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## 'Bare' Strange Stars Might Not Be Bare \*

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It is proposed that the 'bare' strange matter stars might not be bare, and the observed pulsars might be in fact the 'bare' strange stars. As intensely magnetized strange matter stars rotate, the induced unipolar electric fields would be large enough to construct magnetospheres. This situation is very similar to that discussed by many authors for rotating neutron stars. Also, the strange stars with accretion crusts in binaries could act as x-ray pulsars or x-ray bursters. There are some advantages if pulsars are 'bare' strange stars.

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The first radio pulsar, CP 1919, was discovered in November 1967.<sup>1</sup> Since then, more radio pulsars have been found, the number of which is approximately 750. However, one of the very interesting and the most important questions is "What is the nature of pulsars?" which, unfortunately, could still not be answered with certainty even now.<sup>2</sup>

Soon after the discovery of pulsars, by removing the possibilities of white dwarf pulsation and rapid orbital rotation (see, e.g., the review by Smith<sup>3</sup>), many people widely accept the concept that pulsars are neutron stars which were conceived as theoretically possible stable structures in astrophysics.<sup>4,5</sup> Following this, many authors discussed the inner structure of neutron stars, especially the properties of possible quark phase in the neutron star core (e.g., Wang *et al.*<sup>6</sup>).

As the hypothesis that strange matter may be the absolute ground state of the strong interaction confined state has been raised,<sup>7,8</sup> Farhi *et al.*<sup>9</sup> pointed out that the energy of strange matter is lower than that of matter composed by nucleus for quantum chromodynamical parameters within rather wide range. Hence, strange stars should be a possible astrophysical object,<sup>10</sup> which can be considered as a ground state of neutron stars. Pulsars might be strange stars. Therefore, the question about the nature of pulsars, which seems to have been answered, rises again.

The important point on this research is to find the difference between the behaviors of strange stars and neutron stars, both observationally and theoretically. The dynamically damping effects, the minimum rotation periods, the cooling curves, and the vibratory mode have been discussed in detail in the literature. However, no direct observational clue has yet shown that the pulsars are neutron stars or strange stars.

Almost all of the proposed strange star models for pulsars have addressed the case generally contemplated by most authors that the strange star core is surrounded by a normal matter crust.<sup>11</sup> The essential feature of this core-crust structure is that the normal hadron crust with about  $10^{-5}M_{\odot}$  and the strange quark matter core with about  $1.4M_{\odot}$  are divided by all electric gap ( $\geq 200$  fm).

It is accepted<sup>10</sup> that a strange star with a bare surface will not supply charged particles to form a ro-

tating space charged magnetosphere because the maximum electric field induced by a rotating magnetized dipole,  $\sim 10^{11}$  V·cm<sup>-1</sup>, is negligible when compared with the electric field at the strange matter surface,  $\sim 10^{17}$  V·cm<sup>-1</sup>. Hence bare strange stars should not be pulsars. However, by computation, the electric field due to electron distribution near the surface decreases quickly outward, from about  $10^{17}$  V·cm<sup>-1</sup> at the surface to about  $10^{10}$  V·cm<sup>-1</sup> at a height of  $10^{-7}$  cm above the surface (Fig. 1). Therefore, a magnetosphere could be established around a bare strange star (see below for a detailed discussion).

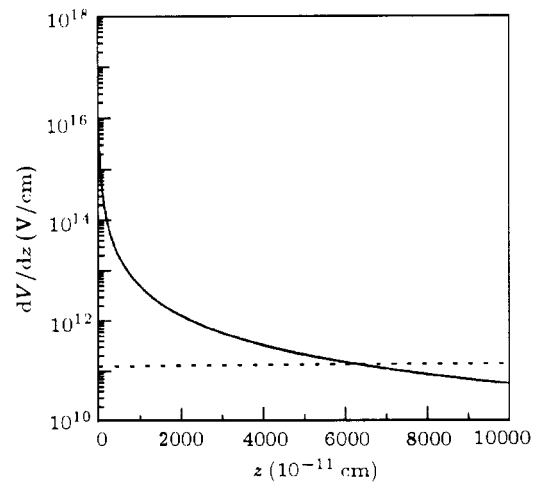


Fig. 1. Electric field  $dV/dz$  variation curve as a function of  $z$  (a space coordinate measuring height above the quark surface), dashed line for the unipolar induced electric field.

For a static and nonmagnetic strange star, the properties of strange quark matter are determined by the thermodynamic potentials  $\Omega_i$  ( $i = u, d, s, e$ ) which are the functions of chemical potential  $\mu_i$  as well as the strange quark mass  $m_s$ , and the strong interaction coupling constant  $\alpha_c$ .<sup>10</sup> For a strange star with a typical pulsar mass,  $1.4M_{\odot}$ , the total energy density  $\rho$  has a very modest variation with the radial distance of a strange star,<sup>10</sup> from about  $4 \times 10^{14}$  g·cm<sup>-3</sup> (near surface) to about  $8 \times 10^{14}$  g·cm<sup>-3</sup> (near center). Our computation shows that the quark charge density would be in the order of from  $10^{16}$  (near the surface)

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to  $10^{15}$  (near the center)  $\text{C}\cdot\text{cm}^{-3}$  in the above energy density range for  $\alpha_c = 0.3$ . Physically, as the Fermi energy of quarks becomes higher (for larger  $\rho$ ), the effect due to  $m_s \neq 0$  would be less important, therefore, the charge density should be smaller.

For a strongly magnetized and rapidly rotating strange star, the space charge separated density near the star is<sup>12</sup>

$$\rho_{\text{GJ}} \sim \frac{\boldsymbol{\Omega} \cdot \mathbf{B}}{2\pi c} = \frac{1}{9} \cdot 10^{-7} B_{12} P^{-1} \text{C} \cdot \text{cm}^{-3},$$

where  $B_{12} = B_p/(10^{12}\text{G})$  ( $B_p$  is the polar cap magnetic field), and  $P$  is the rotation period in units of s. As  $\rho_{\text{GJ}}$  ( $\sim 10^{-8}$ ) is very small compared with the quark charge density  $\rho_q$  ( $\sim 10^{15}$ ) in the strange star interior, it is a good approximation to take that the quarks and electrons are in chemical and thermal equilibrium although charged particles have been slightly separated to balance the unipolar induced electric force in the star interior.

If we have vacuum outside the strange star, the induced electric field along the magnetic field,  $\mathbf{E} \cdot \mathbf{n}_B$ , is given by<sup>12</sup>

$$\begin{aligned} \mathbf{E} \cdot \mathbf{n}_B &= -\frac{2\Omega R}{c} B_p \left(\frac{R}{r}\right)^4 \frac{\cos^3 \theta}{\sqrt{1+3\cos^2 \theta}} \\ &= 1.26 \times 10^{11} R_6 B_{12} P^{-1} \left(\frac{R}{r}\right)^4 \\ &\quad \cdot \frac{\cos^3 \theta}{\sqrt{1+3\cos^2 \theta}} \text{V} \cdot \text{cm}^{-1}, \end{aligned}$$

where a dipole magnetic field is assumed,  $B = (1/2)B_p \sqrt{1+3\cos^2 \theta} (R/r)^3$ ,  $r$  and  $\theta$  are the usual polar coordinates with  $\theta$  measured from the rotation axis,  $R$  is the strange star radius,  $R_6 = R/(10^6 \text{cm})$ , and  $\mathbf{n}_B$  is the direction of magnetic field.

In Fig. 1, the electric field near  $z = 6 \times 10^{-8} \text{cm}$  to bound the electrons to the quark matter,  $dV/dz$ , is comparable to the unipolar induced electric field along  $\mathbf{n}_B$ . When  $z > 6 \times 10^{-8} \text{cm}$ , the motion and distribution of electron should be mainly controlled by  $\mathbf{E} \cdot \mathbf{n}_B$ , as all of the other forces (e.g., gravitation and centrifugal acceleration) can be negligible. Thus, the distributed electrons near and above  $z \sim 6 \times 10^{-8} \text{cm}$  could not be in mechanically or quantum mechanically equilibrium (see the detailed discussion below), and a magnetosphere around strange star could be established.

As discussed above, the unipolar induced electric field does have considerable contribution to the distribution of electrons almost at the strange star surface ( $10^{-8} \text{cm}$  is a very small number in astronomical viewpoint). The induced field can pull or push the electrons near the strange star surface. The potential difference between  $\theta = 0^\circ$  and  $\theta = 90^\circ$  is given by<sup>12</sup>

$$\Delta\phi = 3 \times 10^{16} B_{12} R_6^2 P^{-1} \text{V},$$

if there are no charged particles outside the star. An electron in this electric field cannot be continually accelerated, as pair creation processes could stop this process. Electrons or positrons with large Lorentz

factors should produce  $\gamma$ -rays by, for example, inverse Compton scattering, curvature radiation, and synchrotron radiation and, perhaps, pair annihilation. Also almost all of the produced high energy  $\gamma$ -rays in such strong magnetic field could convert to electron-positron pairs through  $\gamma + B \rightarrow e^\pm + B$  or two photon processes, such as  $\gamma + x \rightarrow e^\pm$  ( $\gamma$ -ray and x-ray are annihilated to be electron-pair). Hence, if a strange star has a vacuum outside, this cascade of pair creation should bring about the appearance of a large enough pair plasma to construct a charge separated magnetosphere around the strange star, both in the corotation part and in the open field line region.<sup>13</sup> According to energy conservation law, the energy of the above cascade process is from the strange star's rotation. As long as the magnetosphere has been established, the detailed discussed pulsar models, such as the polar gap model,<sup>14</sup> the slot gap model,<sup>15</sup> and the outer gap model,<sup>16</sup> would work for the radio as well as higher energy photons' emission due to the electromotive force caused by the potential difference between the center and the edge of the polar cap region.

Let us come to some details. For  $\boldsymbol{\Omega} \cdot \mathbf{B} > 0$ , the induced electric field would pull the electrons out, accelerate them ultra-relativistically. As electrons are lost from the quark matter, the strange star could be positively charged; a global electric circuit<sup>17</sup> might be constructed. However, this global circuit could be in quasi-equilibrium and a small vacuum gap similar to that of Ruderman-Sutherland (RS) model<sup>14</sup> could be possibly near the polar cap. For  $\boldsymbol{\Omega} \cdot \mathbf{B} < 0$ , the induced electric field would push the electrons inward, and a large vacuum region should be above the polar cap. Some physical processes, such as cosmic  $\gamma$ -rays interaction with strong magnetic fields, or electrons (scattered by neutrinos from strange star) synchrotron radiation (jump between two Landau levels) could trigger a pair creation cascade.

If a strange star forms soon after a supernova, a magnetosphere composed by ions would not be possible since a lot of very energetic outward particles and photons are near the star. The time scale  $T$  to form an  $e^\pm$  pair plasma magnetosphere is very small. The total number of  $e^\pm$  pairs in the magnetosphere might be estimated as  $N_{\text{GJ}}$ ,

$$N_{\text{GJ}} \sim R \int_R^{R_c} \frac{\Omega B_p}{2c\pi} \left(\frac{R}{r}\right)^3 dr \approx 3.5 \times 10^{28} R_6^3 B_{12} P^{-1},$$

where the radius of light cylinder  $R_c = cP/(2\pi) \gg R$  (the radius of strange star). The mean free path  $l_p$  of a photon with energy greater than about 1 MeV moving through a region of magnetic field  $B$  can be estimated as<sup>17</sup>

$$l_p \sim \frac{8.8 \times 10^3}{B \sin \alpha} \exp\left(\frac{3}{4\chi}\right) \text{cm},$$

where the parameter  $\chi$  could be approximated as  $1/15$ ,<sup>14</sup>  $\alpha$  is the angle between the direction of propagating photon and the magnetic field,  $l_p \sim 68 \text{cm}$  for  $\sin\theta \sim 1/\gamma \sim 10^{-5}$  ( $\gamma$  is the Lorentz factor of electron). Also, the mean free length  $l_e$  of electron to produce photon by curvature radiation, etc., could be

assumed in order of  $l_p$ . For the cascade processes discussed, the time scale  $T$  for the magnetosphere might be

$$T = \left( \frac{l_p + l_e}{c} \right) \frac{\ln N_{GJ}}{\ln 2},$$

which is in the order of  $10^{-7}$  s for typical pulsar parameters. Considering the photon escaping and the global magnetic field structure, this time scale should not change significantly.

While strange stars are in binaries, the accretion pressure of wind or matter could be greater than the outward pressure, and a strange star could be an accretion powered x-ray source. For an accreting strange star, there could be two envelope crusts shielding the two polar caps because of accretion. As strange matter does not react with ions because of the Coulomb barrier (the height of which is about 15 MeV), there could be an electrostatic gap of thickness of hundreds fm above the surface

If the magnetic field is very strong ( $B_p \sim 10^{12}$  G, high mass x-ray binaries), those accreted crusts should be small. Because of the huge release of gravitational energy and the thermal nuclear reactions above the crusts, the ion penetration probability might be large enough to keep a quasi-equilibrium accretion process, and the accretion-powered strange star could be an x-ray pulsar.<sup>18</sup>

If the magnetic field is less strong ( $B_p \sim 10^8$  G, low mass x-ray binaries), the accreted polar crusts could be large enough to form a united crust. In this case, the accretion process is mild, and the electric gap could prevent strong interactions between the crust and the strange matter for a long time. However, as the accreted matter piled up the crust could be hot enough and dense enough to trigger the thermonuclear flash, this strange star could act as an x-ray burster,<sup>19</sup> and a lot of ions might also be pushed to the strange matter through the Coulomb barrier.

The 'bare' strange stars (rather than neutron stars or strange stars with crusts) being chosen as the interior of pulsars have some advantages:

1. <sup>56</sup>Fe emission lines. An iron emission line at 6.4 keV has been observed in many accretion x-ray pulsars, while, they have never been reported in the seven  $\gamma$ -ray pulsars. If pulsars' interiors are neutron stars, and iron ions could be easily pulled out, there should be un-negligible composition of iron in the magnetosphere. Hence, it is hard to explain why iron lines have not been observed. However, the open field line region of a strange star magnetosphere consists of  $e^\pm$  pairs, no ion can result in the radiative processes.

2. Binding energy problem. The RS model<sup>14</sup> is well-known to pulsar astrophysics both in observation and in theory. Observations show that the radio emission might radiate from near the polar cap, to which the RS inner gap is related. However, the iron binding energy cannot be large enough to support the RS gap of a neutron star. Many authors (example, Neuhauser *et al.*<sup>20</sup>) used different techniques to estimate the binding energy of iron atoms at the neutron star surface. All of them yield the result that iron has the its lowest

energy state as unbound atoms rather than the chains. In the case of a strange star, as the positive charged quark matter near the surface is held by strong interaction, the binding energy should be approximately infinity when  $\Omega \cdot \mathbf{B} < 0$ . Because of the attraction of the quark matter and the quasi-equilibrium of electric current, the electrons could not be easily pulled out when  $\Omega \cdot \mathbf{B} > 0$ .

3. Supernovae explosion. In the collapse of a supernova core, the phase transitions from nuclear matter to two-flavor quark matter and from two-flavor quark matter to three-flavor quark matter may occur,<sup>21</sup> which could result in the enhancement of both the probability of success for supernova explosion and the energy of the revived shock wave.

A critical point to distinguish neutron star and strange star might be that strange stars have very high Coulomb barrier which can support a large body of matter, while, neutron stars do not have. As the bare strange stars acting as the radio or  $\gamma$ -ray pulsars are very similar to the neutron stars (the differences of rotation period and cooling curve between them are hard to be found), we suggest to search the differences between strange star and neutron star in accretion binaries, especially for the bursting x-ray pulsar GRO J1744-28.<sup>22</sup>

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