LOW-MASS QUARK STARS

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Abstract. More and more observational hints of quark stars are proposed these years though pulsars are considered conventionally to be normal neutron stars. The existence of *low-mass* quark stars is a direct consequence of the possibility that pulsar-like stars are actually quark stars, because of the ability that quark matter can confine itself by color interaction. After a brief introduction to the study of quark stars, the various astrophysical implications of low-mass quark stars are investigated. It is addressed that some of the transient unidentified γ-ray sources are probably merging quark stars. The observability of low-mass quark stars is discussed.

Keywords: dense matter, pulsars, neutron stars, elementary particles

1. Introduction to Quark Stars

It challenges still physicists to understand comprehensively the color interaction though we have a general fundamental framework for this strong force: the quantum chromodynamics (QCD). Two well known properties of QCD (asymptotic freedom in $\sim$0.1 fm scales and color confinement in $\sim$1 fm scales) conduce towards two remarkable states in the QCD phase-diagram: the hadron gas and the quark matter (or QGP, quark-gluon plasma). It is a clear goal for part of laboratory physicists to find quark matter in order to research into the problem of the elemental color interaction, whereas to detect astrophysical quark matter may be a shortcut, since astrophysics offers an alternative channel for us to explore the fundamental laws in the nature.

Pulsars, soon after the discovery in 1967, were identified to be *normal* neutron stars (dominantly of neutron fluid) proposed by Landau in 1932. However, since quarks are more fundamental than neutrons, it is possible that quarks enclosed in hadrons could be unconfined in compact stars with much high densities (and probably high temperatures) according to the asymptotic freedom. Stars composed of quark matter are called quark stars. Unfortunately, one is *not* able to determine whether neutron or quark stars remain during supernova explosion or other astrophysical processes via calculations of QCD because of its highly nonlinear nature. In case of this mathematical difficulty of QCD to find a certain answer for "what's the nature of pulsar-like stars?", *how* and *what* can the astrophysical observations *teach* us?

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One kind of quark stars on which astrophysicists focus highly are those with strangeness, so called strange (quark) stars (Xu, 2003a, 2004), the existence of which depends on the Bodmer-Witten's conjecture (Bodmer, 1971; Witten, 1984): strange quark matter is absolutely stable among color interaction systems. Though one can *not* prove or disprove this conjecture by first principles, there are actually several observational hints of strange stars (with *bare* quark surfaces), including drifting subpulses of radio pulsars and super-Eddington bursts of soft γ-ray repeaters ($\Rightarrow$ strong binding of both negatively and positively charged particles above pulsar surfaces), non-atomic thermal X-ray spectra, the discrepancy between free precession and glitch of radio pulsars (Zhou et al., 2004), and pulsar γ-ray profiles (Qiao et al., 2004).

2. The Motivations of Studying Quark Stars with Low Masses

Besides the argument that one can *not* simply rule out the possibility of the existence of low-mass quark stars, we have at least two more reasons for us to study quark stars with low masses.

1. *To identify a quark star in reality*. As is addressed in Section 1, it is very essential to identify a quark star in the new century. Stellar mass and radius are observable parameters, however, they are not distinguishable now for neutron and quark stars with almost the maximum mass (Lattimer and Prakash, 2004). Nevertheless, the term of "*low-mass*" may do us a favor to find crucial evidence for quark stars, since the radii of bare strange stars can be very small, while normal neutron stars (or crusted strange stars) cannot. A neutron star with mass $\sim 0.2 M_\odot$ has a radius of > 15 km, whereas a quark star with mass $0.2 M_\odot$ is only $< \sim 5$ km. It is consequently possible that one can distinguish neutron and quark stars by direct measurements of the radii of low-mass pulsar-like stars by future X-ray satellites.

Also the very distinguishable mass-radius ($M - R$) relations of neutron and quark stars are helpful. The general relativistic effects of both low-mass neutron and quark stars are negligible due to small values of M/R. One is then able to study the structure of low-mass neutron stars by the Lane-Emden equation (Shapiro and Teukolsky, 1983) with $n = 2/3$ (corresponding to the state of non-relativistic neutron gas), which results in neutron star mass

$$M_{\rm NS} = 3.73\ R_6^{-3}\ M_\odot, \tag{1}$$

where the state equation is approximated by perfect neutron gas, $P = 5.52 \times 10^9 \rho^{5/3}$ dyne/cm^2, $R = 10^6 R_6$ cm. In case of very low masses ($M < 0.1 M_\odot$) in Eq. (1), the neutron gas approximation may not be applicable, since the mass and radius of such a star could be controlled by its crust that is not considered in deriving Eq. (1). Realistic neutron star modelling shows that the minimum mass of a stable neutron star is $\sim 0.1 M_\odot$, with radius $R \sim 160$ km (Shapiro and Teukolsky, 1983). However, for low-mass bare quark stars, due to the color self-confinement of quark matter,[1] the density is roughly homogeneous, and the mass would thus be,

$$M_{\rm QS} = \frac{4}{3}\pi R^3 (4\bar{B}) = 0.9\ R_6^3\ \bar{B}_{60}\ M_\odot, \tag{2}$$

where the bag constant $\bar{B} = 60\bar{B}_{60}$ MeV fm^{-3}. In this sense, identifying a pulsar-like star with mass $<0.1M_\odot$ is evident for quark stars. Additionally, this striking difference between $M_{\rm NS} \propto R^{-3}$ and $M_{\rm QS} \propto R^3$ is certainly helpful for us to identify low-mass quark stars.

It is worth noting that, the identification of a low-mass quark star, with mass $<\sim 0.1M_\odot$, may also tell us whether the star has a *bare* quark surface, since the radius of a bare quark star is much smaller than that of a crusted one in this low-mass limit (Xu, 2003b).

2. *To probe the magnetic fields of isolated pulsars*. The conventional method to estimate the polar magnetic fields of isolated radio pulsars *has to* be modified if no certain reason forces us to rule out the possibility that low-mass bare strange stars could be born in the Universe. The energy conservation for an orthogonal star (i.e., the inclination angle between magnetic and rotational axes is $\alpha = 90^{\rm o}$) with a magnetic dipole moment μ, a moment of inertia I, and angular velocity Ω gives

$$\dot{\Omega} = -\frac{2}{3Ic^3}\mu^2\Omega^3. \tag{3}$$

This rule keeps quantitatively for any α, as long as the braking torques due to magnetodipole radiation and the unipolar generator are combined (Xu and Qiao, 2001). For a star with polar magnetic field B and radius R, the magnetic moment

$$\mu = \frac{1}{2}BR^3, \tag{4}$$

if the fields are in pure dipole magnetic configuration or if the star is an uniformly magnetized sphere. One comes then to the conventional way to derive magnetic field from P and $\dot{P}$ ($P = 2\pi/\Omega$ is the spin period),

$$B = 6.4 \times 10^{19}\sqrt{P\dot{P}}\ \ {\rm G}, \tag{5}$$

if "*typical*" values $I = 10^{45}$ g $\cdot$ cm^2 and $R = 10^6$ cm are assumed. Note: the field is only half the value in Eq. (5) if one simply suggests $\mu = BR^3$.

However, neutron star's I and R change significantly for different equations of state, or for different masses even for a certain equation of state (Lattimer and Prakash, 2004). This means that the "typical" values may actually be not typical. The inconsistency becomes more serious if pulsar-like stars are in fact quark stars since such a "star" could be as small as a few hundreds of baryons (strangelets).

3. Astrophysics of Low-Mass Quark Stars

Magnetic field plays a key role in pulsar life, but there is still no consensus on its physical origin although some ideas relevant (e.g., the flux conservation during collapse, the dynamo action) appeared in the literature. As pulsars could be solid quark stars (Xu, 2003c), we may propose an alternative mechanism for the generation of strong magnetic fields: the spontaneously broken ferromagnetism in quark matter when the temperature is lower than the Curie critical one, $T < T_{\rm curie}$. One of the advantages of ferromagnetic origin could be the unchangeable nature of magnetic fields since there is no convincing observation that fields decay in isolated pulsar-like stars. The magnetic domain structure may be destroyed by the turbulent motion in a fluid quark star, but this worry does not exist if pulsars are solid quark stars.

We may define $\mu_{\rm m}$ as the magnetic momentum per unit mass for ferromagnetism-saturated stars. The value of $\mu_{\rm m}$ could certainly depend on the properties of solid quark matter born in different astrophysical processes.

3.1. ROTATION-POWERED LOW-MASS QUARK STARS

Assuming a mass-radius function of Eq. (2) for low-mass quark stars in rotation-powered phases, one can derive (Xu, 2005)

$$P\dot{P} = \frac{320\pi^3\mu_{\rm m}^2}{9c^3}\bar{B}R. \tag{6}$$

A pulsar may evolve along with constant $P\dot{P}$ if its $\mu_{\rm m}$, $\bar{B}$, M, and R are almost not changed during the life. With reasonable bag constant $\bar{B}$ and seven masses detected in pair neutron stars (and thus seven radii by Eq. (2)), we can obtain $\mu_{\rm m}$ for different pulsars. It is found that the values of $\mu_{\rm m}$ are grouped into two classes: high $\mu_{\rm m}{\sim}10^{-4}$ G·cm^3·g^{-1} for normal pulsars but low $\mu_{\rm m} \sim 10^{-6}$ G·cm^3·g^{-1} for millisecond pulsars.

We can draw constant-$P\dot{P}$ lines in the $P - \dot{P}$ diagram, with averaged $\mu_{\rm m}$ for normal and millisecond pulsars, respectively (Xu, 2005). For normal pulsars with three different masses ($2M_\odot$, $1.5M_\odot$, and $1M_\odot$), they evolve passing through almost the middle region of normal pulsars. It is thus suggestive that the distribution of scattered points of normal pulsars could be the result of the variation of $\mu_{\rm m}$, rather than that of pulsar mass. Actually, if the mass is fixed to be $1.5M_\odot$, most of the normal pulsars are between $\mu_{\rm m} = 5 \times 10^{-3}$ and 5×10^{-5} G · cm^3·g^{-1}. However, for millisecond pulsars (e.g., for the case of $\mu_{\rm m} = 10^{-6}$ G · cm^3·g^{-1}), the line with mass $\sim 1M_\odot$ of constant $P\dot{P}$ does *not* pass through the center of the millisecond pulsar points. It is unlikely that the variance of $\mu_{\rm m}$ is responsible for this unless the $\mu_{\rm m}$ values of those millisecond pulsars are not representative. A natural proposal is that some of the millisecond pulsars could be low-mass quark stars, with mass

$\ll M_\odot$. The reason that the observed masses of millisecond pulsars in pair neutron stars are $\sim 1.4 M_\odot$ could be due to the selection effect in astronomy: low-mass quark stars produced in binary may be ejected from the system owing to the strong kick at birth, while only high-mass quark stars can survive.

What can the quark star mass be as low as? This is still a question to be solved by future observations. Possibly the low-limit could be $10^{-1\sim-3} M_\odot$. A quark star with much lower mass than $\sim 10^{-3} M_\odot$ should be called as a strange (quark) planet, rather than a strange (quark) star.

A nucleon has a magnetic momentum of $\sim \mu_{\rm N} = 5 \times 10^{-24}$ erg/G, and the corresponding value $\mu_{\rm m} \sim \mu_{\rm N}/m_{\rm p} \sim 3$ G·cm^3·g^{-1}, which is much larger than that observed in pulsars. This hints that the quark clusters in solid quark stars may have a magnetic momentum per baryon to be $\sim 10^{-(4\sim 6)}$ orders weaker than that of nucleons.

The potential drop in the open-field-line region is essential for pulsar magnetospheric activity. In case of approximately constant $\mu_{\rm m}$, the potential drop between the center and the edge of a polar cap can be expressed as (Xu, 2005),

$$\phi = \frac{64\pi^3}{3c^2} \bar{B} \mu_{\rm m} R^3 P^{-2}. \tag{7}$$

Pair production mechanisms are essential for pulsar radio emission. A pulsar is called to be "death" if the pair production condition cannot be satisfied. Although a real deathline depends upon the dynamics of detail pair and photon production, the deathline can also be conventionally taken as a line of constant potential drop ϕ. Anyway, it is very necessary and worthwhile to investigate the pulsar death in the $P - \dot{P}$ diagram, with the inclusion of this "low-mass" ingredient for the case of pulsars being quark stars, by calculating the magnetospheric dynamics and simulating the spindown behaviors of both normal and millisecond pulsars.

3.2. ACCRETION-DOMINATED SPINDOWN

The physical process of accretion onto rotating pulsar-like stars with strong magnetic fields is very complex but is essential to know the astrophysical appearance of the stars (e.g., the variation of X-ray flux, the evolutional tracks, etc.), which is still not understood very well. Nevertheless, it is possible and useful to describe the physical process of accretion semi-quantitatively.

For an accretion scenario in which the effect of kinematic energy of accreted matter at infinite distance is negligible (such as the case of supernova fall-back accretion), three typical radii are involved. The radius of light cylinder of a spinning star with period P is

$$r_{\rm l} = \frac{cP}{2\pi} = 4.8 \times 10^9 P \text{ cm}. \tag{8}$$

If all of the accretion material is beyond the cylinder, the star and the accretion matter could evolve independently. The magnetospheric radius, defined by equating the kinematic energy density of free-fall particles with the magnetic one $B^2/(8\pi)$, is (Xu, 2005)

$$\begin{aligned} r_{\rm m} &= \left(\frac{32^3\pi^3}{27G}\right)^{1/7} \bar{B}^{3/7}\mu_{\rm m}^{4/7}R^{9/7}\dot{M}^{-2/7} \\ &= 4.9\times 10^7 \bar{B}_{60}^{3/7}\mu_{\rm m}^{4/7}R^{9/7}\dot{M}^{-2/7}, \end{aligned} \tag{9}$$

if a star is homogenously magnetized per unit mass (i.e., with constant $\mu_{\rm m}$). Due to the strong magnetic fields around a spinning star, matter is forced to co-rotate, and both gravitational and centrifugal forces work. At the so-called corotating radius $r_{\rm c}$, these two forces are balanced,

$$r_{\rm c} = \left(\frac{GM}{4\pi^2}\right)^{1/3} P^{2/3} = 1.2\times 10^{-3} M^{1/3}P^{2/3}. \tag{10}$$

Due to the centrifugal inhibition, since the radius of matter nearest to the star could be $r_{\rm m}$, massive accretion onto stellar surface is impossible when $r_{\rm m} > r_{\rm c}$. This is the so-called *supersonic* propeller spindown phase. A star spins down to the equilibrium period $P_{\rm eq}$, defined by $r_{\rm m} = r_{\rm c}$. In the low-mass limit, with the assumption of constant $\mu_{\rm m}$, one has

$$P_{\rm eq} = 15G^{-5/7}\bar{B}^{1/7}\mu_{\rm m}^{6/7}R^{3/7}\dot{M}^{-3/7}. \tag{11}$$

However, accretion with rate $\dot{M}$ onto the stellar surface is not possible, although the centrifugal barrier is not effective when $P > P_{\rm eq}$, until the star spins down to a so-called break period (Ikhsanov, 2003),

$$\begin{aligned} P_{\rm br} &= 60\mu_{30}^{16/21}\dot{M}_{15}^{-5/7}M_1^{-4/21}\ {\rm s} \\ &= 36\bar{B}_{60}^{-4/21}B_{12}^{16/21}\dot{M}_{15}^{-5/7}R_6^{12/7}\ {\rm s} \\ &= 0.49\bar{B}_{60}^{12/21}\mu_{m-6}^{16/21}\dot{M}_{15}^{-5/7}R_6^{12/7}\ {\rm s}, \end{aligned} \tag{12}$$

in the low-mass limit, where the convention $Q = 10^n Q_n$ has been adopted. Pulsars with periods between $P_{\rm eq}$ and $P_{\rm br}$ do still spin down. This phase is called as *subsonic* propeller. Only a negligible amount of accretion matter can penetrate into the magnetosphere (onto the stellar surface) during both the supersonic and subsonic propeller phases (Ikhsanov, 2003), and the expected accretion luminosity is thus very low. It is obviously that pulsars with $P \sim P_{\rm br}$ may spin randomly: to spins up if $P > P_{\rm br}$, but spin down when $P < P_{\rm br}$.

3.3. OTHERS

The implications of low-mass quark stars are more than that presented in Section 3.1. and Section 3.2. We then select some of the issues interested, and try efforts to give general ideas for them.

1. *The birth of low-mass quark stars.* Millisecond pulsars could be of low-mass, but the origin of them is still an open debate even now. Millisecond pulsars are conventionally regarded as recycled ones in low-mass X-ray binaries, the magnetic fields of which decay (by, e.g., enhanced Ohmic dissipation, diamagnetic screening effect, etc.) during accretion process. Recently, five accretion-driven millisecond pulsars have been discovered since 1998, which are important to test the idea. However, besides the old problems (e.g., birthrate, millisecond pulsars with planets, etc.), new puzzling issues are raised in this argument (Rappaport et al., 2004).

The puzzles may disappear if low-mass quark stars, which are rapidly spinning, result directly from accretion-induced collapse (AIC) of white dwarfs, but could be covered by normal matter in their later accretion phases (while the core collapses might produce only normal pulsars with mass $\sim M_\odot$ and radius $\sim 10^6$ cm). The possibility of forming a quark star with $\sim M_\odot$ by AIC might not be ruled out. The newborn low-mass quark stars could rotate very fast, even to be super-Keplerian, and would spin down if the accretion rates are not high enough. Unless the mass is smaller than $(0.1\text{–}0.3)M_\odot$, the thickness of crust could be negligible, and the maximum X-ray luminosity at the break period [$\dot{M} = 2.3 \times 10^{16} P_{\rm br-3}^{-7/5} \bar{B}_{60}^{12/15} \mu_{\rm m-6}^{16/15} R_5^{12/5}$ g/s from Eq. (12)] is approximately,

$$L_{\rm x} = \frac{GM\dot{M}}{R} \sim 2.8 \times 10^{34} P_{\rm br-3}^{-7/5} \bar{B}_{60}^{9/5} \mu_{\rm m-6}^{16/15} R_5^{22/5} \ \ {\rm erg/s}. \tag{13}$$

A quark star with low mass may explain the low time-averaged accretion luminosity in bursting millisecond X-ray pulsars since $L_{\rm x} \propto R^{4.4}$, if it is assumed that bursting X-ray pulsars are in a critical stage of $P \sim P_{\rm br}$. It is worth noting that, in this stage, the real accretion-luminosity could be much lower than $L_{\rm x}$ presented in Eq. (13) because only part of the accretion matter with rate $\dot{M}$ could bombard directly the stellar surfaces. Alternatively, it is recently suggested (Popov, 2004) that low-mass compact objects can form by fragmentation of rapidly rotating protoneutron stars, and that such objects should have large kick velocities. But, fragmentation might hardly be possible for quark stars due to the color-confinement.

It is generally suggested that, during a iron-core collapse supernova, the gravitation-released energy $\mathcal{E}_{\rm g} \sim 10^{53}$ erg is almost in the form of neutrinos, $\sim 10^{-2}$ of which is transformed into the kinetic energy of the outgoing shock and $\sim 10^{-4}$ of which contributes to the photon radiation. However, this ideal is not so successful in modern supernova simulations, since the neutrino luminosity could not be large enough for a successful explosion even in the models with the inclusion of convection below the neutrinosphere (2D-calculations). We note that the bare quark surfaces may be *essential* for successful explosions of both types of iron-core collapse and AIC. The reason is that, because of the color binding, the photon luminosity of a quark surface is not limited by the Eddington limit. It is possible that the prompt reverse shock could be revived by photons, rather than neutrinos. A hot quark surface, with temperature $T > 10^{11}$ K, of a newborn bare quark star will radiate photons at a rate of

$$\dot{E}_{\rm p} > 4\pi R^2 \sigma T^4 \sim 7 \times 10^{50} R_5^2 T_{11}^4 \ \text{erg/s}, \tag{14}$$

while the Thomson-scattering-induced Eddington luminosity is only

$$L_{\rm Edd} = \frac{64\pi^2 c G m_{\rm p}}{3\sigma_{\rm T}} \bar{B} R^3 \sim 10^{35} \bar{B}_{60} R_5^3 \ \text{erg/s}. \tag{15}$$

This means that the photon emissivity may play an important role in both types of supernova explosions (i.e., for the birth of solar-mass as well as low-mass quark stars).

2. *How fast could a low-mass quark star spin?* The fastest rotating millisecond pulsar is PSR 1937+21 ($P = 1.558 \times 10^{-3}$ s, $\dot{P} = 1.051 \times 10^{-19}$ s/s). In order to explain its polarization behavior of radio pulses and the integrated profile (pulse widths of main-pulse and inter-pulse, and the separation between them), this pulsar is supposed to have mass $<0.2 M_\odot$ and radius <1 km (Xu et al., 2001). Additionally, a low-mass quark star may actually favor a high spin frequency Ω during its birth. The Kepler frequency of such stars could be approximately a constant,

$$\Omega_{\rm k} = \sqrt{\frac{GM}{R^3}} = 1.1 \times 10^4 \bar{B}_{60}^{1/2} \ \text{s}^{-1}. \tag{16}$$

The initial rotation periods of strange stars are limited by the gravitational radiation due to r-mode instability (Madsen, 1998). The critical Ω satisfies the equation

$$\frac{1}{\tau_{\rm gw}} + \frac{1}{\tau_{\rm sv}} + \frac{1}{\tau_{\rm bv}} = 0, \tag{17}$$

where the growth timescale for the instability (the negative sign indicates that the model is unstable) is estimated to be,

$$\tau_{\rm gw} = -3.85 \times 10^{81} \Omega^{-6} M^{-1} R^{-4}, \tag{18}$$

and $\tau_{\rm sv}$ and $\tau_{\rm bv}$ are the dissipation timescales due to shear and bulk viscosities, respectively,

$$\begin{cases} \tau_{\rm sv} = 1.85 \times 10^{-9} \alpha_{\rm s}^{5/3} M^{-5/9} R^{11/3} T^{5/3}, \\ \tau_{\rm bv} = 5.75 \times 10^{-2} m_{100}^{-4} \Omega^2 R^2 T^{-2}, \end{cases} \tag{19}$$

and α_s the coupling constant of strong interaction, T the temperature, m_{100} the strange quark mass in 100 MeV.

It is found (Xu, 2005) that low-mass bare strange stars can rotate very fast, even faster than the Kepler frequency (Note: The surface matter is not broken at super-Kepler frequency, due to the self-bounding of quark matter). However, though it needs advanced technique of data collection and analysis to detect sub-millisecond radio pulsar, we have not found one yet. This negative result could be due to: (1) The dynamical processes do not result in a sub-millisecond rotator; (2) No magnetospheric activity exists for very low-mass strange stars whose $\dot{P}$'s are small, since the potential drop is not high enough for pair-production (see Eq. (7) of Section 3.1). In the later case, a nearby sub-millisecond radio pulsar could be found by X-ray observations since a hotspot, powered by rotation and/or accretion, may form on the stellar surface.

3. *What happens when two quark-matter objects collide?* Quark matter with mass $\ll M_\odot$ could be ejected by a massive quark star ($\sim M_\odot$) during its birth, and such low-mass matter may explain a few astrophysical phenomena (Xu and Wu, 2003): the planets around pulsars could be quark matter with mass $\sim 10^{23-28}$ g, while very low mass strange quark matter (called as strangelets) with baryon numbers of $\sim 10^9$ may be the nature of ultra-high energy cosmic rays beyond the GZK cutoff. The bursts of soft γ-ray repeaters could be due to either the starquake-induced magnetic reconnection or the collision between a strange planet and solar-mass bare strange star. The collision chance would be not low if both objects form during a same supernova. Some of the transient unidentified EGRET sources (Wallace et al., 2000) may represent such collision events, the gravitational energy release of which is

$$E_g \sim \frac{G M_a M_b}{\left(R_a^3 + R_b^3\right)^{1/3}} = 2 \times 10^{23} \bar{B}_{60}^2 \frac{R_a^3 R_b^3}{\left(R_a^3 + R_b^3\right)^{1/3}}, \tag{20}$$

where "a" and "b" denotes two objects of strange quark matter. The released energy could be $\sim 10^{45}$ erg if $R_a \sim 10^5$ cm and $R_b \sim 10^4$ cm. This strong (color) interaction may result in photon emission by various hadron process (e.g., hadron annihilation), with energy $> \sim 100$ MeV (the EGRET telescope covers an energy range from 30 MeV to over 20 GeV), and could be another way to produce strangelets.

Merging quark stars, rather than neutron stars (Eichler et al., 1989), may result in cosmic γ-ray bursts observed (GRBs), which could help to eliminate the baryon load problem. The released energy is $\sim 10^{53}$ ergs during the collision of two quark stars with $\sim 10^6$ cm. The residual body should be expected to rapidly rotate, and such a high spin frequency may result in a beaming pattern of emission. A fire ball with low-baryon contamination in this color interaction even may favor the emission of photons and neutrinos with high energy.

4. Conclusions and Discussions

General properties of both rotation- and accretion-powered low-mass quark stars, as well as other issues relevant, are presented. It is suggested that normal pulsars with $\sim M_\odot$ masses are produced after core-collapse supernova explosions, whereas millisecond pulsars with $\sim(0.1\text{–}1)M_\odot$ (and even lower) masses could be the remains of accretion-induced collapses (AIC) of massive white dwarfs. These different channels to form pulsars may result in two types of ferromagnetic fields: weaker for AIC ($\mu_{\rm m} \sim 10^{-6}$ G·cm^3·g^{-1}) while stronger for core-collapse ($\mu_{\rm m} \sim 10^{-4}$ G $\cdot$ cm$^3 \cdot$ g^{-1}). A newborn low-mass strange star could rotate very fast, even with a super-Kepler frequency. It is proposed that some of the transient unidentified EGRET sources may result from the collisions of two low-mass quark stars.

In fact, some potential candidates for low-mass quark stars were addressed (Xu, 2005). One is the radio-quiet central compact object, 1E 1207.4–5209, which could be a low-mass bare strange star with polar surface magnetic field $\sim 6 \times 10^{10}$ G and likely a few kilometers in radius, and be now at a critical point of subsonic propeller phase, $P \sim P_{\rm br}$, in order to understand its timing behavior. Another one is the dim thermal object, RX J1856.5–3754, the radius of which is $R > 0.1$ km if its soft UV-optical component radiates from a spherically quasi-static atmosphere around.

Can we confirm the small radius of a low-mass quark star by a direct observation of future advanced space telescope? This work might be done by the next generation Constellation X-ray telescope (to be launched in 2009–2010), which covers an energy band of (0.25–100) keV. The radii, R, of neutron stars are generally greater than 10 km (R of $0.1M_\odot$ mass neutron stars is $\sim$160 km). If pulsars are neutron stars, their surfaces should be imaged by the Constellation-X with much high space resolution, as long as the separation between the four satellites is greater than $\sim \lambda d/R \sim 3\lambda_{-8} d_{100\rm pc}/R_6$ km (Note: the wavelength of X-ray photon with 10 keV is $\lambda \sim 10^{-8}$ cm, the distance to a neutron star is $d = d_{100\rm pc} \times 100$pc). However, if these objects are quark stars with low masses, Constellation-X may not be able to resolve their surfaces.

Can a core-collapse supernova also produce a low-mass quark star? This possibility could not be ruled out in principle. Likely astrophysical hints could be that the thermal X-ray emission and rotation power of such a star should be lower than expected previously. Additionally, the cooling history of a low-mass quark star should be significantly different from that of solar-mass ones.

It is sincerely proposed to search low-mass quark stars, especially with masses of $\sim(10^{-1}\text{–}10^{-3})M_\odot$, by re-processing the timing data of radio pulsars. Some of the companion masses of pulsar/white-dwarf binaries are *estimated* to be a few $0.1M_\odot$. Are all these companions real white dwarfs (or part of them to be just low-mass quark stars)? Only part of the companions (a few 10%s) of pulsar/white-dwarf systems have been optically detected. A further study on this issue is then surely necessary. Additionally, it is very necessary and essential to probe quark stars through various observations of millisecond-pulsar's environments (planets, accretion disks), in order to distinguish these two scenarios on millisecond-pulsar's nature: to be (A) recycled or (B) supernova-originated. In case (A), planets and residual accretion disks could be around such pulsars, but possible mid- or far-infrared emission is still not been detected, although the formation of pulsar planets is still a matter of debate. In case (B), however, observations relevant could be well understood, since a pulsar (with possibly low mass) and its planet(s) may be born together during a supernova (Xu and Wu, 2003), and no infrared emission can be detected if no significant supernova-fall-back disk exists. If the first scenario is right, infrared radiations from both the disks and the planets could be detectable by the Spitzer Space Telescope and by the present SCUBA-1 or future -2 detectors of JCMT 15-m ground telescope. But if the later is true, the sub-mm emission from pulsar circumambience should be much weak, even not detectable. Surely, these are exciting and interesting subjects to be proposed when these advanced telescopes operate.

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Note

1. Quark stars with masses lower than the maximum mass is bound dominantly by color confinement, whereas other Fermi stars (e.g., neutron stars and white dwarfs) are gravitation-tied bodies.

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