Pulsars and Quark Stars

Ren-Xin Xu

Astronomy Department, School of Physics, Peking University, Beijing 100871, China

Not only is the Universe stranger than we imagine, it is stranger than we **can** *imagine.*
—— Sir Arthur Stanley Eddington (1882 $\sim$ 1944)

Abstract Members of the family of pulsar-like stars are distinguished by their different manifestations observed, i.e., radio pulsars, accretion-driven X-ray pulsars, X-ray bursts, anomalous X-ray pulsars/soft gamma-ray repeaters, certral compact objects, and dim thermal neutron stars. Though one may conventionally think that these stars are normal neutron stars, it is still an open issue whether they are actually neutron stars or quark stars, as no convincing work, either theoretical from first principles or observational, has confirmed Baade-Zwicky's original idea that supernovae produce neutron stars. After introducing briefly the history of pulsars and quark stars, the author summarizes the recent achievements in his pulsar group, including quark matter phenomenology at low temperature, starquakes of solid pulsars, lowmass quark stars, and the pulsar magnetospheric activities.

Key words: pulsars: general — stars: neutron — dense matter

1 INTRODUCTION

Astronomers uncovered compact white dwarfs as early as in 1914, but were not clear how these objects support themselves against gravity. It is Ralph Howard Fowler (1889 $\sim$ 1944) who recognized the quantum pressure of degenerate electrons in white dwarfs, only about two months later after Dirac's paper on the Fermi-Dirac distribution in 1926. Chandrasekhar obtained the equation of state of completely degenerate electron gas, with the inclusion of special relativistic effect, calculated hydrostatic equilibrium of stars composed of this matter, and then found that the degenerate pressure is not omnipotent in standing against the gravitational collapse (i.e., there exists a mass-limit beyond which a white dwarf can not be hydrostatic) in 1931. What if the mass of a star supported by electron degenerate pressure is greater than the Chandrasekhar limit? Landau speculated a state of matter, the density of which "becomes so great that atomic nuclei come in close contact, forming one *gigantic nucleus*" in 1932. A star composed dominantly of such matter is called a "neutron" star, and Baade and Zwicky suggested in 1934 that supernovae could produce neutron stars. A direct observational evidence, proposed by Gold in 1968, is detecting pulsed radio beams (*pulsars*) due to the lighthouse effect of spinning neutron stars, although pulsars were supposed to "be associated with oscillation of white dwarfs or neutron stars" when discovered by Hewish, Bell, and their co-authors.

Are neutrons elementary particles? A success in the classification of hadrons discovered in cosmic rays and in accelerators leaded Gell-Mann (1964) to coin "*quark*" with fraction charges ($\pm 1/3, \mp 2/3$) in mathematical description, rather than in reality. These sub-nucleon particles were treated independently as real components of hadrons by Zweig (1964, called as "*ace*") and by the Chinese group (1966, called as "*straton*"). Now, all the six flavors of quarks (u, d, c, s, t, b) have experimental evidence, and the underlying theory is believed to be quantum chromodynamics (QCD). Gross & Wilczek (1973) and Politzer (1973) noted in QCD that the effective coupling between quarks decreases with energy (the *asymptotic freedom*), which

$\star$ E-mail: `r.x.xu@pku.edu.cn`

was found to agree with the SLAC (the linear accelerator at Stanford) experiments in 1960s. Quark matter (or quark-gluon plasma), the soup of deconfined quarks and gluons, is a direct consequence of asymptotic freedom when temperature or baryon density are high enough since quarks are more fundamental than neutrons (or protons).

Are pulsars really neutron stars? Quarks in nucleons may deconfine at supranuclear density because of asymptotic freedom, but a real question is at what density the deconfinement occurs. Due to a mathematical complex of the nonlinear nature of QCD at low energy, one can *not* tell us the exact density of phase-transition between hadron and quark-matter phases from first principles. Nevertheless, the density could be only $\varrho_c \simeq (4\pi r_n^3/3)^{-1} \simeq 1.5\varrho_0$ ($\varrho_0 = 0.16\,\mathrm{fm}^{-3}$ is the nuclear density) *if* nucleon keeps a radius $r_n \sim 1\,\mathrm{fm}$ since the vacuum outside nucleons decreases as baryon number density gets higher and higher. The center density in most normal neutron star models could reach ϱ_c, and quark-matter cores in neutron stars began actually to be proposed in 1969, long before knowing asymptotic freedom. If quark matter can be stable at zero pressure, *quark stars*, composed completely of quark matter, may then exist in the Universe. This possibility becomes more likely if bulk strange quark matter with almost equal numbers of u, d, and s quarks is absolutely stable (Bodmer 1971; Witten 1984). As strange (quark matter) stars can easily reproduce the rotation and emission features of radio pulsars, it is *not* necessary for us to have to believe that pulsars are normal neutron stars.

It is worth noting that the quark star idea for the nature of pulsars should be pretty good if quark nuggets in cosmic rays are discovered confidently. Strangelets are composed of strange quark matter with small baryon numbers of $\sim 10^2 \sim 10^3$ (or larger). A distinguishable feature of strangelets is a relatively very low ratio of charge to mass. In fact, one doubly charged event, with charge-mass ratio of ~ 0.1, has been detected by the AMS experiment in space (Choutko 2003). This event could be the result of a strangelet, and this opinion could be confirmed if more such events would be recorded in future AMS02 which may detect more than 100 strangelets for 3 years of operation. Additionally, the ultra-high energy cosmic ray (with energy $\gtrsim 10^{19}\,\mathrm{eV}$) events could also be the results of extensive air showers of relativistic strangelets (Madsen & Larsen 2003; Xu et al. 2003).

This paper is a continuation of two previous reviews (Xu 2003a, 2003b), in which recent achievements of quark star as the nature of pulsar-like compact objects are summarized.

2 QUARK MATTER PHENOMENOLOGY AT LOW TEMPERATURE

Asymptotic freedom results in two distinguished phases in the QCD phase-diagram (temperature T v.s. baryon chemical potential μ_B): hadron gas and quark matter (separated by "deconfinement" in figure 1 of Xu 2005a). However, in different locations of the diagram, the vacuum would have different features and is thus classified into two types: the perturbative-QCD (pQCD) vacuum and nonperturbative-QCD (QCD) vacuum. The coupling is weak in the former, but is strong in the latter. Quark-antiquark (and gluons) condensations occur in QCD vacuum (i.e., the expected value of $\langle \bar{q}q \rangle \neq 0$), but not in pQCD vacuum. The chiral symmetry is spontaneously broken in the case that the vacuum is changed from pQCD to QCD vacuums, and (*bare*) quarks become then massive constituent ones (*dressed* quarks). There is no observation that the quark deconfinement and the chiral symmetry restoration should occur simultaneously.

Actually two kinds of quark matter are focused in recent studies: *temperature*-dominated ($T \gg 0$ but $\mu_B \sim 0$) and *density*-dominated ($T \sim 0$, $\mu_B \gg 0$). Previously, Monte Carlo simulations of lattice QCD (LQCD) were only applicable for cases with $\mu_B = 0$. Only recent attempts are tried at $\mu_B \neq 0$ in LQCD. We have then to rely on effective QCD models or phenomenological models to speculate on the properties of density-dominated quark matter. Empirically, one may think that ordinary matter at low T should be solidified. Should quark matter be in a solid state at extremely low temperature ($T \ll 1\,\mathrm{MeV}$) too?

In the region where quarks are deconfined while the chiral symmetry is broken, the coupling between dressed quarks is very strong, which may favor the formation of $n-$quark (n: the number of quarks in a cluster) clusters (Xu 2003c). Such quark clusters could be very likely in an analogy of α-clusters moving in nuclei, which are well known in nuclear physics. The quark clusters in quark matter would be *classical* (rather than quantum) "composite particles" if the clusters' wavepackages do not overlap. Consequently, fluid quark matter would be phase-converted to a solid one if the thermal energy is much smaller than the interaction energy between quark clusters. Quark stars at low temperature could then be conjectured to be solid.

Ferro-magnetization may occur in a solid quark matter, without field decay in the stars. Magnetic field plays a key role in pulsar's life, but there is still no consensus on its physical origin although some related ideas (e.g., the flux conservation during collapse, the dynamo action) appeared in the literatures. Quark clusters with magnetic momentum may exist in solid quark stars. Solid magnetic quark matter might then magnetize itself spontaneously at sufficient low temperature (below its Curie critical temperature, T_{curie}) by, e.g., the flux-conserved field. Ferromagnetism saturated may result in a very strong *dipole* magnetic field. We therefore speculate simply a ferromagnetic origin of pulsar's strong magnetic fields. Magnetic fields forming in this way could not decay since the energy-scale (T_{curie}) is much higher than that of any electric current inside quark stars or in their magnetosphere.

3 GLITCHES AS STARQUAKES OF SOLID PULSARS

A solid stellar object (the most well-studied one is the Earth) would inevitably result in starquakes when strain energy develops to a critical value. It is worth noting that huge energy should be released (and thus large spin-change occurs) after a quake of solid quark stars because of the almost homogenous distribution of total stellar matter with supranuclear density. Starquakes could surely then be a simple and intuitional mechanism for pulsar glitches.

Actually, a quake model for a star to be mostly solid was generally discussed by Baym & Pines (1971), who parameterized the dynamics for solid crusts, and possible solid cores, of neutron stars. Strain energy develops when a solid star spins down until a quake occurs when stellar stresses reach a critical value. As for the solid quark stars, we suggest that, during a quake, the entire stress is almost relieved at first when the quake cracks the star in pieces of small size (the total released energy E_{t} may be converted into thermal energy E_{therm} and kinematic energy E_{k} of plastic flow, $E_{\mathrm{t}} = E_{\mathrm{therm}} + E_{\mathrm{k}}$), but the part of E_{k} might be re-stored by stress due to the anelastic flow (i.e., the kinetic energy is converted to strain energy again). A quark star may solidify with an initial oblateness (or called ellipticity) ε_0; stress increases as the star losses its rotation energy, until the star reaches an oblateness ε_{+1} when a quake occurs. The reference point of strain energy is suggested to be ε_1 (the oblateness of a star without shear energy) after the glitch, but the real oblateness could be $\varepsilon_{-1} < \varepsilon_1$ (Zhou et al. 2004).

The density of quark stars with mass $< \sim 1.5 M_\odot$ can be well approximated to be uniform. As a star, with an initial value ε_0, slows down, the expected ε decreases with increasing period. However, the rigidity of the solid star causes it to remain more oblate than it would be had it no resistance to shear. The strain energy and the mean stress σ are then (Baym & Pines 1971)

$$E_{\mathrm{strain}} = A_2(\varepsilon - \varepsilon_0)^2, \quad \sigma = \left| \frac{1}{V} \frac{\partial E_{\mathrm{strain}}}{\partial \varepsilon} \right| = \mu(\varepsilon_0 - \varepsilon), \tag{1}$$

respectively, where ε is the real oblateness of a star, $V = 4\pi R^3/3$ is the volume of the star, and $\mu = 2B/V$ is the mean shear modulus of the star. The stress could be developed by stellar spindown and by other factors (see discussions below).

The total energy of a star with mass M and radius R is mostly the gravitational energy E_{gravi}, the rotation energy E_{rot}, and the strain energy E_{strain},

$$E = E_{\mathrm{gravi}} + E_{\mathrm{rot}} + E_{\mathrm{strain}} = E_0 + A_1\varepsilon^2 + L^2/(2I) + A_2(\varepsilon - \varepsilon_i)^2, \tag{2}$$

where ε_i is the reference oblateness before the $(i+1)$-th glitch occurs, $E_0 = -3M^2G/(5R)$, I is the moment of inertia, $L = I\Omega$ is the stellar angular momentum, $\Omega = 2\pi/P$ (P the rotation period), and the coefficients A_1 and A_2 measure the gravitational and strain energies (Baym & Pines 1971), respectively,

$$A_1 = \frac{3}{25} \frac{GM^2}{R}, \quad A_2 = \frac{2}{3}\pi R^3 \mu. \tag{3}$$

By minimizing E, a real state satisfies (note that $\partial I(\varepsilon)/\partial \varepsilon = I_0$),

$$\varepsilon = \frac{I_0\Omega^2}{4(A_1 + A_2)} + \frac{A_2}{A_1 + A_2}\varepsilon_i. \tag{4}$$

The reference oblateness is assumed, by setting $B = 0$ in Equation (4), to be

$$\varepsilon_i = I_0\Omega^2/(4A_1). \tag{5}$$

A star with oblateness of Equation (5) is actually a Maclaurin sphere. When the star spins down to Ω, the stress develops to,

$$\sigma = \mu\Big[\frac{A_1}{A_1 + A_2}\varepsilon_i - \frac{I_0\Omega^2}{4(A_1 + A_2)}\Big], \tag{6}$$

from Equations (1), (4), and (5). A glitch occurs when $\sigma > \sigma_c$ (σ_c: the critical stress).

A detail model in this scenario was introduced in Zhou et al. (2004), where it is found that the general glitch natures (i.e., the glitch amplitudes and the time intervals) could be reproduced if solid quark matter, with high baryon density but low temperature, has properties of shear modulus $\mu = 10^{30} \sim 10^{34}$ erg cm^{-3} and critical stress $\sigma_c = 10^{18} \sim 10^{24}$ erg cm^{-3}.

In the model of Zhou et al. (2004), the moment of inertia I decreases suddenly (to result in a jump of $\Delta\nu$, $\nu = \Omega/2\pi$), and then increases gradually (to result in a following post-glitch relaxation). However, three slow-glitches in the PSR B1822–09 have been detected (Shabanova 2005), which were characterized by a gradual increase in ν ($\Delta\nu/\nu \sim 10^{-8}$) during several months, but without obvious relaxation. Such glitches might be understandable in the quake model though one can not rule out the possibility that the glitches are caused by some changes in the magnetospheric structure. As elastic force develops to a critical value, a solid rotator with small shear modulus might not be so violent (e.g., I does not decrease suddenly) but in a gentle way for I to decrease, and could thus reproduce this observational feature. No I-increasing occurs if no significant elastic energy is converted to kinematic energy (and thus no post-glitch). The small glitch at 1994 of PSR B1822–09 may lead to a small effective shear modulus (e.g., significant part of the quark matter would be shiver-like), and thus trigger the slow-glitches. A pre-glitch could then be expected for slow-glitches in the star-quake model of quark stars, in order to have an effective small shear modulus.

Why quake? The key point that a solid star differs from a fluid one is stress energy developed only available in the solid star. Factually, an elastic body can have two kind of changes: *shearing* and *bulk* strains. The volume, V, changes in the latter, but not in the former. If both strains are included, Equation (2) would become,

$$E = E_0 + A_1\varepsilon^2 + L^2/(2I) + A_2(\varepsilon - \varepsilon_i)^2 + K(\Delta V/V_0)^2, \tag{7}$$

where K, which is order of μ, is the bulk modulus, $\Delta V = V - V_0$, and V_0 the volume of the body without stress. Besides the shear strain of ellipsoid change discussed above, azimuthal stress due to the general relativistic effect (being similar to the frame-dragging effect in vacuum) of rotating solid stars may also contribute significantly, though, unfortunately, the theoretical answers to elastic relativistic-stars with rotation are very difficult to be worked out.

Elastic energy develops as a solid bare strange star cools ($\Rightarrow$ bulk strain; even spinning constantly) and spins down ($\Rightarrow$ shearing strain). The temperature-dependent quantity $\Delta V/V_0 \sim (\Delta R/R_0)^3$, with R the radius, $V_0 \simeq 4\pi R_0^3/3$, T the temperature. The value of $R(T = 40\,\mathrm{MeV}) - R(T = 0)$ could be order of a few hundreds of meters (Blaschke et al. 2004). The giant frequency glitch in KS 1947+300 (Galloway et al. 2004) could be evidence for a quake caused by bulk-stress energy release (i.e., bulk elastic force increases to a critical point), but one may expect a sudden decrease in the pulse frequency when a star is spinning up in the glitch model of normal neutron stars. The glitch in KS 1947+300 can be reproduced as long as the star shrinks with $\Delta R/R = -0.5\Delta\nu/\nu \sim 10^{-5}$.

Anomalous X-ray pulsars (AXPs) & Soft γ-ray repeaters (SGRs). AXP/SGRs are supposed to be magnetars, a kind of neutron stars with surface fields of order of $10^{13} \sim 10^{14}$ G, or even higher. But an alternative suggestion is that they are normal-field pulsar-like stars which are in an accretion propeller phase. The very difficulty in the latter view point is to reproduce the irregular bursts, even with peak luminosity $\sim 10^7 L_{\mathrm{Edd}}$ (SGR 0526–66; L_{Edd} the Eddington luminosity). Both shear and bulk strain-induced quakes could occur in AXP/SGRs when the stress energy increase to a critical value. Stress energy as well as magnetic energy (and probably gravitational energy) could be released during quakes. The glitches in AXP/SGRs (e.g., 1E 2259+586, around the 2002 outburst) could be examples of such quakes (Kaspi 2004). For $\sigma_c \sim 10^{22}$ erg cm^{-3}, the total elastic energy released could be order of $\sim 10^{40}$ erg cm^{-3} when a quake

occurs in a solid quark star with radius $\sim 10^6$ cm. This energy is comparable to the observed values of two X-ray flares in 1E 1048.1–5937 (Gavriil & Kaspi 2004).

It is suggested (Lyne 2004; Lin & Zhang 2004) that pulsar-like stars could evolve from normal radio pulsars to magnetars (AXP/SGRs) through un-recoverable glitches (neither the period nor the period derivative are completely recovered for Crab, Vela, and other young pulsars). However, the "appearance" magnetic field, B, increasing could arise from the shrinking of pulsars after quakes. If the effect of decreasing I is included, the appearance value of B should be derived by solving

$$I\dot{\Omega} + \frac{1}{2}\dot{I}\Omega = -\frac{2}{3c^3}B^2R^6\Omega^3, \tag{8}$$

though the real magnetic filed keeps constantly. Significant gravitational wave could radiate during a glitch, which could be detectable in order to test the quake model presented.

4 LOW-MASS QUARK STARS?

It is well known that the mass of quark matter could range from $> 10^2 \sim 10^3$ baryons (strangelets) to $\sim M_\odot$ (quark stars), but the minimum mass of normal neutron stars is $\sim 0.1 M_\odot$. For neutron and quark stars with masses $< M_\odot$, the mass (M) -radius (R) relations are in striking contrast: $M \propto R^3$ for quark stars due to the self color confinement of quark matter but $M \propto R^{-3}$ for normal neutron stars due to the gravitational binding. Therefore, low-mass quark stars would be a direct consequence of the possible existence of astrophysical quark matter.

Up-to-now, there are 7 kinds of members in the family of pulsar-like stars discovered: radio pulsars (normal pulsars and millisecond pulsars), accretion-powered X-ray pulsars, X-ray bursts, AXPs, SGRs, compact center objects (CCOs), and dim thermal "Neutron" stars (DTNs). Could there be any hints that some of these compact objects are actually low-mass quark stars? It is admitted that all the determined masses in binaries with pulsars are $\sim 1.4 M_\odot$. Nonetheless, observationally, the existence of low-mass pulsar-like stars may still not be ruled out since (i) low-mass pulsars could be ejected from binary systems and thus be isolated, and (ii) low-mass pulsars might not have been noted and investigated comprehensively in binaries (e.g., pulsar/white dwarf systems, pulsar/planet systems).

There could be some candidates of low-mass quark stars (Xu 2005b). The planck-spectrum-fitted radiation radii of CCOs (Pavlov et al. 2003) and the seven DTNs (Mereghetti et al. 2002; Haberl 2005) are only a few kilometers. An intuition way to understand these observations could be that these compact stars are actually low-mass quark stars with small radii. According to its peculiar timing behavior, it is proposed that the radio-quiet CCO, 1E 1207.4–5209, could be a low-mass quark star with polar surface magnetic field $\sim 6 \times 10^{10}$ G and a few kilometers in radius. Because of color-confinement, quark stars could spin much faster than normal neutron stars, especially for quark stars with very small radii. It is suggested that the fastest rotating pulsar (Xu et al. 2001), and maybe part of other millisecond radio pulsars, could be low-mass quark stars. The conventional way to estimate the polar magnetic field should be revised if part of both rotation- and accretion-driven pulsars are of low masses.

It is worth noting that the gravitational wave from pulsars should be *mass*-dependent. Based on the data from the second LIGO science run (Abbott et al. 2005) for 28 radio pulsars (3 normal pulsars and 25 millisecond pulsars), the upper limits of ellipticities of these pulsars are obtained (order of 10^{-5} for millisecond pulsars) with an assumption that pulsars have typical masses of $\sim M_\odot$. Owen (2005) concluded that the maximum solid strange quark star ellipticities are comparable to the upper limits obtained by LIGO, while maximum ellipticities of hybrid stars will be detectable by LIGO at initial design sensitivity. However, if pulsars are solid quark stars with approximate Maclaurin spheroids[1], one can only obtain the upper limits of $R \cdot \theta^{1/5}$ (θ: wobble angle) for these millisecond pulsars (Xu 2006). In case of $\theta \sim$ a few degrees, the 25 millisecond pulsars could be quark stars with only a few kilometers in radius, to be comparable to that of X-ray thermal radii detected in CCOs and DTNs.

Searching sub-millisecond pulsars could be an expected way to provide clear evidence for (low-mass) quark stars. Normal neutron stars can not spin with periods being less than $\sim 0.5 M_1^{1/2} R_6^{-3/2}$ ms ($R_6 = R/10^6$ cm), but low-mass bare strange stars can, even less than 0.1 ms. We need thus a much short sampling

---

[1] This approximation is good for the only well-studied solid celestial body, the Earth.
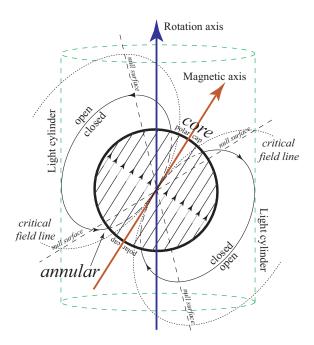
Fig. 1 A schematic illustration of an isolated (i.e., without accretion) quark star and its magnetospheric geometry. The quark star is suggested to be homogeneously magnetized due to the speculation of magnetic symmetry broken spontaneously in solid quark matter as the star cools to a temperature to be lower than a critical Curie temperature.

time, and would deal with then a huge amount of data in order to find a sub-millisecond pulsar. Due to its large receiving area and wide scanning sky, the future radio telescope, FAST (five hundred meter aperture spherical telescope), to be built in Yunnan, China could have this chance (to find *fast* pulsars via *FAST* ˆ‿ˆ).

5 MAGNETOSPHERIC ACTIVITY OF QUARK STARS

As speculated in §2, we propose pulsars to be almost homogenously magnetized rotators, with non-zero inclination angles between spinning and magnetic axes (Fig. 1). For electromagnetism-torqued pulsars without accretion environments, the closed region in their magnetospheres are limited by the light cylinders with radius of $cP/(2\pi)$. In case of accretion (in a binary or with a debris disk), the closed field lines is limited by a magnetospheric radius, $r_{\rm m}$, rather than the light cylinder radius, $r_{\rm lc} = c/\Omega$. The charge density near a pulsar in its magnetosphere is $\rho_{\rm gj} \simeq -\mathbf{\Omega} \cdot \mathbf{B}/(2\pi c)$, which is zero at the null surface. Lines with $\rho_{\rm gj} = 0$ at light cylinder are called *critical field lines*. Relativistic pair plasma may flow out along open filed lines, which could result in lighthouses of multi-waveband (from radio to γ-ray) emissions.

It is believed that primary pairs are produced and accelerated in regions (gaps) with a strong electric field along the magnetic line ($E_\parallel$) while more secondary pairs (with multiplicity $\sim 10^2 - 10^4$) are created outside the gaps ($E_\parallel \neq 0$). Numerous models have been suggested concerning gap acceleration, which are classified into two groups: vacuum inner and outer gaps (e.g., Ruderman & Sutherland 1975; Cheng, Ho & Ruderman 1986), and free-flow gaps (e.g., Arons & Scharlemann 1979; Harding & Muslimov 1998). The former depends on strong binding energy of charged particles on the pulsar surface, but the latter on negligible one. Since different radiative characters could be expected in those two groups of models, we may probe into the nature of particles on pulsar surface, and thus of pulsar interior, through emission features.

Both positively and negatively charged particles on surfaces of normal neutron stars can not be enough bound for vacuum gaps, but that of bare quark stars can. We thus expect vacuum inner gaps work for quark star's magnetospheric activities (see next about the outer gap). Sparking process is a direct consequence of vacuum gaps, which results naturally inhomogeneous plasma ejecta in open field-lines. The electrody-

namic description to calculate the acceleration of pairs would then not easily be formulated mathematically. Observations in favor with the above scenario of polar-cap sparking include short time-scale events (microstructure pulses, nanosecond giant radio bursts), drifting subpulses, and no intrinsic rotation measure ($RM \simeq 0.81 \int_{PSR}^{\oplus} n_e \boldsymbol{B} \cdot d$s) detected in pulsar magnetospheres.

The region of open-field lines can be divided into core and annular ones. The boundary of the former is all of the critical field lines, while the latter is between the surfaces of critical and last-open field lines. Sign-changed plasma would flow out from these two regions in order to close the global electric circuit of magnetosphere. Two inner vacuum gaps (inner core and annular gaps) may occur, which could explain the pulse profiles of multi-band emission (Qiao 2004a) and the bi-drifting phenomenon (Qiao 2004b). There is a competition between the inner annuler gap and the outer gap. If pair production favors near polar caps due to high opacity of photons and strong B and $E_\parallel$, dense pair plasma ejected may quench the outer gap.

A pulsar could be monopole-charged with an electricity, Q, depending on its radius r, polar magnetic field B, and spin (Xu et al. 2006). The sign-changed plasma could be separated by critical field lines if $Q \sim 10^{-3}(r/10^6\,\mathrm{cm})^3(B/10^{12}\,\mathrm{G})/P^2$ Coulomb. However, if a pulsar has not such charge, the core and annular regions would not be separated by the critical field lines. This could consequently affect the radiative locations of radio as well as higher energy emission, which might be checked by the multi-wavelength observations of pulse profiles.

6 CONCLUSIONS

Quark matter and quark stars are reviewed at an astrophysical viewpoint. In addition to test Einstein's general relativity in strong field, pulsar-like stars are also useful to test and to improve our understanding of the fundamental strong interaction. Some characteristics of quark stars are proposed, which may lead finally to a successful identification of them. The physics relevant to the elementary chromatic interaction would certainly be improved if pulsar-like stars are really quark stars. Based on variety of astrophysical observations, a solid state of quark matter is suggested and possible.

References

Abbott B. et al., (LIGO Scientific Collaboration) 2005, Phys. Rev. Lett., 94, 181103

Arons J., Scharlemenn E. T., 1979, ApJ, 231, 854

Baym G., Pines D., 1971, Ann. Phys., 66, 81

Blaschke D., Fredriksson S., Grigorian H., Öztas A. M., 2004, Nucl. Phys., A736, 203

Bodmer A. R., 1971, Phys. Rev., D4, 1601

Cheng K. S., Ho C., Ruderman M., 1986, ApJ, 300, 500

Chinese group, 1966, Acta Scientiarum Naturalium Universitatis Pekinensis, 12(2), 103; and references in this special issue on the structure theory of "elementary particles"

Choutko V., 2003, in: proceedings of 28th International Cosmic Ray Conference, Universal Academy Press, 1765

Galloway D. K., Morgan E. H., Levine A. M., 2004, ApJ, 613, 1164

Gavriil F. P., Kaspi V. M., 2004, ApJ, 609, L67

Gell-Mann M., 1964, Phys. Lett., 8, 214

Gross D. J., Wilczek F., 1973, Phys. Rev. Lett., 30, 1343

Kaspi V. M., 2004, in: Young neutron stars and their environments, IAU Symp. 218, eds. F. Camilo and B. M. Gaensler, p.231

Haberl F., 2005, in: Proceedings of the 2005 EPIC XMM-Newton Consortium Meeting, edts. U.G. Briel, S. Sembay and A. Read, MPE Report 288, in press (astro-ph/0510480)

Harding A. K., Muslimov A. G., 1998, ApJ, 508, 328

Lin J. L., Zhang S. N., 2004, ApJ, 615, L133

Lyne A. G., 2004, in: Young neutron stars and their environments, IAU Symp. 218, eds. F. Camilo and B. M. Gaensler, p.257

Madsen J., Larsen J. M., 2003, Phys. Rev. Lett., 90, 121102

Mereghetti S. et al., 2002, in: Neutron stars, pulsars and supernova remnats, edts. W. Becker, H. Lesch and J. Trümper, p.29

Owen B. J., 2005, Phys. Rev. Lett., 95, 211101 (astro-ph/0503399)

Pavlov G. G., Sanwal D., Teter M. A., 2004, in: Young Neutron Stars and Their Environments, IAU Symposium 218, eds F. Camilo and B. M. Gaensler, p. 239 (astro-ph/0311526)

Politzer H. D., 1973, Phys. Rev. Lett., 30, 1346

Qiao G. J., Lee K. J., Wang H. G., Xu R. X., Han J. L., 2004a, ApJ, 606, L49

Qiao G. J., Lee K. J., Zhang B., Xu R. X., Wang H. G., 2004b, ApJ, 616, L127

Ruderman M. A., Sutherland P. G., 1975, ApJ, 196, 51

Shabanova T., 2005, MNRAS, 356. 1435

Witten E., 1984, Phys. Rev., D30, 272

Xu R. X., 2003a, in: High Energy Processes, Phenomena in Astrophysics, Proceedings of IAU Symposium No. 214, eds. X. D.Li, Z. R. Wang, V. Trimble, p.191-198 (astro-ph/0211348)

Xu R. X., 2003b, in: Stellar astrophysics — a tribute to Helmut A. Abt, eds. K. S. Cheng, K. C. Leung, T. P. Li, Kluwer Academic Publishers, p.73-81 (astro-ph/0211563)

Xu R. X., 2003c, ApJ, 596, L59

Xu R. X., 2005a, Chin. J. Astron. Astrophys. (ChJAA), Vol.5 (Supplement), 353

Xu R. X., 2005b, Mon. Not. Roy. Astron. Soc., 356, 359

Xu R. X., 2006, Astroparticle Physics, 25, 212

Xu R. X., Cui X. H., Qiao G. J., 2006, Chin. J. Astron. Astrophys. (ChJAA), 6, 217

Xu R. X., Wu F., 2003, Chin. Phys. Lett., 20, 806

Xu R. X., Xu X. B., Wu X. J., 2001, Chin. Phys. Lett., 18, 837

Zhou A. Z., Xu R. X., W, X. J., Wang N., 2004, Astropart. Phys., 22, 73

Zweig G., 1964, CERN preprints, No. 8182/TH401, No. 8419/TH412