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To cite this article: Renxin Xu 2009 *J. Phys. G: Nucl. Part. Phys.* **36** 064010

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Strange quark stars: observations and speculations

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Received 23 December 2008

Published 13 May 2009

Online at stacks.iop.org/JPhysG/36/064010

Abstract

Two kinds of difficulties have challenged the physics community for many years: (1) knowing nature's building blocks (particle physics) and (2) understanding interacting many-body systems (many-body physics). Both of them exist in the research of quark matter and compact stars. This paper addresses the possibility that quark clustering, rather than a color superconducting state, could occur in cold quark matter at realistic baryon densities of compact stars, since a weakly coupling treatment of the interaction between quarks might not be reliable. Cold quark matter is conjectured to be in a solid state if thermal kinematic energy is much lower than the interaction energy of quark clusters. Different manifestations of pulsar-like compact stars are discussed, as well as modeled in a regime of solid quark stars.

(Some figures in this article are in colour only in the electronic version)

1. Introduction: what is the nature of pulsar-like stars?

There are strange and interesting stories about success and failure in the road to understand nature. As an example, we will briefly review some significant moments in the research of neutron stars and pulsars. In 1932, soon after Chandrasekhar found a unique mass (the mass limit of white dwarfs), Landau speculated a state of matter, the density of which 'becomes so great that atomic nuclei come in close contact, forming one *gigantic nucleus*'. A star composed mostly of such matter is called a 'neutron' star, and Baade and Zwicky even suggested in 1934 that neutron stars (NSs) could be born after supernovae. NSs theoretically predicted were finally *discovered* when Hewish and his collaborators detected radio pulsars in 1967. More kinds of pulsar-like stars, such as x-ray pulsars and x-ray bursts in binary systems, were also discovered later, and all of them are suggested to be NSs.

However, the simple and beautiful idea proposed by Landau and others had one flaw at least: nucleons (neutrons and protons) are in fact *not* structureless point-like particles although they were thought to be elementary particles in 1930s; they (and other hadrons) were

proposed to be composed of *quarks* already in the 60s! Naively that question becomes: can the quark degrees of freedom appear when nucleons approach each other in a compact star with supra-nuclear density? The answer turned to be a little bit more affirmative after physicists recognized that the elementary strong interaction between quarks is actually asymptotically free, i.e., the interaction becomes weak (and quarks are thus deconfined) when density and/or temperature are extremely high. Therefore, quark matter could possibly exist in compact stars, either in the cores of neutron stars (mixed or hybrid stars [1]) or in the whole stars (quark stars [2–4]). Now, after more than 40 years since the discovery of the first pulsar CP 1919, the real nature of pulsars is still uncertain because of difficulties in both theories and observations (e.g. [5]).

2. Cold quark matter: color superconducting versus quark clustering?

Quark matter (or quark–gluon plasma) not only is a state predicted theoretically in quantum chromodynamics (QCD), the underlying theory of the elementary strong interaction, but also would be the key to sub-quarkian physics. Hot quark matter could be reproduced in the experiments of relativistic heavy-ion collisions, and hadronization occurs soon as the fireball cools. The final states of hadrons recorded in detectors are used to infer the hot quark matter. On the other hand, extremely high chemical potential is required to create cold quark matter, and it can only exist in rare astrophysical conditions, the compact stars. Cold quark matter is relatively long-lived, and, in principle, we could reliably know its real state by astronomical observations since there is possible evidence that pulsar-like stars are actually quark stars.

What kind of cold matter can we expect from QCD theory, in effective models or even based on phenomenology? This is a question too hard to answer because of (i) the non-perturbative effect of strong interaction between quarks at low-energy scales and (ii) the many-body problem due to vast assemblies of interacting particles. A color-superconductivity (CSC) state is currently focused on in QCD-based models, as well as in phenomenological ones (e.g. [6]). However, an alternative suggestion that cold quark matter could be in a solid state [7–9] cannot be ruled out yet in both astrophysics and particle physics. Recently, based on an approximation scheme of a large number of colors, N_c , a quarkyonic state of matter [10] was also proposed to exist at ultra-high density, where a baryonic ‘skin’ with depth of a few 100 MeV may form near the Fermi surface due to strong color interaction.

Let us discuss this in more details, beginning with a brief introduction to the essence of QCD related to strong interaction. In quantum field theory, the strength of the interaction is measured by a coupling parameter g whose dependence on the energy scale, μ , is determined by the relation of $\beta(g) \equiv \partial g / \partial \ln \mu = \mu \partial g / \partial \mu$. The beta-function, $\beta(g)$, represents the running of coupling. In an Abelian gauge theory as QED, the beta-function is positive. However, in a non-Abelian gauge theory β is negative, and hence, the QCD coupling decreases at high energies, which goes approximately as [11]

$$\alpha_s(\mu) \equiv \frac{g_s^2}{4\pi} \approx \frac{1}{\beta_0 \ln(\mu^2/\Lambda^2)}, \quad (1)$$

where $\beta_0 = (11 - 2n_f/3)/(4\pi)$, n_f is the number of quark flavors, and the renormalization parameter $\Lambda = (200 \sim 300)$ MeV. Certainly, the coupling is strong at low energies, and the perturbative formulation is not applicable.

For cold dense quark matter, the order of the scale μ is determined by the baryonic chemical potential, $\mu \simeq (3\pi^2)^{1/3} \hbar c n_B^{1/3}$ for $T \ll \mu$, where T denotes the temperature, and n_B is the baryon number density. It is evident from equation (1) that perturbative QCD is reliable in the limit of high density ($n_B \rightarrow \infty$) because of asymptotic freedom. The ground state

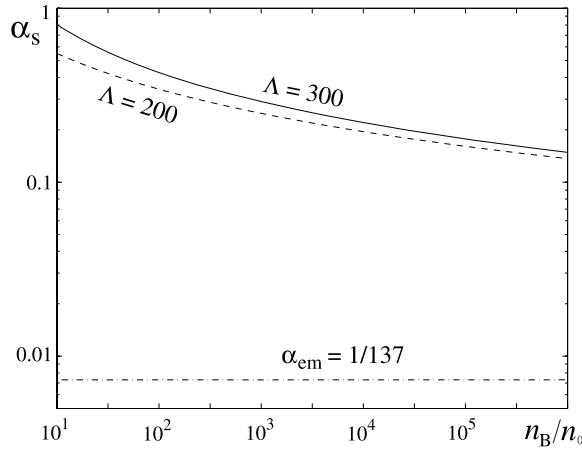


Figure 1. The running coupling, α_s , in cold quark matter as a function of baryon density, n_B , for the cut-off parameter $\Lambda = 200$ (solid line) and 300 (dashed line), respectively. For comparison, the usual electromagnetic coupling constant $\alpha_{em} \simeq 1/137$ (dash-dotted line) is also drawn. A weakly coupling treatment could be dangerous for cold quark matter at a realistic baryon density (\sim a few nuclear density, n_0).

of extremely dense quark matter could certainly be that of an ideal Fermi gas. Nevertheless, it has been found that the highly degenerate Fermi surface is unstable against the formation of quark Cooper pairs, which condense near the Fermi surface due to the existence of color-attractive channels between the quarks. A BCS-like color superconductivity, similar to electric superconductivity, has been formulated within perturbative QCD at ultra-high baryon densities. It has been argued, based on QCD-like effective models, that color superconductivity could also occur even at the more realistic baryon densities of pulsar-like compact stars [6].

Can the realistic stellar densities be high enough to justify the use of perturbative QCD? Let us see the numerical coupling strength from equation (1), shown in figure 1, with $n_f = 3$ for strange quark matter. It is observed that $\alpha_s = (0.5 \sim 0.8)$ when $n_B = 10n_0$ ($n_0 = 0.16 \text{ fm}^{-3}$), and $\alpha_s \simeq 0.15$ even if $n_B = 10^6 n_0$. It is worth noting that the dimensionless electromagnetic coupling constant (i.e., the fine-structure constant) is $1/137 < 0.01$, which makes QED tractable. That is to say, a weakly coupling strength comparable with that of QED is possible in QCD only if the density is unbelievably and unrealistically high ($n_B > 10^{123} n_0!$). At realistic densities of a few nuclear densities, $n_B \geq n_0$, the color coupling should be very strong rather weak, $\alpha_s = (0.8 \sim 1.5)$ for $n_B = 3n_0$, according to equation (1). This surely means that a weakly coupling treatment could be dangerous for cold quark matter, i.e., the non-perturbative effect in QCD should not be negligible if we try to know the real state of compact stars.

However, non-perturbative QCD is one of the daunting challenges nowadays in understanding the fundamental strong interaction between quarks. Is there any other way for us to understand the physics of cold dense matter at supra-nuclear density? Compact stellar objects are the natural astrophysical laboratories to probe the mystery of cold quark matter! As addressed in section 1, pulsar-like compact stars could be quark stars, and there is possible evidence for quark stars [5, 12, 13]. In a word, both physicists and astrophysicists are troubled with cold dense matter, and they have to cooperate in order to completely solve the problem, as illustrated in figure 2. It is crucial to develop a close communication between them.

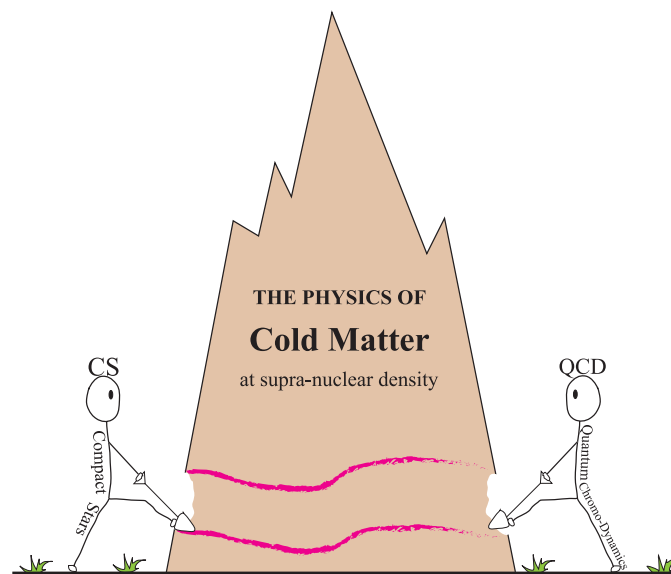


Figure 2. Astronomers interested in pulsar-like compact stars and physicists expert at doing with QCD now face the same challenge to know the real state of cold matter at supra-nuclear density. They have to exchange information during their work when trying to ‘dig a tunnel’ to solve the problem.

What valuable information can astrophysics provide for us to know the state of cold (quark) matter at supra-nuclear density? Drifting sub-pulses of radio pulsars, non-atomic spectra of isolated ‘neutron’ stars, and even successful supernova and γ -ray bursts may hint to determine if pulsar-like compact stars could be (bare) quark stars. Similarly, pulsar glitches, both normal and slow, precessions, huge energy release of soft γ -ray repeaters, and even the quantitative spectra of isolated ‘neutron’ stars may suggest that such compact stars could globally be in a solid state, i.e., they might be solid quark stars. The details of these phenomena are presented and explained in the following section. The effects of the strong magnetic fields typically present in neutron stars are ignored throughout this paper. However, it is known that in the case of color superconductivity these fields can influence the ground state of the system [14, 15], produce new phases [16] or even trigger and/or cure chromomagnetic instabilities [17, 18]. Hence, it remains an open question whether the magnetic fields of the stars can also have relevant effects on a solid state of quark matter (e.g., the ferromagnetization [19]).

Can cold quark matter be in a solid state? This is possible because of quark clustering [7] (normal solid) and the CSC gap-parameter modulating [20] (super solid). Quark clusters may form in relatively low-temperature quark matter due to the strong interaction¹, and the clusters could be in periodic lattices (normal solid) when temperature becomes low enough. Although it is hitherto impossible to know if quark clusters could form in cold quark matter via calculation from first principles, there could be a few points that favor clustering. *Experimentally*, though quark matter is argued to be weakly coupled at high energies and thus deconfined, it is

¹ As an example to show the effect of strong coupling between particles on the state of a particle system, we discuss a ‘ $p + e$ ’ system. If the interaction is turned off, the system is certainly a Fermi gas with two degrees of freedom (p and e), when the temperature T is so low that the de Broglie wavelength ($\propto T^{-1/2}$) is \geq the distance between particles. However, a realistic ‘ $p + e$ ’ system at low temperature and density is hydrogen (or even H_2) gas, i.e. particle clusters form due to electric coupling there.

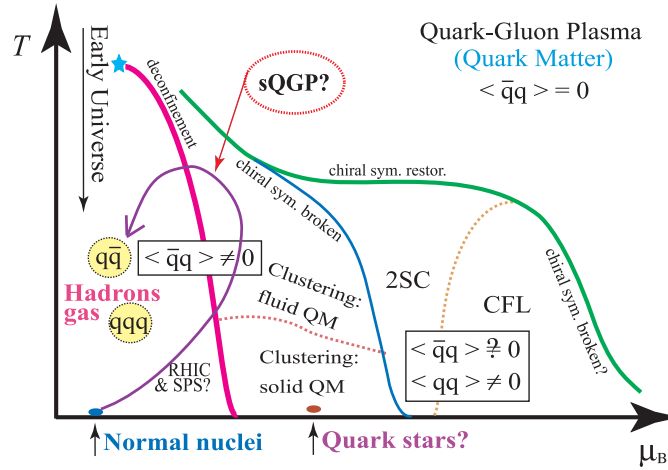


Figure 3. Schematic illustration of the QCD phase diagram speculated from different manifestations of astrophysical compact stars. A quark cluster state is conjectured when chiral symmetry is broken though quarks are still unconfined. The cold quark matter with quark clusters should be in a solid state at low temperature.

worth noting that, as revealed by the recent achievements in relativistic heavy-ion collision experiments, the interaction between quarks in a fireball of quarks and gluons is still very strong (i.e. the strongly coupled quark–gluon plasma, sQGP [21]). The strong coupling between quarks may naturally render quarks grouped in clusters, i.e., a condensation in position space rather than in momentum space. *Theoretically*, the baryon-like particles in quarkyonic matter [10] might be grouped further due to residual color interaction if the baryon density is not extremely high, i.e. $\mu > \sim \Lambda$, and quark clusters would form then.

In fact, strongly coupled particles are very complex systems, even in the case of electromagnetic interaction [22–24]. It is recognized that in the BCS superfluid, fermions are condensed in momentum space to form loosely bound Cooper pairs. On the other hand, in the Bose–Einstein condensation (BEC), fermions are condensed in position space to form tightly bound fermion pairs. These are two limiting cases of same theory. As for cold quark matter, although BCS-like CSC can occur at a ultra-high density according to perturbative QCD, the interaction becomes stronger and stronger as the density decreases, and the quark pairs may get localized to create diquark boson (i.e., the system crosses from BCS to BEC states). Can diquarks condense further in position space to form quark clusters? This could be possible in cold quark matter at lower density, an experimental analogy of which could be of the ^{87}Rb boson system [25].

Interaction can certainly play an essential role to cluster particles. For instance, the elements of water are H_2O molecules, a cluster of ten electrons, two protons and one oxygen nucleus. However, if the electromagnetic interaction is turned off, the degenerate electron chemical potential of ordinary water at a temperature of $\geq 0^\circ\text{C}$ is 18 eV, being in the same order of the Rydberg constant 13.6 eV, the interaction energy between an electron and a proton in the ground state. For cold quark matter at $3n_0$ density, the distance between quarks is $\sim 0.9\text{ fm} \gg$ the Planck scale $\sim 10^{-20}\text{ fm}$, and quarks and electrons can well be approximated as point-like particles. If Q_α -like clusters are created in the quark matter [7], the distance between clusters are $\sim 2\text{ fm}$. We may also estimate the length scale, ℓ , of quark clusters by the uncertainty relation, assuming quarks are as dressed as speculated in figure 3 (the constituent quark mass is $m_q \sim 300\text{ MeV}$) and move non-relativistically in a cluster. The quarks typically

have a kinematic energy of $\sim \hbar^2/(m_q \ell^2)$, and are bound by color interaction, with an energy of $\sim \alpha_s \hbar c/\ell$. We have then $\ell \sim \hbar c/(\alpha_s m_q c^2) \simeq 1$ fm if $\alpha_s \sim 1$, and the color interaction energy $\sim \alpha_s^2 m_q c^2$ could be greater than the baryon chemical potential if $\alpha_s > \sim 1$. Quark clusters could be considered as classical particles in cold quark matter and would be in lattices at a lower temperature. Therefore, we would like to learn QCD dynamics at a scale of ~ 1 fm from the dense matter in pulsar-like compact stars.

Alternatively, a crystalline color superconducting phase (super solid) with rigidity is proposed by calculation in an effective model [20], in which the quarks are certainly not condensed in position space but in momentum space. It is surely interesting to experimentally or observationally distinguish between and to search evidence for possible normal and super solid states although the latter might be more robust than the former only from a theoretical point of view. Starquakes could naturally occur in both normal and super solid quark stars, and the observations of pulsar glitches [26] and SGR giant flares [27] could qualitatively be understood (when the solid matter breaks) in both those two models. Nonetheless, there might still be some quantitative differences between the predictions (e.g. the post-glitch recovery and the global stellar structure) in those two models, which are very necessary for further researches. Additionally, because the normal solid depends on quark clustering while the super solid on gap modulating, the interaction behaviors between quarks should be different, that could be tested in sQGP by the LHC and/or FAIR experiments. For instance, one may test the phenomenological interaction models for sQGP at the laboratory through calculating the quark clusters by the quark molecular dynamics (qMD) [28].

An astrophysically conjectured QCD phase diagram, with the inclusion of strong coupling between quarks, is shown in figure 3. In different locations of the diagram, the vacuum has different features which can be classified into two types: the perturbative-QCD (pQCD) vacuum and the 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). As is addressed, the idea of quark clustering (quark–molecular) could be tested in sQGP.

3. To understand observations in solid quark star models

Various astrophysical observational phenomena could be understood in terms of (solid) quark star models, including those that are challenging in conventional neutron star models. Two kinds of solid quark matter are possible, and it could be interesting to observationally distinguish between and search evidence for normal-solid and super-solid states in the future.

Radio pulsars. It is generally suggested that radio pulsars of strange quark matter should have crusts (with mass $\sim 10^{-5} M_\odot$), being similar to the outer crusts of neutron stars [4]. This view was criticized by Xu and Qiao [29], who proposed that *bare* strange stars (i.e., strange stars without crusts), being chosen as the interior of radio pulsars, have three advantages: (1) the spectral features, (2) the binding energy and (3) the core collapse process during supernova. This opens thus a new window to distinguish quark stars from neutron stars via their magnetosphere and surface radiation according to the striking differences between the exotic quark surfaces and the normal matter surfaces. Clear drifting sub-pulses suggest that vacuum inner gap acceleration works on polar caps and both positively and negatively charged particles should be strongly bound, and a bare quark star model is attractive for explaining the pulse sequences [30], and even the x-ray polar caps [31], of PSR 0943+10.

The timing behavior may also favor a solid quark star model. The observed precessions in PSR B1828-11 and PSR B1642-03 challenge astrophysicists today to re-consider the internal structure of radio pulsars [32], since the conventional model involves vertex pinning and even MHD coupling between the crust and the core. More precession sources besides radio pulsars are also proposed. While normal glitches are suggested to be the results of the vertex pinning effect, the recently discovered slow glitches can hardly be explained. A solid pulsar with rigidity could solve these problems, and both normal and slow glitches can then be modeled [26, 33]. It is shown that torque variability increases with Reynolds numbers (and thus spin frequency) [34], suggesting that at least the timing noise in fast radio pulsars would be high. This is in conflict with the fact that the noise in millisecond pulsars is much lower than that of normal pulsars.

Dead pulsars. With regard to the possible ways of identifying quark stars (e.g. by the mass–radius relations or the maximum spin frequencies), hard evidence for quark star may be obtained by studying the surface conditions since the other avenues are subject to poorly known microscopic physics. Although the bare quark surface could help us to understand the radio emission [30], it should be direct and intuitive if one can detect real thermal radiation from a quark surface. Because the thermal component can hardly be separated from the strong magnetospheric emission of active pulsars, dead pulsars with negligible magnetospheric components should be the ideal targets (a pulsar becomes dead when the potential drop in the open field line region is lower than a critical value $\sim 10^{12}$ V as the pulsar spins down), i.e. dead pulsars are good ones.

Thanks to the advanced x-ray missions, more and more dead pulsar-like compact objects are discovered, being classified as central compact objects (CCOs, in supernova remnants) and dim thermal ‘neutron’ stars (DTNs, not associated with supernova remnants). One would expect that both thermal x-ray emission radiating from neutron star atmospheres, and atomic spectral lines that formed there should have been discovered by *Chandra* or *XMM-Newton*. However, no clear atomic feature has been found. Such a thermal featureless spectrum could be a probe for identifying bare quark stars [29, 35]. The absorption features of 1E 1207 were suggested to be cyclotron lines soon after the discovery [37], and 1E 1207 could still be a bare quark star, even with a low mass [19], in a propeller phase. Recent timing observation [38] of the magnetic field favors the electron–cyclotron idea for 1E 1207. Due to a very high plasma frequency of ~ 20 MeV, fluid quark stars with the exposed quark surface could be silver-like spheres in the x-ray band [4]. Nevertheless, what if quark matter is solid [7]? In fact, the well-observed Planck-like thermal spectrum of RX J1856 could be better fitted phenomenologically by a metal-like model in the solid quark star regime [36].

Anomalous x-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). Spin power was generally thought to be the only free energy for pulsar-like compact stars until the discovery of accretion-powered pulsars in x-ray binaries. However, the x-ray luminosities of AXPs/SGRs are much higher than their spindown powers, and no binary companion of them has been discovered. AXPs/SGRs are then suggested to be in an accretion propeller phase; however, the very difficulty for this viewpoint is to reproduce the irregular bursts, even super-flares with peak luminosity $\sim 10^7$ times of the Eddington luminosity. The elastic energy as well as gravitational energy of solid quark stars could be new kinds of free energy to power AXPs/SGRs [8, 27, 39]. A solid stellar object would inevitably result in starquakes when strain energy develops to a critical value, and huge gravitational and elastic energies would then be released, especially during accretion. This is called accretion-induced starquake (AIQ) mechanism.

Supernova and gamma-ray bursts (GRBs). The essential difficulty of reproducing two kinds of astronomical bursts is challenging today's astrophysicists to find realistic explosive mechanisms. Besides the puzzling center engines of GRBs, it is still a long-standing problem to simulate supernovae successfully in the neutrino-driven explosion model. Nevertheless, it is evident that both kinds of explosions could be related to the physics of cold matter at supra-nuclear density. One of the direct and important consequences could be the low baryon-loading energetic fireballs formed on quark star surfaces, which might finally result in both supernova and GRBs. A one-dimensional supernova calculation shows that the lepton-dominated fireball supported by a bare quark surface does play a significant role in the explosion dynamics under a photon-driven scenario [40]. Two kinds of central engines for GRBs could be available if pulsars are actually solid quark stars (i.e., the SNE-type and SGR-type GRBs), and stochastic quakes after initial GRBs may be responsible for the x-ray flares of both types [41].

Others. The ultra-high-energy cosmic rays detected via air-showers could be actually strangelets [42] since strangelets can behave as cosmic rays beyond the GZK-cut-off and could be effectively accelerated in pulsar magnetospheres. Part of the radio pulsar timing noise could reflect ultra-compact object binaries [43], two bare quark stars (or planets) in close binary systems. We cannot yet rule out that some precession pulsars are torqued by quark planets [44]. It is also interesting to search for low-mass quark stars (or planets), especially with masses of $\sim(10^{-1} - 10^{-3})M_{\odot}$, in white dwarf binaries [19].

4. Conclusions

In this paper it is argued that clustering, rather than color superconducting, occurs in cold quark matter at realistic baryon densities. Cold quark matter is then conjectured to be in a solid state. Possible evidence for quark stars are summarized.

Acknowledgments

We thank Professors Vivian de la Incera and Efrain Ferrer for their substantial help to improve the language and an anonymous referee for valuable suggestions, and acknowledge the contributions by our colleagues at the pulsar group of PKU. This work is supported by NSFC (10573002, 10778611), the National Basic Research Program of China (grant 2009CB824800) and by LCWR (LHXZ200602).

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