

A solution to the puzzling symbiotic X-ray system 4U 1700+24 *

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Abstract A circumstellar corona is proposed to explain a strange quark-cluster star during an accretion phase, which could be essential for understanding the observations of the puzzling symbiotic X-ray system 4U 1700+24. The state of cold matter at supranuclear density is still an important matter of debate, and one of the consequences of a strange star acting as a pulsar is the self-bound phenomenon on the surface, which makes extremely low-mass compact objects unavoidable. In principle, both the redshifted O VIII Ly- α emission line and the change in the blackbody radiation area could naturally be understood if 4U 1700+24 is a low-mass quark-cluster star which exhibits wind accretion.

Key words: pulsars: individual (4U 1700+24) — dense matter — stars: neutron

1 INTRODUCTION

It has been more than 80 years since the first idea of stars that are composed of matter at nuclear (or even supranuclear) density (see summaries and new achievements edited by van Leeuwen (2013) from IAU Symposium 291), but (un)fortunately, scientific challenges and opportunities still exist, especially after the discoveries of massive pulsars (Demorest et al. 2010; Antoniadis et al. 2013). Great efforts, though difficult due to unknown microphysics, have tried to model the inner structure of pulsar-like compact stars. Traditionally, quarks are believed to be confined in hadrons of neutron stars, but quark matter would exist in the core of a hybrid/mixed star whose central density could be high enough to make quarks de-confined, and a radical but logical argument is that an entire compact star could be composed of quark matter, which is called a quark star. In addition to all of the above, among different models of pulsar structures, a quark-cluster star is a condensed object composed of quark clusters that form via residual color interaction, which is different from both conventional neutron and quark stars (Xu 2010, 2013).

Hadron stars and hybrid/mixed stars are bound by gravity, and are covered by crusts with nuclei and electrons, whereas quark stars and quark-cluster stars are strongly self-bound on their surface. It is then unavoidable that the mass of a strange quark/quark-cluster star could be extremely low, even as low as the mass of a planet (a so called strange planet; Xu & Wu 2003; Horvath 2012), although massive quark-cluster stars as high as $\sim 3 M_{\odot}$ are still possible because of the very stiff equation of state for quark-cluster matter (Lai & Xu 2009; Lai et al. 2013). Besides massive pulsars, it is also

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necessary to find evidence for low-mass compact objects in order to test the quark-cluster model. In this paper, we will address that the discovery of the redshift from 4U 1700+24 (Tiengo et al. 2005, confirmed recently by Nucita et al. (2014) with publicly available X-ray data) could be one such attempt.

In fact, there has been a long history of searching for atomic transitions from spectral features of either non-accreting (e.g., Burwitz et al. 2001) or accreting (e.g., Cottam et al. 2002) compact stars, but we have not yet confirmed a successful case (e.g., Kong et al. 2007). The detected redshift may imply that there is an emission cloud at a distance of 160 – 1000 km from the central object if one assumes 4U 1700+24 is a neutron star with mass of $\sim 1.4 M_{\odot}$ (Nucita et al. 2014). However, our solution of the system in the regime of a quark-cluster star is that the central object has an extremely low mass of only $\sim 10^{-2} M_{\odot}$.

We will show that a corona-like plasma may exist above a quark-cluster star, and atomic transition lines could form in the corona if, in a high accretion phase, its density is larger than a critical value. In the limit of $z \ll 1$, the gravitational redshift z of a compact star reads (e.g., Xu 2003),

$$z \simeq \frac{GM}{c^2 R}, \quad (1)$$

for a stellar mass of M and a radius of R . For low mass quark/quark-cluster stars, where $M \ll M_{\odot}$, their densities are nearly uniform, so we have

$$R = \sqrt{\frac{3c^2}{4\pi G\rho_{\star}}} z, \quad M = \frac{4\pi}{3} R^3 \rho_{\star}, \quad (2)$$

where ρ_{\star} is the uniform density of a quark-cluster star in a pressure-free state. We are applying $\rho_{\star} = 2\rho_0$ in the following calculations (e.g., Lai & Xu 2009), with ρ_0 being the nuclear saturation density. For $z = 0.009$, we have $R = 2.3$ km and $M = 0.014 M_{\odot}$, which hints that the compact object could be an extremely low-mass quark-cluster star, which has negligible gravity (see fig. 1 of Xu 2010). Section 2 describes the model of a corona above strange quark-cluster star's surface, with special attention paid to 4U 1700+24. Conclusions and discussions are given in Section 3.

2 THE MODEL

2.1 Polar Corona of an Accreting Strange Quark-cluster Star

For a pure strange quark star, on one hand, if the kinematic energy of ions above the quark surface is zero (ie., without inclusion of barrier penetration), the Coulomb force formulated in Equation (3) could support a crust with mass as much as $\sim 10^{-5} M_{\odot}$ (Alcock et al. 1986; unfortunately, the authors concluded that the transmission probability of $\sim 10^{-104}$ is negligible if $A = 118$ and $Z = 36$, but the probability is $\sim 10^{-18}$ for ^{16}O with the same approximations presented). However, on the other hand, with the inclusion of barrier penetration, even ions in thermal equilibrium may significantly penetrate (see a discussion in Sect. 2.2) and consequently become deconfined quark matter (note: the kinematic energy of a free-falling ion is usually higher than ~ 10 MeV).

Note that things are very different for a strange quark-cluster star. We will demonstrate here that, when its accretion rate is much lower than the Eddington limit (ρ -low case, see below), a quark-cluster star would become surrounded by ions that form a corona above the polar cap. If the accretion rate is high (ρ -high case), then ions in the corona may diffuse across magnetic field lines, spreading over almost the entire stellar surface. A key point in this scenario is that although ions may significantly penetrate the barrier, most of them would bounce back into corona again. In addition, we would expect a two temperature system in the corona, where the temperature of ions T_i should generally be much higher than that of electrons T_e because an electron in a strong magnetic field

could lose its energy very effectively (but not for ions). The observed thermal X-rays are related to electron temperature T_e .

Because of the strong electron screening effect, the Coulomb barrier for an ion with charge number Z is (Xu & Qiao 1999)

$$V_{\text{Coul}} = \frac{3ZV_q}{\sqrt{6\alpha/\pi V_q \hat{z}/(\hbar c) + 4}} \propto \frac{1}{\hat{z}}, \quad (\text{when } \hat{z} \gg 10^2 \text{ fm}), \quad (3)$$

where \hat{z} is the height above the stellar surface, $\alpha = e^2/\hbar c$ is the fine-structure constant and $V_q^3/(3\pi^2\hbar^3 c^3)$ is the charge density of quark-clusters. It is evident, fortunately, that the Coulomb potential looks like that of a point charge so that we could apply some textbook conclusions (e.g., Gamow energy in Eq. (14)) about approximations related to nuclear reactions. The value of V_q depends on breaking symmetry of light-flavor in strange matter, which is difficult to calculate exactly, but would be on the order of 10 MeV.

We could approach the physics of a polar corona in two limiting cases: high (ρ -high) and low (ρ -low) density, which would be separated by a critical density of ions in the corona,

$$\rho_c \simeq \frac{Am_u}{r_L^3} \sim 5.5 \times 10^{-8} \beta^{-3} A^{-2} Z^3 B_{12}^3 \text{ g cm}^{-3}, \quad (4)$$

where the Larmor radius of an ion (A, Z) in a constant magnetic field $B = B_{12} \times 10^{12}$ reads,

$$r_L = \beta \frac{Am_u c^2}{ZeB} \sim 3.1 \times 10^{-6} \beta \frac{A}{Z} B_{12}^{-1} \text{ cm}. \quad (5)$$

For $v_f = 0.1c$ (i.e., $\beta \equiv v/c = 0.1$) in Equation (8), we have this ρ_c if we choose those parameters ($v_f, A/Z, Z$ and B_{12}). If $A/Z = 2, Z = 10$ and $B_{12} = 1$, one has $\rho_c \sim 10^{-4} \text{ g cm}^{-4}$ (i.e., an ion number density of $\sim 10^{18} \text{ cm}^{-3}$, approximately the density of air).

In the ρ -low case of $\rho \lesssim \rho_c$, the ion plasma could be collision free, with a temperature of $kT_i \sim E_g \sim 10 \text{ MeV}$ (see Eq. (7) in Sect. 2.2). All the falling ions could penetrate the Coulomb barrier, but may bounce back outside almost along the magnetic field lines, forming a corona with energetic ions, because of a very low rate of weak interaction to change up and down to strange quarks. Bondi accretion from the interstellar medium may power the thermal X-ray emission of a dead pulsar, like the ‘‘Magnificent Seven’’ (e.g., Mereghetti 2011) with an X-ray luminosity of $L_X \sim 10^{30} - 10^{31} \text{ erg s}^{-1}$. The density of ions in the corona could be estimated as

$$\rho_{\text{Bondi}} \sim \frac{L_X}{\eta c^2 v_f r_p^2} \left(\frac{r_p}{R'} \right)^2 \sim 10^{-10} \eta^{-1} \text{ g cm}^{-3}, \quad (6)$$

for $v_f \simeq 0.1c$ in Equation (8) and polar ions diffuse over the star’s surface with radius $R' \sim 10^5 \text{ cm}$. The density could be too low to result in lines from atomic features in thermal X-ray spectra if the probability $\eta > 10^{-10}$ (see Sect. 2.2 for a discussion of the η -value). Also, the polar hot spot could not be clear because of a low temperature gradient and high thermal conductivity inside the compact star.

In the ρ -high case of $\rho \gg \rho_c$, ion collision dominates, and a falling ion may quickly lose kinematic energies both perpendicular and parallel to the field lines. The ion plasma temperature $kT_i \gtrsim \text{keV}$ would be much lower than E_g . This is the case where significant accretion occurs, via either Roche lobe overflow or wind accretion. As for the X-ray spectrum, atomic features could form in this case. In addition, a massive quark-cluster star may manifest as an X-ray burster or even a superburst when its strain energy develops inside the solid star and reaches a critical value, i.e., a quake occurs, because significant gravitational and elastic energies are released. Certainly, more detailed researches are necessary for this scenario, that do not include a cool crust in the conventional X-ray burst model of a neutron star (Altamirano et al. 2012).

As for the composition of ions in the corona, nuclei with high nuclear binding energy are expected there, otherwise they would be destroyed due to frequent collisions with quark-clusters. Most of the nuclei in the corona could then be α -nuclei (e.g., ^{16}O , ^{56}Fe , etc.) and protons/neutrons.

2.2 An Order-of-magnitude Model for the Polar Corona

The kinetic energy of an ion (with atomic number A) accreted onto the surface would be

$$E_g \sim \frac{GAMm_u}{R} \simeq \frac{4\pi}{3}Gm_u\rho AR^2 \simeq 8.4A \text{ MeV}, \quad (7)$$

with a velocity of

$$v_f = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{8\pi}{3}G\rho R} \simeq 0.13c, \quad (8)$$

where m_u is the atomic mass unit and the stellar radius R is suggested to be a few kilometers.

We first consider the polar cap of an accreting quark-cluster star. In an environment of radiation with electron temperature $T_e \sim 1 \text{ keV}$, atoms with $Z < 10$ would be totally ionized, becoming a gas of free nuclei and electrons. Because electrons feel an outward radiation pressure, a radiation-induced electric field will form. The radiation force should be balanced by an electric one E_r ,

$$a\sigma_T T_e^4 \simeq eE_r, \quad (9)$$

with a being the radiation density constant and σ_T the Thomson cross section. One then has $E_r \simeq a\sigma_T T_e^4/e \simeq 3 \times 10^{-3}T_6^4 \text{ V cm}^{-1}$, where $T_6 = T_e/10^6 \text{ K}$, which is really negligible compared with the electric field $E_s \sim 10^{17} \text{ V cm}^{-1}$ on the surface of a strange star (e.g., Xu & Qiao 1999), both directed outward.

Although $E_r \ll E_s$, it does not mean that the radiation-induced electric field E_r could not significantly halt an accreted ion falling onto the polar cap. The length-scale of a decelerating ion by E_s is the order of 10^3 fm , but that by E_r would be the order of the polar cap radius r_p ,

$$r_p = R \arcsin \sqrt{\frac{2\pi R}{cP}} \simeq 4.6 \times 10^3 P_{-3}^{-1/2} R_6^{3/2} \text{ m}, \quad (10)$$

where $P = P_{-3} \times 10^{-3} \text{ s}$ is the spin period and $R_6 = R/10^6 \text{ cm}$. Therefore the electrostatic potential barrier induced by E_s could be $V_{\text{Coul}} \sim 10Z \text{ MeV}$, but that by E_r could be $V_r \sim ZE_r r_p \sim 14.5ZP^{-1/2}R_6^{3/2} \text{ eV}$. We can also have $V_r \ll V_{\text{Coul}}$ even if $P = 1 \text{ ms}$ and $R_6 = 1$. We thus neglect the radiation-induced electric field in the following calculations.

The cyclotron radiation power of an ion would be (e.g., Rybicki & Lightman 2004),

$$P_c = \frac{2}{3} \frac{Z^4 e^4}{A^2 m_u^2 c^3} \beta^2 B^2 \simeq 1.1 \times 10^{-15} \beta^2 B^2 \frac{Z^4}{A^2} \left(\frac{m_e}{m_u}\right)^2 \text{ erg s}^{-1}, \quad (11)$$

for an isotropic distribution of ion velocities, $v = \beta c$. The lifetime of an ion emitting cyclotron radiation is then

$$\tau \simeq \frac{Am_u v^2}{2P_c} = \frac{m_u^3 c^2}{2.2 \times 10^{-15} m_e^2} \frac{A^3}{Z^4 B^2} \simeq 2.3 \times 10^{-6} B_{12}^{-2} \frac{A^3}{Z^4} \text{ s}. \quad (12)$$

One can conclude that ions in the corona may move along the magnetic field lines due to cyclotron radiation.

We then turn to the reaction between ions and the quark-cluster star. In comparison with the thermal nuclear reaction (e.g., Clayton 1983), there are differences (the geometrical factor is $\sim E^{-1}$

for nuclear interactions, but it could be approximately one in our case) and similarities (occasionally weak interactions may occur in both cases to change the quark flavors).

The kinematic energy of ions (with typical temperature T_i) in a polar corona with height $h \ll R$ could be approximated as

$$kT_i \sim E_k \simeq \frac{4\pi}{3} G A m_u \rho R h = 1.6 A \frac{R}{\text{km}} \frac{h}{\text{m}} \text{ keV}, \quad (13)$$

which could be much lower than the Gamow energy (e.g., Perkins 2009)

$$E_G = \left(\frac{2m}{\hbar^2} \right) \left(\frac{Z_1 Z_2 e^2}{4} \right)^2 \sim 10 \text{ MeV}. \quad (14)$$

The average penetration probability of one ion (note: only $\sim 10^{-5}$ part of ions are in the Gamow window, being energetic enough to possibly penetrate) is then $\sim 10^{-5} \times \exp[-\sqrt{E_G/E_k}] \sim 10^{-18}$. It is then expected that, if without replenishment by accretion, all the ions would penetrate the Coulomb barrier during a timescale of $\sim 10^4$ seconds in the case that the bottom ion number density of the polar corona is about 10^{26} cm^{-3} (with mass density 10^2 g cm^{-3}) due to frequent collisions (see Eq. (15)).

However, a successful barrier penetration does not mean fusion of an atomic nucleus occurs and the condensed matter of quark clusters forms because of weak interactions: either an up or a down quark has to be converted to be a strange quark with a relatively long timescale (typically $\tau_{\text{weak}} \sim 10^{-7} \text{ s}$, but sometimes as long as $\sim 10^2 \text{ s}$). Without changing flavor, nuclear fusion is the result of the quick strong force, but for weak interactions that change flavor, the cross section is significantly suppressed. For instance, in the environment of stellar nucleosynthesis, the $S(E)$ factor is about $10^0 \text{ keV}\cdot\text{barn}$ for the reaction $\text{C}^{12}(p, \gamma)\text{N}^{13}$ (figs. 4 and 5 in Clayton 1983), but the $S(E)$ factor is only $\sim 10^{-22} \text{ keV}\cdot\text{barn}$ for the flavor-changing reaction $p + p \rightarrow d + e^+ + \nu_e$ (sect. 5-1 in Clayton 1983). This hints that only a negligible (at a relative probability of order 1 in 10^{20}) number of nuclei that penetrate would participate in weak interactions. Note that the fusion of a nucleus with strange matter also happens via weak interactions, to create strangeness. So, in summary, most of the ions that penetrate are scattered elastically via strong interactions, forming a polar corona with height h . It is then reasonable to assume that the structure of the corona evolves secularly over a longer timescale, and we may think that the number of ions that have weak interactions equals that of accreted ones.

There is still uncertainty about calculating the relative probability η at which ions that penetrate would successfully change flavor to strange matter. Nevertheless, one may estimate a value of $\eta \sim \text{fm}/(v\tau_{\text{weak}})$ that is from 10^{-25} to 10^{-13} if $\tau_{\text{weak}} \in (10^{-7}, 10^3) \text{ s}$ and $v \in (10^{-3}, 10^{-1})c$. By an analogy with spontaneous emission from an atom via electromagnetic interactions, with the inclusion of energy-dependence (E^3 , e.g., see van Driel et al. (2005) for a test of the E^3 -dependence) of the rate, the probability of weak interactions η would be enhanced by a factor of $10^{3\sim 5}$ if about (30 \sim 100) MeV of energy would be released per baryon during the phase conversion. Note that, as quark-cluster mass is comparable to that of a falling ion, the fraction of ions that penetrate would lose most of their kinematic energy during bombardment so that they could not be energetic enough to penetrate back to the corona, and finally be converted to strange matter. It is thus possible that the η -value could be as high as $> 10^{-5}$. This speculation cannot be ruled out now, but more elaborate work is needed to better understand these phenomena.

The charged ions can also diffuse across the magnetic field lines due to collisions between the ions that gyrate around the lines, since a collision will alter an ion's direction and make it gyrate around another field line. The direction of movement changes when the Coulomb energy approaches kT_i , and the collision timescale is

$$\tau_c \simeq \frac{A^{1/2} m_u^{1/2} (kT_i)^{3/2}}{\alpha^2 \hbar^2 c^2 Z_1^2 Z_2^2 n} \sim 10^{-14} A^{1/2} Z_1^{-2} Z_2^{-2} (kT_i/\text{keV})^{3/2} \frac{10^{26} \text{ cm}^{-3}}{n} \text{ s}, \quad (15)$$

where n is the ion number density. Ion diffusion across magnetic field lines could also be considered to be random walk (e.g., Goldston & Rutherford 1995). The timescale for ions in the polar corona to diffuse over the whole stellar surface would be

$$\tau_{\text{diffu}} \simeq \left(\frac{R}{r_L}\right)^2 \tau_c \sim 10^3 \beta A^{3/2} Z^{-5} B_{12}^{-1} (kT_i/\text{keV})^{3/2} R_6^2 \frac{10^{26} \text{cm}^{-3}}{n} \text{ yr}. \quad (16)$$

From this, one can infer that accreted matter could effectively diffuse from the polar cap to other parts of the surface.

When the high-accretion process ceases, the polar corona would not remain the same due to fusion and diffusion, but be converted from ρ -high to ρ -low phases. The residual corona is cool, nonetheless, it could be heated by falling ions during a phase with a low accretion rate (even via Bondi accretion from the interstellar medium), increasing the temperature T_i from $\sim \text{keV}$ to $\sim 10 \text{ MeV}$. A higher ion temperature ($T_i > T_e$) of 4U 1700+24 in case of wind accretion could also be responsible for an emission (rather than an absorption) Ly- α line.

2.3 The Case of 4U 1700+24

One of the symbiotic X-ray binaries, 4U 1700+24, is suggested to be a wind accretion system (Nucita et al. 2014), with X-ray luminosity $L_X \sim 10^{34} \text{ erg s}^{-1}$ and variability on both long- (months to years) and short-term timescales (10 to 1000 s). We propose that 4U 1700+24 could be a strange quark-cluster star surrounded by a polar corona with a height of h . Because the density of accreted matter is much lower than that of the corona (see Eq. (6) for an estimation), the detected redshift $z = 0.009 \pm 0.001$ of an O VIII Ly- α emission line would hint that there is a gravitational redshift, rather than the Doppler contributions due to the falling plasma velocity of Equation (8).

If $h \ll R$, one may infer that there is a compact star with a radius of a few kilometers (corresponding to $\sim 10^{-2} M_\odot$) from the redshift. However, if the height of the corona is not negligible,

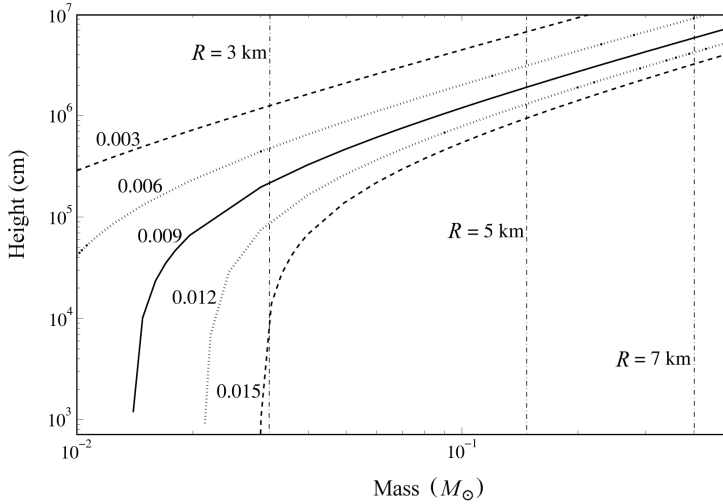


Fig. 1 Contour lines of the redshift in the mass-height diagram. Different redshifts ($z = 0.003, 0.006, 0.009, 0.012, 0.015$) are labeled for five contour lines. The dash-dotted vertical lines ($R = 3, 5, 7 \text{ km}$) denote the radii of a compact star as the radius could easily be calculated for a compact star with a certain mass by Eq. (2).

the gravitational redshift should be modified to be

$$z \simeq \frac{GM}{c^2(R+h)}. \quad (17)$$

Figure 1 shows the height of the corona and stellar mass implied by the observed redshift, according to Equation (17). It is evident that 4U 1700+24 should be a low-mass quark-cluster star as long as $h < R$.

It is observed that the radius of the X-ray emitting region by the best-fit blackbody model decreases as the overall X-ray luminosity decreases, from a few hundred meters down to a few tens of meters (Nucita et al. 2014). This can also be well understood in the scenario that has been presented. From Equation (10), one has the polar radius $r_p \simeq 16$ m if $R = 2.3$ km and $P = 1$ s. In the case of a high accretion rate, ion diffusion is significant so that the polar hot spot is large, but in the case of a low accretion rate, the radius of the hot spot could approach the polar radius, r_p . We note that the radius of the hot spot could be much smaller than the radius of the corona, although the corona could be as large as the whole star due to long term diffusion.

3 CONCLUSIONS AND DISCUSSION

We propose that the compact object in the symbiotic X-ray binary 4U 1700+24 is a low-mass quark-cluster star in a wind accretion phase. Because of very weak interactions that convert up or down quarks to strange quarks, most of the accreted ions bounce back after collisions with quark-clusters, and material accreted through open-field lines may finally result in the formation of a secular corona above the stellar surface, with stronger ion-diffusion at higher accretion rates. Both the redshifted O VIII Ly- α line and a change in the blackbody emitting region could be naturally understood in this scenario.

The nature of three kinds of isolated pulsars are explored in the literatures. Their X-ray luminosity L_X scales from $10^{30} \sim 10^{31}$ erg s $^{-1}$ for the ‘‘Magnificent Seven,’’ to $10^{32} \sim 10^{33}$ erg s $^{-1}$ for central compact objects (CCOs), and to $10^{34} \sim 10^{35}$ erg s $^{-1}$ for anomalous X-ray pulsars and soft γ -ray repeaters (AXP/SGRs). The spin periods of CCOs are small, only a few hundred milliseconds, but those of the other two are larger than a second, and clustered around 10 s. CCOs are proposed to be anti-magnetars (e.g., Mereghetti 2011) in order to explain their X-ray pulsations. However, in the regime of quark-cluster stars, accretion from either the interstellar medium or a fossil disk could contribute significant heating to the polar caps. A similar polar corona would also form there, with a clearer pulsation for higher L_X (note: some CCOs may also be heated by spindown powers). In addition, the period clustering of AXP/SGRs and the Magnificent Seven could also be understood by the inclusion of accretion torques (e.g., Liu et al. 2014).

It is conventionally believed that Type-I X-ray bursts are the results of unstable thermonuclear burning on the surface of neutron stars with binary accretion (e.g., Lewin et al. 1993). However, this popular point of view has been challenged recently by a superburst detected in EXO 1745–248. Altamirano et al. (2012) concluded that their observations of that superburst are very challenging for current superburst ignition models even assuming there were a few days of low-level accretion before the onset of the superburst. Nevertheless, in the regime of a solid quark-cluster star (e.g., Xu 2010), internal gravitational and elastic energy release during the quake of a massive compact star might be responsible for triggering the bursts, manifesting as Type-I X-ray bursts. Magnetic waves (e.g., Alfvén waves, Kaghshvili 1999) could effectively transport kinematic energy in the form of oscillations from the stellar interior out into the corona, significantly heating ions rather than electrons since the stellar oscillation frequency is much lower than the cyclotron frequencies of electrons and ions. A nuclear flash accompanying a starquake could also be possible. A recent study (Qu et al. 2014) of the flux evolution of three AXPs/SGRs does show that the ratios of persistent emission to the time averaged short bursts are comparable to those in the case of Type I X-ray bursts. In any case, an extensive study of this scenario is necessary in the future.

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References

- Alcock, C., Farhi, E., & Olinto, A. 1986, *ApJ*, 310, 261
- Altamirano, D., Keek, L., Cumming, A., et al. 2012, *MNRAS*, 426, 927
- Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, *Science*, 340, 448
- Burwitz, V., Zavlin, V. E., Neuhäuser, R., et al. 2001, *A&A*, 379, L35
- Clayton, D. D. 1983, *Principles of Stellar Evolution and Nucleosynthesis* (Chicago: Univ. of Chicago Press)
- Cottam, J., Paerels, F., & Mendez, M. 2002, *Nature*, 420, 51
- Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, *Nature*, 467, 1081
- Goldston, R. J., & Rutherford, P. H. 1995, *Introduction to Plasma Physics* (Bristol and Philadelphia: Institute of Physics Publishing)
- Horvath, J. E. 2012, *RAA (Research in Astronomy and Astrophysics)*, 12, 813
- Kaghashvili, E. K. 1999, *Geophys. Res. Lett.*, 26, 1817
- Kong, A. K. H., Miller, J. M., Méndez, M., et al. 2007, *ApJ*, 670, L17
- Lai, X. Y., & Xu, R. X. 2009, *MNRAS*, 398, L31
- Lai, X. Y., Gao, C. Y., & Xu, R. X. 2013, *MNRAS*, 431, 3282
- Lewin, W. H. G., van Paradijs, J., & Taam, R. E. 1993, *Space Sci. Rev.*, 62, 223
- Liu, X.-W., Xu, R.-X., Qiao, G.-J., Han, J.-L., & Tong, H. 2014, *RAA (Research in Astronomy and Astrophysics)*, 14, 85
- Mereghetti, S. 2011, in *Astrophysics and Space Science Proceedings, High-Energy Emission from Pulsars and Their Systems*, eds. D. F. Torres, & N. Rea, 345 (Berlin: Springer-Verlag), arXiv:1008.2891
- Nucita, A. A., Stefanelli, S., De Paolis, F., et al. 2014, *A&A*, 562, A55
- Perkins, D. H. 2009, *Particle Astrophysics* (Oxford: Oxford Univ. Press)
- Qu, Z., Li, Z., Chen, Y., et al. 2014, arXiv:1403.6244
- Rybicki, G. B., & Lightman, A. P. 2004, *Radiative Processes in Astrophysics* (Wiley-VCH Verlag GmbH & Co)
- Tiengo, A., Galloway, D. K., di Salvo, T., et al. 2005, *A&A*, 441, 283
- van Driel, A. F., Allan, G., Delerue, C., et al. 2005, *Physical Review Letters*, 95, 236804
- van Leeuwen, J. 2013, *Neutron Stars and Pulsars (IAU S291)* (Cambridge: Cambridge Univ. Press)
- Xu, R.-X. 2003, *ChJAA (Chin. J. Astron. Astrophys.)*, 3, 33
- Xu, R. 2010, *International Journal of Modern Physics D*, 19, 1437
- Xu, R. 2013, *Scientia Sinica Physica, Mechanica & Astronomica*, 43, 1288
- Xu, R.-X., & Qiao, G.-J. 1999, *Chinese Physics Letters*, 16, 778
- Xu, R.-X., & Wu, F. 2003, *Chinese Physics Letters*, 20, 806