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Differentiating Neutron Star Models by X-Ray Polarimetry [*]

LU Ji-Guang(卢吉光)[1], XU Ren-Xin(徐仁新)[1**], FENG Hua(冯骅)[2]
[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871*
[2]*Department of Engineering Physics and Center for Astrophysics, Tsinghua University, Beijing 100084*

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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 ∼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.[1] 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 atomospheric 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/γ-ray bursts).[2] 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,[3] 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[4] 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, $B_{\mathrm{q}} \simeq 4\times 10^{13}$ G. For a weak magnetic field, i.e. $B < B_{\mathrm{q}}$, 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.[5] 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 $\omega \ll \omega_{\mathrm{c}} \equiv eB/m_{\mathrm{e}}c = 11.6 \times B_{12}$ 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 $\theta > (\omega/\omega_{\mathrm{c}})^{1/2}$,[6]

$$\sigma_{\mathrm{O}} = \sigma_{\mathrm{T}} \sin^2\theta, \tag{1}$$
$$\sigma_{\mathrm{E}} = \sigma_{\mathrm{T}} (\omega/\omega_{\mathrm{c}})^2 (1/\sin^2\theta), \tag{2}$$

where σ_{O}, σ_{E} are the cross sections of the O-mode and E-mode, respectively, and σ_{T} is the Thomson scatter-

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[**]Correspondence author. Email: r.x.xu@pku.edu.cn

ing cross section. For normal pulsars of $B \simeq 10^{12}$ G, $\theta \gg (\omega/\omega_c)^{1/2}$, one has $\sigma_{\rm O} \gg \sigma_{\rm E}$. 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%.[4]

In the case of magnetic field $B > B_{\rm q}$, an additional quantum vacuum effect due to quantum electrodynamics (QED) will also cause polarization of thermal x-ray radiation.[7–9] Lai and Ho[9] 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.[8]

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 (κ) of degenerate electrons inside quark or quark-cluster stars can be conveniently expressed through effective electron collision frequencies, $\nu_{\rm ee}$,[10]

$$\kappa = \frac{\pi^2 k_{\rm B}^2 T_{\rm S} n_{\rm e}}{3 m_{\rm e} \nu_{\rm ee}}, \tag{3}$$

where $n_{\rm e}$, $T_{\rm S}$ denote the number density of the electron and the temperature of the quark star surface, respectively, and $k_{\rm B}$ is the Boltzmann constant. The effective electron collision frequencies can be derived by[11]

$$\nu_{\rm ee} \simeq \frac{3}{2\pi}\left(\frac{\alpha}{\pi}\right)^{1/2}\frac{(k_{\rm B}T_{\rm S})^2}{\hbar\varepsilon_{\rm F}} J(\varsigma), \tag{4}$$

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

$$\varsigma = 2\sqrt{\frac{\alpha}{\pi}}\frac{\varepsilon_{\rm F}}{k_{\rm B}T_{\rm S}}, \tag{6}$$

where $\alpha = e^2/\hbar c$ is the fine structure constant, and $\varepsilon_{\rm F} = \hbar c(\pi^2 n_{\rm e})^{1/3}$ 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 $\theta = 90°$,

$$P_{\max} = \frac{|J_{\rm O} - J_{\rm E}|}{J_{\rm O} + J_{\rm E}} \sim \frac{|\sigma T_1^4 - \sigma T_2^4|}{\sigma T_1^4 + \sigma T_2^4} = \frac{|T_1^4 - T_2^4|}{T_1^4 + T_2^4}, \tag{7}$$

where $J_{\rm O}$ and $J_{\rm E}$ is the x-ray intensity of the O-mode and E-mode, respectively, T_1 (T_2) is the average temperature where the O-mode (E-mode) photons could come out from, and σ 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 $T_{\rm S} - T_1 \ll T_{\rm S} - T_2 \ll T_{\rm S}$, and Eq. (7) will be reasonable,

$$P_{\max} \simeq \frac{|T_{\rm S}^4 - T_2^4|}{T_{\rm S}^4 + T_2^4} \simeq \frac{T_{\rm S}^3 \cdot \Delta T}{2T_{\rm S}^4} = \frac{\Delta T}{T_{\rm S}}, \tag{8}$$

where $\Delta T \equiv T_2 - T_{\rm S}$.

For the approximation of black body radiation, the energy flux density $J_{\rm r}$ is

$$J_{\rm r} = \sigma T^4. \tag{9}$$

However, for thermal conduction, the energy flux density $J_{\rm c}$ is expressed as

$$J_{\rm c} = \kappa \cdot \nabla T \simeq \kappa \frac{\Delta T}{L_2}. \tag{10}$$

One has $J_{\rm r} = J_{\rm c}$ since there is no energy source near the quark-cluster star surface. Combining Eqs. (9) and (10),

$$\Delta T = \frac{\sigma T_{\rm S}^4 L_2}{\kappa}. \tag{11}$$

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

$$L_2 \simeq \frac{1}{n_{\rm e}\sigma_{\rm E}}\frac{\varepsilon_{\rm F}}{k_{\rm B}T_{\rm S}}, \tag{12}$$

where a factor of $\varepsilon_{\rm F}/k_{\rm B}T_{\rm S}$ 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

$$P_{\max} \simeq \frac{6\sigma T_{\rm S} m_{\rm e} \nu_{\rm ee} \omega_{\rm c}^2 \varepsilon_{\rm F}}{\pi^2 k_{\rm B}^3 n_{\rm e}^2 \sigma_{\rm T,corr} \omega^2}, \tag{13}$$

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

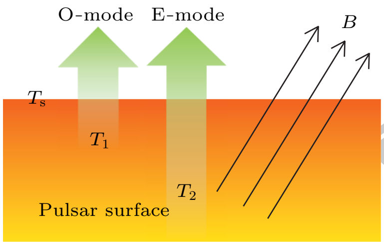

Fig. 1. A schematic diagram of thermal x-ray polarization originating from the pulsar surface, where the QED vacuum polarization effects are not included. The E-mode photons come from a deeper and hotter place than that of the O-mode.

We calculate the maximum linear polarization (to maximize the polarization, we consider the head-on collisions of photons and electrons) for typical parameters of $n_{\rm b} = 1.5n_0$ and $n_{\rm e} = 10^{-4}n_{\rm b}$, where $n_{\rm b}$ 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.

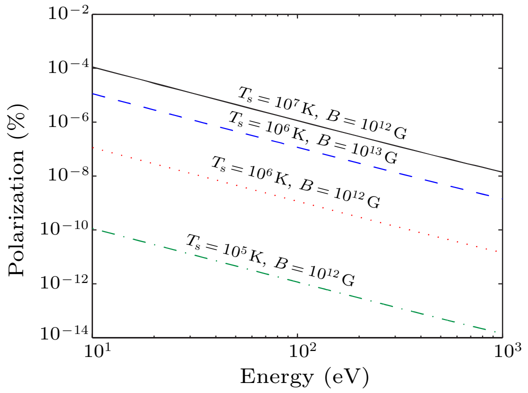

Fig. 2. The thermal x-ray polarization of a quark-cluster star as a function of photon energy, for parameterized temperatures (T) and magnetic fields (B).

There is an unexceptionable source to test the models: RX J1856.5-3754. Discovered in 1996,[13] 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,[14,15] although the stiff EoS could be understood by a Lennard–Johns quark matter model.[16] 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 $3M_\odot$,[17] and the pulsar mass statistics of recent results[18] 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.[19]

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.[21]

Soft γ 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.[22] 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[23]). Therefore, x-ray polarimetry can also be a powerful way to test the magnetar model.

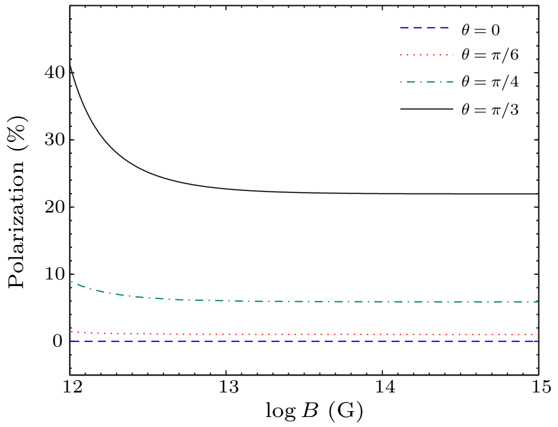

Fig. 3. The x-ray polarization of thermal radiation directly from a degenerate metallic condensed surface with a strong magnetic field (B). The vacuum polarization of QED is included, for a photon energy at 0.25 keV, while different emergence angles (θ, the angle between the magnetic field and the wave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