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## Thermal and Non-thermal radiation from pulsars: hints of physics

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**Abstract.** Thermal and non-thermal radiation from pulsars carries significant information from surface and would have profound implications on the state of dense matter in compact stars. For the non-thermal radio emission, subpulse drifting phenomena suggest the existence of Ruderman-Sutherland-like gap-sparking and strong binding of particles on pulsar polar caps. While conventional neutron star models can hardly provide such a high binding energy, the strong self-bound surface of quark-cluster stars can naturally solve this problem. As for the thermal one, the featureless X-ray spectra of pulsars may indicate a bare surface without atmosphere, and the ultrarelativistic fireball of  $\gamma$ -ray bursts and supernovae would also require strong self-bound surfaces. Recent achievements in measuring pulsar mass and mass-radius relation further indicate a stiff equation of state and a self-bound surface. Therefore, we conjecture that matters inside pulsar-like compact stars could be in a quark-cluster phase. The surface of quark-cluster stars is chromatically confined and could initially be bare. Such a surface can not only explain above features, but may also promote a successful core-collapse supernova, and the hydro-cyclotron oscillation of the electron sea above the surface could be responsible for those absorption features detected in the X-ray spectrum.

It was meaningful to celebrate Janusz' 60th birthday on the occasion of the 80th anniversary that Landau speculated dense matter at nuclear density inside stars. The speaker (RX) is focusing on pulsars from the dense matter point of view. Janusz has made contributions to pulsar study, in both observation and modeling. Certainly we had effective discussions and a close relationship, just as the fact that pulsar magnetospheric and inner researches are strongly coupled. Wish Janusz a happy and healthy life!

### 1. Non-thermal radiation: bound strongly on surface?

Radio radiation is the most important non-thermal radiation from pulsars, and it seems that all radio subpulses are drifting. In Ruderman & Sutherland (1975), a vacuum gap above the polar cap of a pulsar was first suggested. In this scenario, the sparks produced by the inner-gap breakdown result in the sub-pulses, and the  $E \times B$  drift causes the observed drifting features. However, in order to form such a vacuum gap, the binding energy of particles on pulsar polar caps must be very high, and calculations have shown that the binding energy of Fe at the neutron star surface is not enough (Flowers et al. 1977; Lai 2001). One way to solve this binding energy problem could be the partially screened inner gap model in the regime of conventional neutron star (Gil et al. 2003, 2006), but an alternative way would be in the bare quark-cluster star model (Yu & Xu 2011).

Quarks on the surface of quark-cluster stars are chromatic confined, so the binding energy of quarks can be considered as infinity compared to electromagnetic interaction. As for electrons on the surface, the binding energy is determined by the difference between the height of the potential barrier in the vacuum gap and the total energy of electrons. In Yu & Xu (2011), the magnetospheric activity of bare quark-cluster star was investigated in quantitative details, and they have shown that the huge potential barrier built by the electric field in the vacuum gap above the polar cap can usually prevent electrons from streaming into the magnetosphere, unless the electric potential of a pulsar is sufficiently lower than that at the infinite interstellar medium. Therefore, both positive and negative particles on the surface of quark-cluster stars are bound strongly, and a vacuum gap above the polar cap could be naturally formed to reproduce the drifting subpulses.

## 2. Thermal radiation: featureless spectrum and clear fireball?

The thermal spectra of pulsars differ substantially from Planck-like ones in conventional neutron star models (Zavlin et al. 1996). Many calculations (e.g. Romani 1987; Zavlin et al. 1996) also showed that spectral lines should be detectable with the spectrographs on board Chandra and XMM-Newton. However, up to now, no atomic line has been observed with certainty, and detailed spectral analysis of the combined X-ray and optical data of RX J1856.5–3754 have shown that no atmosphere model can fit the data well (Burwitz et al. 2001). These results may suggest a bare surface of pulsars.

Nevertheless, the best absorption features were detected for the central compact object 1E 1207.4–5209 at  $\sim 0.7$  keV and  $\sim 1.4$  keV (Sanwal et al. 2002; Mereghetti et al. 2002; Bignami et al. 2003). These lines might be of electron-cyclotron origin (Gotthelf & Halpern 2007; Halpern & Gotthelf 2011), but such a simple single particle approximation might not be reliable due to the high electron density on strange stars. Xu et al. (2012) investigated the global motion of the electron sea on the magnetized surface of quark-cluster stars. Their calculations showed that both the frequency and strength of the absorption features can be understood by the hydrocyclotron oscillations of the electron sea. This mechanism may also explain the detected lines in the burst spectrum of SGR 1806–20 and those in other dead pulsars (Xu et al. 2012).

The ultrarelativistic fireball of  $\gamma$ -ray bursts and supernovae also requires a bare and strong self-bound surface, since the total mass of baryons can not be too high, otherwise baryons would carry out too much energy of the central engine. However, the number of baryons loaded with the fireball is unlikely to be small for conventional neutron stars, considering their weak-bound surface and the extremely high luminosity of the fireball. This baryon contamination problem can be solved if the central compact objects are strange stars, because baryons are confined by strong color interaction while  $e^\pm$ -pairs, photons, neutrino pairs and magnetic fields can escape from the surface (Paczynski & Haensel 2005; Cheng & Dai 1996). Such a self-bound surface may also promote core-collapse supernovae. A nascent quark-cluster star born in the center of GRB or supernova would radiate Planck-like thermal emission due to its ultrahigh surface temperature, and the photon luminosity is not constrained by the Eddington limit since the surface of quark-cluster stars could be bare and is chromatic confined. Enormous thermal emissions could provide strong radiation pressure and are promising to alleviate the current difficulty in core-collapse supernovae (Chen et al. 2007).

### 3. Hints from surface: a quark-cluster state in the QCD phase diagram?

It is challenging to understand the states in the QCD phase diagram, especially at high density. Conventional neutron and quark stars are models for us to understand the inner structure of pulsars. For conventional neutron stars, the highly non-perturbative strong interaction makes quarks grouped into neutrons, while for quark stars, the perturbative strong interaction inside makes quarks to be almost free if the coupling is weak. However, quarks in dense matter at realistic baryon densities ( $\rho \sim 2-10\rho_0$ ) could be coupled strongly and grouped into quark clusters, as relativistic heavy ion collision experiments have shown that the interaction between quarks is very strong even in hot quark-gluon plasma (Shuryak 2009). We conjecture that matters inside pulsars could be in a quark-cluster phase, and the star could be in a solid state since the kinetic energy of quark clusters should be much lower than the interaction energy between the clusters.

Such solid quark-cluster stars are different from conventional neutron stars in two aspects (Xu 2011): (1) The equation of state determines the global structure: liquid or rigid? soft or stiff? (2) The surface is gravity-bound for neutron stars while it is self-confined by strong force for quark-cluster stars. The global solid state of quark-cluster stars can explain the observation of possible precessions of pulsars (Stairs et al. 2000). The latent heat released during the phase transition of quark-cluster stars from liquid to solid may provide a long-term steady central engine, and interpret the long-lived plateau in some GRB afterglows (Dai et al. 2011). The huge gravitational and elastic energy released during star quarks may also power the flares and bursts of soft  $\gamma$ -ray repeaters and anomalous X-ray pulsars (Xu 2007).

The peculiar surface properties of quark-cluster stars would result in different manifestations from that of conventional neutron stars and may indicate the state of dense matter inside pulsars. On one hand, the bare and chromatic confined surface can naturally explain the drifting subpulses and featureless thermal spectra of pulsars, and provide clean fireball for supernovae and  $\gamma$ -ray bursts as we discussed above. On the other hand, the mass-radius (M-R) relation of quark-cluster stars would be different from that of conventional neutron stars, because self-bound quark-cluster stars have non-zero surface density, and their radii usually increase as masses increase. Additionally, the state equation of quark-cluster stars is stiff because of the non-relativistic motion of quark clusters, and then a much larger maximum mass is expected. Recent mass and radius determination of the Rapid Burster (MXB 1730-335) (Sala et al. 2012) and the two solar mass neutron star (Demorest et al. 2010) have set strict constraints on the M-R relation and maximum mass of pulsars. Because of the hyperon puzzle (Haensel, this proceedings) and possible quark-deconfinement puzzle due to asymptotic freedom, most conventional neutron star and quark star models are hard to satisfy these two constraints, but quark-cluster stars can pass these tests (Lai & Xu 2009; Na & Xu 2011). Both global and surface properties of quark-cluster stars are quite different from that of conventional neutron stars. Future observations and studies are hopeful to distinguish them, and then promote our understanding of the state of dense matter and the strong interaction.

### 4. Conclusions

Diverse manifestations of thermal and non-thermal radiation from pulsars hint the surface properties and the state of compact stars. The drifting subpulses of non-thermal

radio radiation suggest the strong binding of particles on pulsar polar caps, and the featureless thermal spectra and the ultrarelativistic fireball of  $\gamma$ -ray bursts and supernovae indicate that pulsars may be strong self-bound and bare without atmosphere.

The bare and chromatic confined surface of quark-cluster stars can not only explain the drifting subpulses and featureless thermal spectra, but also promote core-collapse supernovae and understand the absorption features by the hydrocyclotron oscillations of the electron seas. What is more, the self-bound surface and the stiff equation of state of quark-cluster stars can fit the measurement of mass and radius of compact stars.

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