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## Differentiating Neutron Star Models by X-Ray Polarimetry \*

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The nature of pulsars is still unknown because of the non-perturbative effects of the fundamental strong interaction, so various models of pulsar inner structures are suggested, either for conventional neutron stars or quark stars. Additionally, a quark-cluster matter state is conjectured for cold matter at supranuclear density, and as a result pulsars can be quark-cluster stars. Besides understanding the different manifestations, the most important issue is to find an effective way to observationally differentiate these models. X-ray polarimetry plays an important role here. The thermal x-ray polarization of quark/quark-cluster stars is focused on, and while the thermal x-ray linear polarization percentage is typically higher than  $\sim 10\%$  in normal neutron star models, the percentage of quark/quark-cluster stars is almost zero. This could then be an effective method to identify quark/quark-cluster stars by soft x-ray polarimetry. We are therefore expecting to detect thermal x-ray polarization in the coming decades.

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The study of pulsars is not only important in understanding the diverse phenomena of high-energy astrophysics, but also significant in fundamental physics. The nature of the compressed baryonic matter in pulsars is still uncertain because of the non-perturbative effects of the fundamental color interaction.<sup>[1]</sup> In view of the high density, there are two types of models: gravitation-bound and self-bound ones. The normal neutron star model is a typical representative of the former, while the quark/quark-cluster model belongs to the latter. Although both models might explain the thermal x-ray spectra of pulsars, the polarization behaviors would be quite different.

A normal neutron star (more generally, a hadron star or mixed star) as a gravitationally confined object must have an atmospheric envelope composed of normal matter with a pressure gradient to link the high pressure interior and zero pressure outside. However, this envelope would not be necessary for a self-bound body, such as a bare quark star or quark-cluster star. Phenomenologically, some observations may hint that a bare and self-confined surface might exist in order to naturally understand different observational manifestations (e.g., sub-pulse drifting, a non-atomic spectrum, and clean fireballs for supernova/ $\gamma$ -ray bursts).<sup>[2]</sup> It is expected that because of the low temperature gradient of a surface with degenerate electrons, the linear polarization of thermal x-ray emissions from quark-cluster stars will be very low,<sup>[3]</sup> however, a quantitative calculation has never been presented. In this Letter, we calculate the polarization behavior of quark-cluster stars and compare

our results to the pre-existing conclusion of neutron stars<sup>[4]</sup> in order to test pulsar structure models by future advanced x-ray polarimetries.

There are two mechanisms for generating the thermal x-ray polarization of pulsars. The separatrix is the critical magnetic field,  $B_q \simeq 4 \times 10^{13}$  G. For a weak magnetic field, i.e.  $B < B_q$ , the quantum vacuum effect can be negligible. It is worth noting that the accretion-induced neutron star magnetic field away from the polar could still be very strong, even though accretion makes the polar field decay.<sup>[5]</sup> X-ray polarimetry may hence provide a direct measurement of the surface field.

When x-rays propagate across the magnetic  $B$ -field, there are two independent linear polarization eigenmodes: the ordinary mode (O-mode, the electric field in the plane of the wave vector and the  $B$ -field) and the extraordinary mode (E-mode, perpendicular to the plane). However, the opacity coefficients of a magnetized thermal plasma are different for them.

Gnedin and Sunyaev (1974) presented an approximation about the cross section of photon-electron scattering for photon frequency  $\omega \ll \omega_c \equiv eB/m_e c = 11.6 \times B_{12}$  keV ( $m_e$  is the mass of the electron and  $B_{12} = B/10^{12}$  G) and the angle between the wave vector and the  $B$ -field  $\theta > (\omega/\omega_c)^{1/2}$ ,<sup>[6]</sup>

$$\sigma_o = \sigma_T \sin^2 \theta, \quad (1)$$

$$\sigma_E = \sigma_T (\omega/\omega_c)^2 (1/\sin^2 \theta), \quad (2)$$

where  $\sigma_o$ ,  $\sigma_E$  are the cross sections of the O-mode and E-mode, respectively, and  $\sigma_T$  is the Thomson scatter-

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ing cross section. For normal pulsars of  $B \simeq 10^{12}$  G,  $\theta \gg (\omega/\omega_c)^{1/2}$ , one has  $\sigma_o \gg \sigma_e$ . This implies that the average free path length of the O-mode photon  $L_1$  is far less than that of the E-mode photon  $L_2$  (see Fig. 1, i.e., different photospheres for these two modes), and hence the optical depth depends on its polarization behavior. Due to the temperature gradient, the E-mode intensity will be much higher than the O-mode one, and the thermal x-rays are thus polarized. X-ray polarimetry will therefore provide a temperature gradient measurement of the pulsar surface. Pavlov and Zavlin (2000) concluded that the linear polarization of a normal neutron star could be as high as 10%–30%.<sup>[4]</sup>

In the case of magnetic field  $B > B_q$ , an additional quantum vacuum effect due to quantum electrodynamics (QED) will also cause polarization of thermal x-ray radiation.<sup>[7–9]</sup> Lai and Ho<sup>[9]</sup> demonstrated that a QED vacuum effect, called vacuum birefringence, emerges for  $B \geq 7 \times 10^{13}$  G, and found a very high average polarization at 10%–100% for magnetars.<sup>[8]</sup>

The above are previous thermal x-ray polarization results of normal neutron stars/magnetars. For comparison, we calculate the thermal x-ray polarization in the quark-cluster star model, as follows.

Thermal conductivities ( $\kappa$ ) of degenerate electrons inside quark or quark-cluster stars can be conveniently expressed through effective electron collision frequencies,  $\nu_{ee}$ ,<sup>[10]</sup>

$$\kappa = \frac{\pi^2 k_B^2 T_S n_e}{3m_e \nu_{ee}}, \quad (3)$$

where  $n_e$ ,  $T_S$  denote the number density of the electron and the temperature of the quark star surface, respectively, and  $k_B$  is the Boltzmann constant. The effective electron collision frequencies can be derived by<sup>[11]</sup>

$$\nu_{ee} \simeq \frac{3}{2\pi} \left(\frac{\alpha}{\pi}\right)^{1/2} \frac{(k_B T_S)^2}{\hbar \varepsilon_F} J(\varsigma), \quad (4)$$

$$J(\varsigma) = \frac{1}{3} \frac{\varsigma^3 \ln(1 + 2\varsigma^{-1})}{(1 + 0.074\varsigma)^3} + \frac{\pi^5}{6} \frac{\varsigma^4}{(13.9 + \varsigma)^4}, \quad (5)$$

$$\varsigma = 2\sqrt{\frac{\alpha}{\pi}} \frac{\varepsilon_F}{k_B T_S}, \quad (6)$$

where  $\alpha = e^2/\hbar c$  is the fine structure constant, and  $\varepsilon_F = \hbar c(\pi^2 n_e)^{1/3}$  is the Fermi energy of the degenerate electrons.

In order to explicate that the polarization of thermal radiation from a quark-cluster star is small enough to be ignored, we calculate the maximum linear polarization ( $P_{\max}$ ) just for  $\theta = 90^\circ$ ,

$$P_{\max} = \frac{|J_O - J_E|}{J_O + J_E} \sim \frac{|\sigma T_1^4 - \sigma T_2^4|}{\sigma T_1^4 + \sigma T_2^4} = \frac{|T_1^4 - T_2^4|}{T_1^4 + T_2^4}, \quad (7)$$

where  $J_O$  and  $J_E$  is the x-ray intensity of the O-mode and E-mode, respectively,  $T_1$  ( $T_2$ ) is the average tem-

perature where the O-mode (E-mode) photons could come out from, and  $\sigma$  is the Stefan–Boltzmann constant. If the thermal conductivities of strange quark-cluster matter are extremely high, then the temperature gradient would be very small. Therefore, approximation  $T_S - T_1 \ll T_S - T_2 \ll T_S$ , and Eq. (7) will be reasonable,

$$P_{\max} \simeq \frac{|T_S^4 - T_2^4|}{T_S^4 + T_2^4} \simeq \frac{T_S^3 \cdot \Delta T}{2T_S^4} = \frac{\Delta T}{T_S}, \quad (8)$$

where  $\Delta T \equiv T_2 - T_S$ .

For the approximation of black body radiation, the energy flux density  $J_r$  is

$$J_r = \sigma T^4. \quad (9)$$

However, for thermal conduction, the energy flux density  $J_c$  is expressed as

$$J_c = \kappa \cdot \nabla T \simeq \kappa \frac{\Delta T}{L_2}. \quad (10)$$

One has  $J_r = J_c$  since there is no energy source near the quark-cluster star surface. Combining Eqs. (9) and (10),

$$\Delta T = \frac{\sigma T_S^4 L_2}{\kappa}. \quad (11)$$

Considering the propagation of E-mode photons, we could have the free path length,

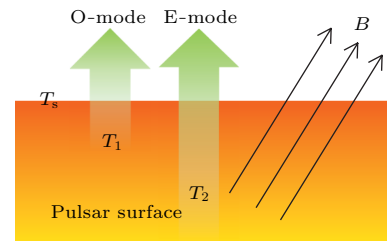
$$L_2 \simeq \frac{1}{n_e \sigma_E} \frac{\varepsilon_F}{k_B T_S}, \quad (12)$$

where a factor of  $\varepsilon_F/k_B T_S$  is introduced because only electrons near the Fermi surface could scatter off the x-rays.

According to Eqs. (2), (3), (8), (11) and (12), one comes to

$$P_{\max} \simeq \frac{6\sigma T_S m_e \nu_{ee} \omega_c^2 \varepsilon_F}{\pi^2 k_B^3 n_e^2 \sigma_{T, \text{corr}} \omega^2}, \quad (13)$$

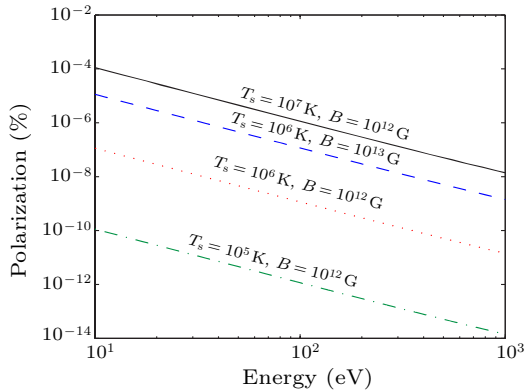
i.e.,  $P_{\max} \propto \omega^{-2}$ , where the relativity correction is included.<sup>[12]</sup>



**Fig. 1.** A schematic diagram of thermal x-ray polarization originating from the pulsar surface, where the QED vacuum polarization effects are not included. The E-mode photons come from a deeper and hotter place than that of the O-mode.

We calculate the maximum linear polarization (to maximize the polarization, we consider the head-on

collisions of photons and electrons) for typical parameters of  $n_b = 1.5n_0$  and  $n_e = 10^{-4}n_b$ , where  $n_b$  is the number density of baryon in a quark-cluster star, with  $n_0$  the number density of nuclear matter. The results are shown in Fig. 2, which shows that the polarization of thermal radiation from a quark-cluster star is too small to detect.



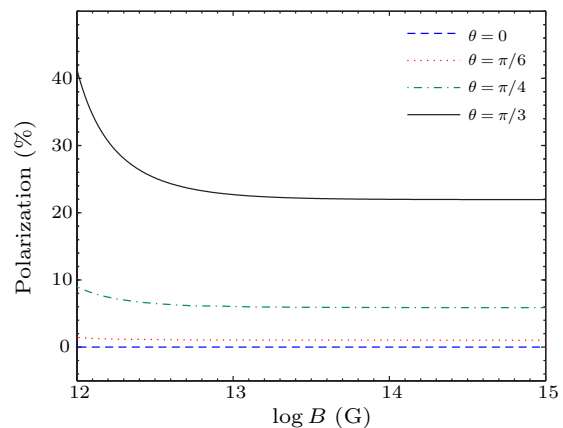
**Fig. 2.** The thermal x-ray polarization of a quark-cluster star as a function of photon energy, for parameterized temperatures ( $T$ ) and magnetic fields ( $B$ ).

There is an unexceptionable source to test the models: RX J1856.5-3754. Discovered in 1996,<sup>[13]</sup> it is the brightest of all the isolated neutron stars. The x-ray spectrum of RX J1856.5-3754 can be adequately fitted by a blackbody spectrum. The non-variable thermal spectrum shows that we indeed see the surface of this pulsar directly. The state of matter for a very stiff equation of state (EoS) constrained by its small radius is always controversial,<sup>[14,15]</sup> although the stiff EoS could be understood by a Lennard–Johns quark matter model.<sup>[16]</sup> It is demonstrated that the maximum mass of a H-cluster (a particular but realistic kind of quark cluster) star could approach or even exceed  $3M_\odot$ ,<sup>[17]</sup> and the pulsar mass statistics of recent results<sup>[18]</sup> could then be understood, although one should know both the mass and radius to infer the composition. Furthermore, the neutron star model needs a very strong magnetic field to explain the absence of spectral lines, while the quark/quark-cluster star model does not.<sup>[19]</sup>

In the regime of a normal neutron star, the featureless Planckian spectrum of RX J1856.5-3754 may hint at a superstrong  $B$ -field, in which unique signatures of the vacuum polarization emerge. The field would be so strong that the outermost layer might be in a condensed solid or liquid. We can also calculate the polarization of the neutron star in the model provided in Ref. [20], and the results are shown in Fig. 3, with the photon energy fixed at 0.25 keV. It is evident that significant linear polarization could also be detectable even if the  $B$ -field is really so strong that the surface is condensed. It is worth noting that the

observed x-ray flux peaks are located at a few hundred electron-volts, where x-ray polarization can be measured using a multilayer-based polarimeter.<sup>[21]</sup>

Soft  $\gamma$  repeaters (SGRs) and anomalous x-ray pulsars (AXPs) are all magnetar candidates. However, it is not necessary to assume such a strong field to explain the large period derivative and enormous energy release in the solid quark-cluster star model.<sup>[22]</sup> Nonetheless, energy release due to magnetic field reconnection will still be significant in order to understand the observations of SGR/AXPs (especially those of superflares) in conventional liquid quark star models (e.g., in a magnetic CFL phase<sup>[23]</sup>). Therefore, x-ray polarimetry can also be a powerful way to test the magnetar model.



**Fig. 3.** The x-ray polarization of thermal radiation directly from a degenerate metallic condensed surface with a strong magnetic field ( $B$ ). The vacuum polarization of QED is included, for a photon energy at 0.25 keV, while different emergence angles ( $\theta$ , the angle between the magnetic field and the wave vector) are illustrated.

In summary, we have shown that x-ray polarimetry will be a powerful tool to differentiate neutron star models. In the weak field regime, as charged particles can hardly move perpendicularly to the magnetic field, this leads to lower opacity for E-mode photons with polarization perpendicular to the magnetic field. Thus, E-mode photons can escape from deeper and hotter regions (Fig. 1) in the atmosphere of neutron stars than O-mode photons, resulting in high polarization for thermal emission. The thermal x-ray polarization of quark/quark-cluster stars is truly negligible because of the high thermal conductivity on the surface. In normal neutron stars or magnetar models, however, the linear polarization of thermal x-rays will be high enough to be detectable. The brightest compact object, RX J1856.5-3754, with pure thermal radiation, should be an ideal source for the soft x-ray polarization observation, and a testbed of the compressed baryonic matter problem. It is therefore worth verifying the conjectures by advanced x-ray polarimetry.

The distinct thermal polarization predicted for normal neutron stars and quark/quark-cluster stars can be readily tested by future soft x-ray polarimeters, for example, the lightweight asymmetry and magnetism probe (LAMP) project being developed in China. LAMP will detect x-ray polarization at 250 eV using multilayer mirrors at incidence angles near  $45^\circ$  with a sensitivity, in terms of minimum detectable polarization, of 5% or less for objects as bright as RX J1856.5-3754. Therefore, it is capable of distinguishing these two competing models.

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