Color-charged Quark Matter in Astrophysics?

Congxin Qiu\(^1\), Renxin Xu\(^2\)

\(^1\)School of Space and Earth Sciences, Peking University, Beijing 100871; q.x.q@yeah.net
\(^2\)School of Physics, Peking University, Beijing 100871; r.x.xu@pku.edu.cn

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Color confinement is only a supposition, which has not been proved in QCD yet. It is proposed here that macroscopic quark gluon plasma in astrophysics could hardly maintain colorless because of causality. The authors expected that the existence of chromatic strange stars as well as chromatic strangelets preserved from the QCD phase transition in the early universe could be unavoidable if their colorless correspondents do exist.

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The elementary strong interaction is believed to be recognized by two distinct features: asymptotic freedom and color confinement. Though Politzer \(^1\) and Gross and Wilczek \(^2\) proved asymptotic freedom in Quantum Chromodynamics (QCD), QCD in nonperturbative regime is still unsolved and becomes one of the top challenges for physics today. Nambu \(^3\) discussed the possibility of color confinement since the QCD vacuum is supposed to be a condensation of virtual quark–antiquark pairs and gluons. In the strong coupling approximation, lattice gauge calculation shows that the QCD potential is linear in the infrared region \(^4\). Certainly, we have never found a chromatic particle in an accelerator experiment. However, unfortunately, all that evidences mentioned above should not be enough to convince us a strictly hold nature of color confinement, since infrared and ultraviolet regions could be separated by one or more discontinuous phase transitions \(^4\).

The special QCD vacuum may probably explain the color-singlet of particles in the high energy experiments. Color-charged quarks, exchanging madly gluons, are supposed to be confined in color-neutral hadrons (baryons or mesons) with others. When one of the quarks in a given particle is “pulled” away from its neighbors, it would be energetically favorable for the virtual quark–antiquark pairs to become valency and to keep the hadrons in singlet states again. However, things would be much different in case of a huge bulk of astrophysical quark gluon plasma. Let’s consider a bulk of quark matter which is initially colorless. It should evaporate or split if it has to reduce its volume for certain reasons. In case of evaporating particles (e.g., baryons or mesons), color-singlet might keep easily since this evaporation could be considered as a local process \(^21\). But in the splitting process, it could be hard for us to believe that every splitting pieces happen to be colorless because, in this non-local case, the time needed for transforming information (even as fast as light) from one part of the bulk to the other should not be negligible (Fig. 1).

There is a great difference between electroneutral and colorless states. An electrically charged body may discharge via ejecting electrons or operating virtual $e^+e^-$ pairs in the vacuum. How about chromatic quark matter? Note that the QED vacuum is screening, while the QCD vacuum is anti-screening. It might be energetically favorable for chromatic quark matter to locally excite and eject color-singlet particles, and the color-charge keeps then. The interaction between chromatic bulks of quark matter might only be in very short distance if single color-gluon interchange is not allowed since mesons or glueballs as intermediate particles are very massive. All the observations above could show us that it would be hard for chromatic quark matter to drop its color off unless by random collision.

If color confinement is not exactly hold, chromatic quark matter could be in an extremely high energy scale, which should be too high for nowadays accelerators to achieve. Surely, the energy scale would be hard to estimate in the framework of quantum field theory since the matter is in a non–local and bound state. We have then tried two phenomenological models \(^5\) to make sense of

FIG. 1: An illustration of splitting a large bulk of quark matter. If a red quark in the center (labelled as “$R$”) wants to decide which way to go, it should be able to count instantaneously the color-charges of quarks in at least one side in order to keep the divided two parts in color-singlet states. It could then be very difficult to maintain color-singlets of the splitting pieces in a macroscopic scale.
this. In the first model, we considered a bulb in a color dia-electric medium which has color dielectric constant less than one. The bulb can change its radius to minimize its total energy. And in the second model, we simply laid up a lot of color dipoles in the vacuum and calculate their response for a valence color charge in the center. Both the models show us that the minimum energy scale, $U_{\text{min}}$, for exciting chromatic quark matter should depend on the radius, $R$, of the bulk, with a likely relation of $U_{\text{min}} \approx \text{const} \cdot 1/R$. The constant in this relation can be estimated if we pay attention to the fact that no accelerator (which have a energy scale of about 100GeV) is powerful enough to create a chromatic particle (which have a typical radius of about 1fm). The constant could then be greater than $\sim 10^{-10} \text{MeV} \cdot \text{m}$. It is observed then that color confinement can only be hold exactly only if the constant is infinity. Therefore, the conclusion could be: if color confinement is exactly hold for microscopic particles ($\sim 1 \text{ fm}$), it is also exactly hold for a bulk of quark matter; but if it is just approximately hold, to create a bulk of chromatic quark matter is much easier (i.e., to need lower energy) than to create a chromatic microscopic particle.

The first implication of chromatic quark matter could be of splitting strange stars. Strange stars are potential candidates for the nature of pulsar-like stars [4, 5], see [2] for a review. They are a kind of fermion stars, which are bound by strong interaction (and gravity if stellar masses approach the maximum limit) and are in fact large bulks of quark gluon plasma. There could be two conceivable channels to split bulk quark matter: merge of binary strange stars and supernova explosion. It is very uncertain to calculate the former process, and we then think about the later one only as following.

Based on the kick velocity, $v_k$, of pulsars, which we choose 1000km·s$^{-1}$ as an upper limit [10], the kinematic energy scale of supernova explosion can be estimated. Assuming an equipartition rule for stellar rotational energy and kick energy, we could then estimate the critical condition for splitting a strange star [5]. The relation between spin frequency and equilibrium shape of a liquid star was given by Maclaurin in the framework of Newtonian gravity, with an equation [11] of

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\Omega^2 = 2\pi G \rho \left[ \frac{\sqrt{1 - \epsilon^2}}{\epsilon^3} (3 - 2\epsilon^2) \arcsin \epsilon - \frac{3(1 - \epsilon^2)}{\epsilon^2} \right],
$$

where $\rho$ is the density of the star, $\Omega$ is the angular velocity, $\epsilon$ is the eccentricity of the meridian plane, and $G$ is the Newtonian gravitational constant. A rotating star would disintegrate at the bifurcation point of the Jacobian sequence branches, with $\epsilon = 0.8127$ [12, 13]. Assuming $I \Omega^2 = M v_k^2$, one can calculate the rotational energies for different stellar masses, $M$, where $I$ is the moment of inertia and $v_k$ is $10^8$ cm/s. In Fig. 2 the rotation energy ($E_{r,\text{split}}$) of a star with $\epsilon = 0.8127$ is shown by a solid line (i.e., $\epsilon$ is fixed in Eqn. (1)), whereas the actual rotation energy is shown by a dashed line (i.e., $\Omega$ is determined by $v_k$). Comparing those two kinds of rotation energies, we could see that a strange quark star with initial matter of $\sim 10^{-5} M_\odot$ may split into two or more bulks of quark matter.

The calculation shown in Fig. 2 can only applicable to rotating rigid body kicked during in the supernova explosion, but a real star should not be in this situation. During the birth of protoquark stars with high temperature, $T$, and high $\nabla T$ [14], hot turbulent convective quark stars may eject low-mass quark matter (quark nuggets) [15]. Also during supernova explosions, small quark nuggets could possibly be kicked out from the protoquark stars if they are not rigid rotators. For the sake of simplicity, we assumed that the energy kicked to the small piece is the same as to the quark star (which is related to the observable kick velocity of pulsars). To compensate the gravitational potential energy (for a quark star not too massive, the typical density is a constant) in the framework of Newtonian, the maximum piece can be kicked to infinity has a typical mass $M = 7.5 \times 10^{28}$g and radius $R = 0.35$km (for a constant density of $\rho = 4.1 \times 10^{14}$g·cm$^{-3}$). In the calculation above we neglect the energy loss caused by gravitational radiation, which is very effective [2] but hard to calculate. The maximum mass of splitting pieces might then be actually smaller than $\sim 10^{28}$ g. This kind of splitting pieces of quark matter could be candidates for the planets of pulsars [10]. However, it is worth noting that, even though the kicked nuggets take color-charges, the colors might not have dynamical contrition to be as strong as gravity if chromatic quark matter would not interact in a long distant.

The second implication could be about the chromatic strangelets preserved during the QCD phase transition.
of the early Universe. In the standard model [17], a first-order QCD transition leads to bubble nucleation. Bubbles of quark–gluon plasma form during the transition. In case of homogeneous nucleation, the mean distance of nucleation, \( d_{\text{nuc}} \), could be \(<2\, \text{cm} \), while the value of \( d_{\text{nuc}} \) may be several meters in the case of heterogeneous nucleation [18]. The strangelets proposed by Witten [19] seems unlikely since that suggestion needs \( d_{\text{nuc}} \gtrsim 300 \mu\text{m} \) [17]. However, things could be much different if chromatic strangelets were created during cosmic QCD phase-transition. As we have mentioned, it could be energetically favorable to exist huge bulk of chromatic quark matter since \( U_{\text{min}} \propto R^{-1} \). In this sense, the hadronization of chromatic quark nuggets could not be very effective and may still be residual today.

Let’s estimate roughly the number density of such strangelets in the Universe, assuming that all the strangelets take color-charges and could survived. Lattice gauge calculations shows us that the QCD phase transition occurs at a temperature of \( T_c = 170\, \text{MeV} \) [17]. Using the relation of “\( a(t) \cdot T(t) = \text{const} \)” for radiation field in the expanding Universe, where the scale factor \( a(t) \) and the temperature \( T(t) \) are function of cosmic time \( t \), and choosing \( d_{\text{nuc}} = 2\, \text{cm} \) and \( T(\text{today}) = 2.73 \, \text{K} \) of cosmic microwave background, we obtain a number density of \( \sim (0.1\, \text{AU})^{-3} \) in today’s Universe.

It is not easy to estimate the mass of that kind of strangelets since one can not have a believable method to calculate the total energy of chromatic quark matter. A possible restriction for the mass could be obtained by noting that the total mass of these strangelets should be lower than that of dark matter. If we choose the Hubble constant \( H_0 = 72\, \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1} \) and assume that 25% of the total energy density of the Universe is in the form of dark matter in the concordance model [17], we could have an upper limit of the strangelets’ mass: \( m_{\text{s}} \lesssim 7.4 \times 10^6 \, \text{g} \).

The radius of strangelets with mass of \( \sim 10^6 \, \text{g} \) is about \( 10^{-3} \, \text{cm} \). It is possible that such strangelets, which are lighter than asteroids, are wandering in our solar system, but we can hardly observe them since they seems to contribute only gravitational interaction in the space. Nevertheless, these strangelet bidders may have had significant consequence during the early Universe (e.g., the period of galaxy formation).

Is there any experimental feature of chromatic quark matter? This is really an interesting question to be answered by future more investigations. Similar to the Schwinger process [20] of the QED vacuum polarization by a prescribed electromagnetic field, a highly color-charged quark matter may radiate colorless hadrons in the nearby polarized QCD vacuum, but could become more and more difficult and may finally stop when its mass decreases to a critical value due to the fact of \( U_{\text{min}} \propto 1/R \). A particularly fascinating process could be that a chromatic relativistic strangelet goes into the Earth’s atmosphere. It may absorb nucleons at first, and then its temperature increases to be high enough to evaporate hadrons. The character of its atmospheric shower depends on the detail interactions, which is certainly model-dependent. Are some cosmic events (e.g., the ultra-high energy cosmic rays) related to chromatic strangelets? We can not know at this time.

Let’s summarize briefly our opinion. Chromatic strange quark stars as well as strangelets could be unavoidable if their colorless counterparts do exist, but evidence for color-charges might hardly be obtained nowadays. We suggest that color confinement would not be hold exactly in the nature.

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[21] Note that QCD is a local gauge theory, and color confinement would then be a local concept.