p^2/m_q \sim \hbar^2/(m_q l^2)$, which has to be comparable to the color interaction energy of $E \sim \alpha_s \hbar c/l$ in order to have a bound state, where α_s is the coupling constant of strong interaction. One then finds if quarks are dressed,

$$l \sim \frac{1}{\alpha_s}\frac{\hbar c}{m_q c^2} \simeq \frac{1}{\alpha_s}\ \mathrm{fm},\ E \sim \alpha_s^2 m_q c^2 \simeq 300\alpha_s^2\ \mathrm{MeV}. \quad (3)$$

It is evident that the interaction energy, E, would be approaching and even larger than the Fermi energy ($\sim$ 400 MeV) if $\alpha_s > 1$ for CBM at a few $\rho_{\rm nucl}$, which means that quarks in CBM might not behave like Fermi gas.

In summary, for CBM manifesting as pulsar-like compact stars, we know that there are $\sim 10^{57}$ quarks (with strangeness?), and non-perturbative color interaction should play an important role in determining the equation of states (EoS). But what can we understand more about CBM?

3 What we do not know about CBM

There are many things that we do not know about CBM, as CBM is hard to be created in terrestrial laboratory, and a direct calculation from first principle is difficult due to non-perturbative effects of low-energy QCD.

To begin with, a challenging problem is whether the quarks are confined or de-confined in CBM, according to which different scenarios are suggested for pulsar-like compact stars. In hadron star model [4, 5, 6], quarks are confined in hadrons such as neutron/proton and hyperon, while quark matter would exist in a core of hybrid/mixed star [7] whose central density could be high enough to make quarks de-confined. A quark star is a condensed object dominated by free quarks [8, 9, 10, 11]. Strictly speaking, a quark-cluster star, however, is neither a hadron star nor a quark star, in which strong coupling cause individual quarks grouped in clusters. Among these scenarios, hadron star and hybrid star are gravity-bound, which are covered by crusts with nuclei and electrons, while quark star and quark-cluster star are self-bound on surface. This surface difference may have profound implications for observations.

There exists another essential problem: would 3-flavor symmetry be restored in CBM? In an ordinary nucleus, a symmetry is kept between proton {uud} and neutron {udd}, which is essentially equivalent to a 2-flavor symmetry. As an up quark carries $+2/3$ charge and a down quark just $-1/3$ charge, to keep electric neutrality, electrons as many as u/d quarks would participate in matter with 2-flavor symmetry.

In ordinary case, electrons are outside the nucleus and their energy E_e is far less than 1 MeV, so atoms could be stable with 2-flavor symmetry. Nevertheless, things are different in case of CBM, for that electrons are inside the gigantic nucleus and the kinematic energy of electron would be $E_e \sim 100$MeV. Such a high energy might intensify the interaction $e+p \to n+\nu_e$, thus E_e decreases but, unfortunately, the nuclear symmetry energy $E_{\rm sym}$ increases. This embarrassed situation does not exist if strange quark is invoked in CBM (gigantic nucleus); the number of electrons there could be only 10^{-5} less than that of u/d quarks as s quark is heavier.

If 3-flavor symmetry is restored, the number of electrons in CBM would be much less, which makes $E_e \sim 10$ MeV, and the gigantic nucleus would be stable. Certainly the argument above is not suitable for ordinary nucleus, as the surface energy would increase with decreasing radius, and different from gigantic nucleus, electrons are outside the ordinary one, which causes a much smaller kinetic energy not sufficient for s quark to be excited.

From the theoretical arguments above, there is a possibility that CBM could be strange quark-cluster matter, which distinguishes from neutron star matter and quark matter.

4 What if CBM is made of quark-clusters?

If CBM is composed of strange quark-cluster matter, there would be mainly three consequences.

First, CBM would have a stiff EoS, because quark-cluster should be non-relativistic particle for its large mass, and because there could be strong short-distance repulsion between quark-clusters. As we all know, the relation between energy and momentum is $E = (c^2p^2 + m^2c^4)^{1/2}$, which can be approximated as $E = p^2/2m$ in non-relativistic (NR) case, while $E = pc$ for extra-relativistic (ER) case. From relations above we can get the EoS $P \sim \rho^\gamma$, and γ would be larger in NR case, which means a stiffer EoS. As for interaction between quark-cluster matter, recently, H-dibaryon has been found in lattice QCD simulations by two independent groups, with binding energy of about 10 to 40 MeV [12, 13].

Second, different from traditional neutron stars, quark-cluster star would be self-bound by residual interaction between clusters, which could be a crucial difference providing observational manifestations to distinguish the two models.

Last but not least, CBM could be in a global solid state if the kinetic energy kT is less than interaction energy between quark-clusters, where k is the Boltzmann constant and T is the temperature. Solid quark-cluster star could possess more free energy reserved as elastic and gravitational ones, which might be alternative energy sources for the bursts and even giant flares in anomalous X-ray pulsars (AXP) and soft gamma-ray repeaters (SGR).

Except these qualitative features analyzed, how shall we model quark-cluster star? Certainly, it is extremely difficult to calculate from first principles due to non-perturbative effects, but phenomenologically, there may be some feasible ways to probe the properties of quark-cluster matter.

Motivated by recent lattice QCD simulations, a possible kind of realistic quark-cluster, H-cluster, is considered [14]. Assuming that interaction between H-clusters is mediated by σ-ω mesons, we can derive EoS as well as the mass-radius relations of H-cluster stars in different cases of the in-medium stiffening effect and surface density. Under a wide range of parameter-space, the maximum mass of H-cluster stars can be well above $2M_\odot$, and the calculated mass-radius relations are consistent with both observations of the massive $2M_\odot$ pulsar PSR J1614-2230 [15] and the rapid burster MXB 1730-335 [16].

We have also studied the properties of quark-cluster matter by a corresponding-state approach [17]. Considering a group of substances described by potential in this form: $\varphi = \varepsilon f(r/\sigma)$, we can express macroscopic quantities, such as pressure P, volume V and temperature T, in dimensionless terms,

$$P^* = P\sigma^3/\varepsilon, \quad (4)$$

$$V^* = V/(N\sigma^3), \quad (5)$$

$$T^* = kT/\varepsilon. \quad (6)$$

Through constructing another dimensionless parameter $\Lambda^* = h/(\sigma\sqrt{m\varepsilon})$, corresponding to the de Broglie wavelength, to measure the importance of quantum effects, it can be proved that the reduced EoS expressed in these dimensionless quantities, $P^* = f(V^*, T^*, \Lambda^*)$, is a universal relation, as formulated by the law of corresponding states [18]. For inert gases described by Lennard-Jones potential, $\varphi = \varepsilon\{\frac{4}{(r/\sigma)^{12}} - \frac{4}{(r/\sigma)^6}\}$, the universal EoS could be acquired by their experimental data. If quark-cluster matter could be analogized to inert gases, and the corresponding ε and σ could be determined, we can get the EoS of quark-cluster matter by employing the corresponding-state approach. According to the derived mass-radius relation, the maximum mass could also be well above $2M_\odot$ under reasonable parameters.

5 What can observations teach us?

The realistic state of CBM is very difficult to directly calculate from first principles, nonetheless, pulsar-like compact stars are excellent astrophysical laboratory, observations of which could give us useful hints for the nature of CBM.

For example, radio observations of PSR J1614-2230, a binary millisecond pulsar with a strong Shapiro delay signature, imply that the pulsar mass is $1.97 \pm 0.04\ M_\odot$ [15], which indicates a stiff EoS for CBM. It is conventionally thought that the state of dense matter softens and thus cannot result in high maximum mass if pulsars are quark stars, and that the discovery of $2M_\odot$ pulsar may make pulsars unlikely to be quark stars. However, as shown by qualitative analysis and empirical calculations in §4, quark-cluster star could not be ruled out by PSR J1614-2230, and the observations of pulsars with higher mass, e.g. $> 3M_\odot$, would even be a support to our quark-cluster star model, and give further constraints to the parameters.

In measurements of black hole mass distribution, a significant mass gap between the maximum pulsar mass detected ($2M_\odot$) and the low end of the black hole mass distribution ($\sim 5M_\odot$) has been identified previously [19], which may suggest that the maximum mass of pulsar would be in the middle range of $2M_\odot - 5M_\odot$. However, after revising systematic errors in the mass measurements, GRO J0422+32 and 4U 1543-47 may have small black hole masses (below $\sim (4-5)M_\odot$), which may doubt the mass gap identified in the previous work [20].

Although both neutron star and quark-cluster star could account for the discovery of high mass pulsars, many observation phenomena might imply a self bound surface for CBM. Drifting subpulses phenomena in radio pulsars suggest the existence of Ruderman-Sutherland-like gap-sparking and thus strong binding of particles on pulsar polar caps to form vacuum gap, but the calculated binding energy in neutron star models could not be so high unless the magnetic field is extremely strong. This problem could be naturally solved in quark-cluster star scenario due to the strong self bound nature on surface [21, 22].

In addition, many theoretical calculations predict the existence of atomic features in the thermal X-ray emission of neutron star atmospheres, which should be detectable by Chandra and XMM-Newton. However, none of the expected spectral features has been detected with certainty up to now, and such non-atomic thermal spectra of dead pulsars also hint that there might not exist the atmospheres speculated in neutron star models. Though conventional neutron star models cannot be ruled out by only non-atomic thermal spectra since modified atmospheres with very strong surface magnetic fields [23, 24] might reproduce a featureless spectrum too, a natural suggestion to understand the general observation is that pulsars are actually quark-cluster star without atoms on the surface [25].

Additionally, the bare and chromatic confined surface of quark-cluster star could overcome the baryon contamination problem and create a clean fireball for γ-ray burst and supernova. The strong surface binding would result in extremely energetic exploding because the photon/lepton luminosity of a quark-cluster surface is not limited by the Eddington limit, and supernova and γ-ray bursts could then be photon/lepton-driven [26, 27, 28].

In order to explain observations, one needs either neutron stars with super strong magnetic fields (i.e., magnetars, $> 10^{14}$ G) or quark-cluster stars with self-bound surfaces and normal fields ($\sim 10^{12}$ G). How shall we distinguish the two models? As neutron star is gravity-bound while quark-cluster star self-bound by chromatic interaction, there is atmosphere on the surface of neutron star while not on quark-cluster star, and thus a larger temperature gradient in the former case. The neutron star atmosphere would be ionic polarized in strong magnetic field, so its thermal radiation would be linearly polarized ($\sim 10\%$), while the polarization degree of quark-cluster star could be almost zero [29]. That means neutron star and quark-cluster star can be clearly distinguished by measuring linear X-ray polarization of dead pulsars with pure thermal radiation.

Except for hints from the surface, there are some observations implying global properties. As addressed before, quark-cluster stars would be in a global solid state like "cooked eggs", while for normal neutron stars, only crust is solid like "raw eggs". Rigid body would precess naturally when spinning, either freely or by torque, and the observation of possible precession or even free precession of B1821-11 [30] and others could suggest a global solid structure for pulsar-like stars.

Star-quake is a peculiar action of solid compact stars, during which huge free energy, such as gravitational and elastic energy, would be released. Assuming the two kinds of energies are of same order, for a pulsar with mass M and radius R, the stored gravitational energy is $E_{\text{stored}} \simeq GM^2/R \sim 10^{53}$ erg if $M \sim M_\odot$ and $R \sim 10$ km, so energy released would be as high as $\sim 10^{53}\Delta R/R$ erg when the radius changes from R to $(R - \Delta R)$. Compared with magnetars powered by magnetic energy, quake-induced energy in solid quark-cluster stars may also power the bursts, flares and even superflares of AXPs and SGRs [31]. The question whether there is strong magnetic field in pulsar-like compact stars is encountered again, which could be answered by observations of linear X-ray polarization.

Another observational hint for the nature of CBM comes from low-mass compact stars, including km-radius compact stars and planet-mass compact objects. As we know, neutron stars are gravitationally bound, while quark-cluster stars are bound not only by gravity but also by additional strong interaction. This fact results in an important astrophysical consequence that quark-cluster star can be of very low mass with small radii, while neutron stars cannot. Thermal radiation components from some pulsar-like stars are detected, and the radii are usually much smaller than 10 km in blackbody models, which suggests the existence of km-radius compact stars [32]. Besides, the compact companion of PSR J1719-1438 with a Jupiter-like mass is suggested to be an exotic quark object rather than a light helium or carbon white dwarf [33].

X-ray bursts on stellar surface are believed to be evidence for curst, which could be well explained by elaborate modeling in neutron star model. Can it be reproduced in quark-cluster star model? The key to the mechanism of X-ray bursts is to have unstable energy release during accretion, which could be implemented in quark-cluster star by either thermal nuclear flash on crust formed above quark-cluster star or star-quake-induced burst. Other phenomena such as cooling, glitch and braking could also provide hints for the nature of

CBM [34, 35, 36, 37].

Various observations hint a new answer for the nature of CBM: a solid state of quark-cluster matter. In the future, further observations realized by more advanced telescopes would teach us more. In radio band, Chinese five hundred meter aperture spherical telescope (FAST [38]), the biggest single-dish radio telescope to be built, is capable to measure the mass and even the inertial of momentum of radio pulsars, and possibly find sub-millisecond radio pulsars. In X-ray band, Chinese lightweight asymmetry and magnetism probe (LAMP) is also designed to detect X-ray polarization, which may shed light on the nature of astrophysical CBM.

6 Conclusions

Why should one study CBM of astrophysics? Frank Wilczek's answer is recommended [39]: "because it's there" (a variation on the one George Mallory gave) and because it is a mathematically well-defined domain (to understand Yang-Mills theory). It is challenging for both physicist and astrophysicist to solve the problem.

The history of astrophysical CBM study can date back to about eighty years ago, when Landau proposed the idea of gigantic nucleus. The discovery of pulsar in 1967 is a breakthrough in the study, and Landau's speculation gradually developed to the standard neutron star model today. It is also conjectured, from an astrophysical point of view, that CBM would actually be quark-cluster matter, which could be necessary to understand different manifestations of pulsar-like compact stars. Besides this, we are expecting key observations to test the models.

We would like to thank many contributions and useful discussions of members at the pulsar group of PKU. This work is supported by the National Basic Research Programme of China (Grant Nos. 2012CB821800, 2009CB824800) and the National Natural Science Foundation of China (Grant Nos. 11225314, 10935001).

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