

A THERMAL FEATURELESS SPECTRUM: EVIDENCE FOR BARE STRANGE STARS?

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ABSTRACT

In an effort to understand the absence of spectral lines in the thermal components of the X-ray compact sources observed recently by *Chandra* and *XMM-Newton*, we propose that these sources might simply be bare strange stars. We investigate the formation, cooling, and thermal photon radiation of bare strange stars. It is suggested that a thermal featureless spectrum could be a new probe for identifying strange stars.

Subject headings: dense matter — elementary particles — pulsars: general — stars: neutron

1. INTRODUCTION

To affirm or negate the existence of strange stars is an exciting and meaningful approach to guiding physicists in studying the quantum chromodynamical nature of strong interaction. With regard to the three possible ways of finding strange stars (e.g., see Xu & Busse 2001 for a short review), *hard* evidence to identify a strange star may be found by studying only the surface conditions since the other two avenues are subject to many complex nuclear and/or particle physics processes that are poorly known. The new advanced X-ray detectors *Chandra* and *XMM-Newton* increase the possibility of discovering the surface differences between neutron stars (NSs) and bare strange stars (BSSs), since the exteriors of both NSs and BSSs should be thermal X-ray radiators.

Many calculations, first developed by Romani (1987) and then by others (e.g., Zavlin, Pavlov, & Shibano 1996), show that spectral lines form in the atmospheres of NSs or crusted strange stars, which should be detectable with the spectrographs on board *Chandra* and *XMM-Newton*. However, *none* of the sources reported recently has significant spectral features in the observations made with *Chandra* or *XMM-Newton*. These sources are collected in Table 1, the spectra of which can be well fitted with blackbody models for the thermal components. An observation presented by Marshall & Schulz (2002) indicates still no significant line feature, even in the pulse-phased spectra over the 0.15–0.80 keV band, which does not favor atmospheric models of either heavy elements or pure hydrogen. Although this discrepancy could be explained for some of the sources by assuming a low-*Z* element (hydrogen or helium) photosphere or by adjusting the magnetic field, we address in this Letter a simple and intuitive suggestion that these “NSs” are actually just BSSs, especially the nearest one, RX J1856.5–3754 (no NS atmosphere model available can fit its X-ray and optical data; Burwitz et al. 2001), since almost no atoms appear above a bare quark surface.

Strange stars can be bare and BSSs can exist as compact stars (Xu & Qiao 1998; Xu, Zhang, & Qiao 2001). Drifting subpulses of radio pulsars may be evidence for BSSs (Xu, Qiao, & Zhang 1999b), which represent the strong binding of particles above pulsar surfaces. Super-Eddington emission of soft gamma-ray repeaters (SGRs) may be further evidence for BSSs (Zhang, Xu, & Qiao 2001; Usov 2001a). If further observations with much higher signal-to-noise ratios still find no spectral features in the thermal components of the sources listed in Table 1, the featureless thermal spectrum should be new evidence for BSSs.

2. STRANGE STARS: CRUSTED OR BARE?

Current research shows that it is possible for a core-collapse-type supernova explosion to leave a strange star. However, it depends on whether the strange star is bare or crusted to distinguish NSs and strange stars based on their sharp differences in surface conditions. Although relevant qualitative arguments are addressed separately in many published papers, it is worth concisely summarizing those discussions, with the inclusion of some quantitative estimates and modifications. A protostrange star may be bare owing to strong mass ejection and high temperature (Usov 1998), whereas a BSS could still possibly be covered by a crust owing to the accretion of (1) supernova fallback and (2) the debris disk. It follows below that such an accretion-formed crust is unlikely.

In case 1, as Xu et al. (2001) suggest, owing to rapid rotation and strong magnetic field, most of the fallback matter may temporarily form a fossil disk, and the initial accretion onto a star is almost impossible. Recently, three-dimensional simulations by Iguemshchev & Narayan (2002) have shown that the gravitational energy of the infall-magnetized plasma has to be converted to other energies and that the initial accretion rate might be reduced significantly.

Nevertheless, Xu et al. (2001) proposed that supernova ejecta are trapped by magnetic fields rather than by gravity, as suggested by Chevalier (1989). This trapped material with a mass of $\sim 10^{-15} M_{\odot}$ could fall back onto the surface to form a massive atmosphere *if* there exists no other force but gravity. However, the radiative pressures of *strong* photon and neutrino emission are not negligible because of high temperature ($T \sim 10^{11}–10^8$ K; see § 3). Only many years later could the photon luminosity be smaller than the Eddington one ($L_{\text{Edd}} \sim 10^{38}$ ergs s^{-1}). A possible scenario could be as follows: The trapped ions, forced by radiation, move along the magnetic lines to the outermost region of each line, where these enriched ions go across the field lines (higher density increases the kinematic energy density) and may merge eventually into a debris disk.

Accretion in case 2 was supposed to power the X-ray emission of anomalous X-ray pulsars (AXPs) and SGRs (e.g., Marsden & White 2001) during the nonstationary “propeller” phase, since the X-ray powers of these sources are much higher than the energy loss rates of their spin downs. These accretion energy rates of $L < 10^{36}$ ergs s^{-1} could be expected (the maximum persistent X-ray luminosity of AXPs and SGRs). Can a crust be formed during such accretion? As a result of strong fields, infalling matter is funneled toward the polar caps then free falls until feeling the deceleration due to the radiation pressure gen-

TABLE 1
 “NEUTRON STARS” WITH X-RAY THERMAL SPECTRUM OBSERVED BY CHANDRA OR XMM-NEWTON

| Name | Period (s) | B-Field (G) | Temperature ^a (eV) | Radius ^a (km) | $\gamma_{\text{pl}}^{\text{b}}$ | Age (yr) |
|---|-----------------------|----------------------|-------------------------------|--------------------------|---------------------------------|-----------------------|
| RX J1856.5–3754 (INS) | ... | ... | 20 (g), ~60 (l) | ≤10 (g), 2.2 (l) | ... | ~10 ⁶ |
| RX J0720.4–3125 (INS) | 8.39 | ... | 86 (l) | ... | ... | ... |
| 1E 1048.1–5937 (AXP) | 6.45 | Magnetar? | ~600 (l) | ... | ~3 | ... |
| 4U 0142+61 (AXP) | 8.69 | Magnetar? | 418 (l) | ... | 3.3 | ... |
| PSR J0437–4715 (msPSR) ^c | 5.76×10^{-3} | 3×10^8 | 181 (core), 46.5 (rim) | 0.1 (core), 2 (rim) | 2.2 | 4.9×10^6 (?) |
| PSR B0833–45 (Vela) | 89.3×10^{-3} | 3.4×10^{12} | 129 (l) | 2.1 (l) | 2.7 | 1.1×10^4 |
| PSR B0656+14 (PSR) | 385×10^{-3} | 4.7×10^{12} | 69.0 (g), 138 (l) | 22.5 (g), 1.7 (l) | ... | 1.0×10^5 |

NOTE.—Data from Burwitz et al. 2001, Pons et al. 2002, Paerels et al. 2001, Tiengo 2002, Juett et al. 2002, Zavlin et al. 2002, Sanwal et al. 2002, and Marshall & Schulz 2002. INS stands for isolated NS, and msPSR stands for millisecond pulsar.

^a Letters “g” and “l” denote global and local (e.g., polar cap) blackbody spectra, respectively.

^b Photon index of a nonthermal power-law spectrum.

^c The temperature and radius here are for the fitting of the data with the two-temperature hydrogen polar caps but could have qualitatively similar parameters for a two-temperature blackbody polar cap model.

erated by the accreted material on the caps. Without this halting, a proton could have a kinematic energy of ~100 MeV near the surface of a BSS and could thus penetrate the Coulomb barrier (~20 MeV) and dissolve. But in a radiation field with energy density U , a hydrogen atom will actually have a back force of $f_r \sim \sigma_T U$, with σ_T the Thompson cross section. For a low accretion limit, such force is not negligible only when atoms are near the hot spot powered by accretion and the height of this region is about the polar cap radius r_p . In view of the fact that the accretion energy has been reemitted above the polar cap only ϵ times (see Appendix), by $f_r r_p = GMm_p/R$, we obtain a critical accretion rate L^* ,

$$L^* = \frac{2\pi Gc r_p M m_p}{\epsilon \sigma_T R} = \frac{9.1 \times 10^{35}}{\epsilon} M_1 R_6^{-1} P^{-1/2} \text{ ergs s}^{-1}, \quad (1)$$

which is $\sim 1/\epsilon$ times higher than the critical value presented by Basko & Syunyaev (1976). If $L < L^*$, an atom may still have enough kinematic energy to penetrate after the deceleration. We expect that the accretion of interstellar medium or a fossil disk can also keep a strange star bare since $L < 10^{36} \text{ ergs s}^{-1} < L^*$. It is very likely that $L^* > L_{\text{Edd}}$, since ϵ can be as small as 10^{-4} (see Appendix). This means that BSSs may also survive some of the accretions with super-Eddington rates. A crust covering a strange star could be formed via accretion if $L > L^*$, which ensures no distinction between the faced and magnetospheric radiations of SSs and NSs. But such a high accretion rate might be possible only for binary X-ray sources. Recycled millisecond pulsars could be BSSs as long as the accretion rates remained less than L^* during their accretion phases.

There may be another way to produce BSSs. A nascent rapidly-rotating magnetized NS could form with a mass reaching the Oppenheimer limit, but it would quickly lose its angular momentum via gravitational (driving the rotation modes unstable) and electromagnetic (magnetic dipole) radiations. An NS central density has to be high enough for a phase conversion to a strange star¹ before the NS is so slow and cool that a super-Oppenheimer mass is possible. Such a strange star should also be bare since (1) the phase transition energy is much greater than the crust gravitational binding and (2) the photon emission rate is much greater than L_{Edd} .

In conclusion, BSSs can exist in nature. Some of them probably act as the X-ray sources in Table 1.

¹ This process was supposed to be a candidate for the “center engines” of gamma-ray bursts (e.g., Xu et al. 1999a).

3. COOLING AND THERMAL EMISSION OF BARE STRANGE STARS

We can expect a nascent strange star with thermal energy $\epsilon_i \geq 10^{52}$ ergs since the gravitational and degenerate energies are of the same order, $\sim 10^{53}$ ergs, even if other energy sources (e.g., the rotation energy, the phase transition energy) are included. The specific heat of strange quark matter is (e.g., Usov 2001b) $C = C_q + C_e$, with $C_q = 1.9 \times 10^{12} \rho_{15}^{2/3} T_c \exp(-\Delta/T) \times [2.5 - 1.7T/T_c + 3.6(T/T_c)^2]$ ergs $\text{cm}^{-3} \text{K}^{-1}$ and $C_e = 1.3 \times 10^{11} Y_e^{2/3} \rho_{15}^{2/3} T$ ergs $\text{cm}^{-3} \text{K}^{-1}$. The specific heat of unpaired electrons dominates, $C_e > C_q$, when $T < 7.45 \times 10^9$ K. The electron fraction $Y_e \sim 10^{-3}$. The energy gap is very uncertain, and whether the color superconducting (CSC) occurs is therefore still undetermined. We choose $\Delta = 50$ MeV for the following discussion, so a strange star should be in a CSC state except for at the very beginning of its birth. The critical temperature $T_c \sim \Delta/2$ in the Bardeen, Cooper, & Schrieffer superconductivity model. By $\epsilon_i = CT_i 4\pi R^3/3$, one obtains the initial temperature $T_i \geq 10^{10}$ K, which means the strange star is very hot soon after supernova explosion. Effective neutrino emissivity of a newborn hot strange star rapidly expels the thermal energy, making the strange star have a much cooler temperature at which the photon emission dominates.

The dividing temperature T_ν , a solution of

$$3 \times 10^{-4} \sigma T_\nu^4 = R \epsilon_\nu(T_\nu), \quad (2)$$

is $T_\nu \sim 4 \times 10^{10}$ K for typical parameters, where the neutrino emissivity (e.g., Usov 2001b) is $\epsilon_\nu = 7.8 \times 10^{-28} \alpha_s Y_e^{1/3} \times \rho_{15} T^6 \exp(-\Delta/T)$ ergs $\text{cm}^{-3} \text{s}^{-1}$ and σ is the Stefan-Boltzmann constant. The factor 10^{-4} in equation (2) is due to the upper limit on photon emissivity of strange quark matter at energies of less than 20 MeV (Chmaj, Haensel, & Slomiński 1991). This T_ν estimate is on the high side if CSC does not occur at the very beginning; nevertheless, this value implies that photon emission dominates almost the entire life of a strange star. This conclusion is strengthened if the Usov (1998) photon emission mechanism is included.

The equation governing a BSS’s cooling history is

$$\frac{4}{3} \pi R^3 C \frac{dT}{dt} = -\xi \sigma T^4 4\pi R^2, \quad (3)$$

where $\xi \sim 1$ for $T > 10^9$ K, at which the Usov mechanism works, whereas $\xi \lesssim 10^{-4}$ for $T < 8 \times 10^8$ K (Usov 2001c). When $T < 7.45 \times 10^9$ K, assuming a constant ξ , equation (3) can be

solved to be

$$T = T_0(1 + 2J\xi\dot{T}_0^2 t)^{-1/2}, \quad (4)$$

where $J = 3\sigma/(\check{C}_e R)$, $\check{C}_e = C_e/T$, and t is the time duration for a BSS to cool from temperature T_0 to T . According to equation (4), a BSS cools to $T \sim 10^6$ K after $\sim 10^3$ yr. However, because of the magnetospheric polar cap heating, powered by the bombardment of downward-flowing particles, a BSS should keep a minimum temperature, T_{\min} . As a rough estimate at first, equating the photon emission rate to the pulsar spin-down power, $\xi\sigma T_{\min}^4 4\pi R^2 \sim 6.2 \times 10^{27} B_{12}^2 R_6^2 (2\pi/P)^4$, one has $T_{\min} = 3.4 \times 10^6 R_6 B_{12}^{1/2} P^{-1}$ K.

For PSR J0437–4715 and PSR B0833–45, $T_{\min} \sim 9 \times 10^2 R_6$ and $6 \times 10^3 R_6$ eV, respectively. Considering that the photon emission power is $\xi \lesssim 10^{-4}$ times that of a blackbody, these temperatures, modified by a factor of ~ 0.1 , are comparable with observations (Table 1).

In fact, the minimum temperature is model dependent, and it is worth discussing T_{\min} in some pulsar emission models. Owing to the high binding energy of a bare quark surface, the space-charge-limited flow model (e.g., Arons & Scharlemenn 1979) cannot work for BSSs. We focus thus on the polar cap heatings in the vacuum polar model (Ruderman & Sutherland 1975) and the outer gap model (Cheng, Ho, & Ruderman 1986), both of which are depicted in Xu et al. (2001). The polar heating rate of an Ruderman-Sutherland-type gap is $\sim 1.1 \times 10^{31} \times \gamma_7 B_{12} P^{-2}$ ergs s^{-1} , and the minimum temperature is thus $T_{\min}^{\text{RS}} \approx 3.5 \times 10^6 \gamma_7^{1/4} R_6^{-1/2} B_{12}^{1/4} \times P^{-1/2}$ K, with $\gamma = 10^7 \gamma_7$ the typical Lorentz factor of the primary particles. If outer gaps exist, the luminosity deposited onto the surface is $\sim 8.2 \times 10^{30} B_{12} \times P^{-5/3}$ ergs s^{-1} and the correspondence temperature is $T_{\min}^{\text{CHR}} \approx 3.3 \times 10^6 R_6^{-1/2} B_{12}^{1/4} P^{-5/12}$ K.

We see that these three values of T_{\min} , T_{\min}^{RS} , and T_{\min}^{CHR} are almost the same. This is not surprising because although the total energy deposit fluxes differ, the thermal temperature is the amount of flux to the power of one-quarter.

As for the AXPs (or SGRs), the thermal energy with temperature T_{\min} cannot account for their persistent X-ray emissivity since the observed X-ray power is many orders higher than the energy loss rate of rotation. Nonetheless, there are actually two suggestions for supplying extra energy: magnetism powered (the so called magnetar model; e.g., Thompson & Duncan 1995) and accretion powered (e.g., Marsden & White 2001). Both these mechanisms have been widely discussed in the literature recently. Since BSSs can also act as magnetars as long as the dynamo action in protostrange stars is effective enough (see Xu & Busse 2001), we deem that magnetic field line reconnection on BSS surfaces can also work to produce abundant energy. As discussed in § 2 (see eq. [1]), accretion in AXPs and SGRs can still keep a strange star bare. So it is also possible that AXPs (or SGRs) are accretion-powered BSSs. Therefore, the energy budget problem of AXPs and SGRs is solved if those two popularly discussed mechanisms are adapted to fit BSSs.

In principle, one can study the thermal radiative properties by comparison of theoretically modeled spectra with those of observations. Unfortunately, no emergent spectrum calculation of BSSs appears in the literature. The total power of photon emissivity of BSSs was calculated by Chmaj et al. (1991). Nevertheless, we can expect the spectra to be close to those of blackbodies, which represent the general form of the X-ray spectra observed, since, e.g., for the quark bremsstrahlung radiation mechanism (Chmaj et al. 1991), quarks are nearly in

thermal equilibrium owing to intercollisions within a depth less than the mean free path (~ 10 fm) of photons with energy lower than $\hbar\omega_p \sim 20$ MeV. A BSS with surface temperature T may have a slightly harder spectrum than a blackbody with $\sim 10^{-1}T$. New fits by BSS emergent spectra may significantly alter the physical quantities derived through thermal radiation. For example, one power law and only one thermal spectrum might be enough to model precisely the observed spectrum of PSR J0437–4715 (Zavlin et al. 2002). Because of this lack of fits, the temperatures and radii listed in Table 1 may not be relevant if we want to obtain observationally the thermal properties (e.g., the temperature distribution) of a BSS surface.

This kind of research may provide real information on photons from quark matter astrophysically, whereas in terrestrial physics, direct photons and lepton pairs have been recognized to be the clearest signatures for quark-gluon plasma (e.g., Cassing & Bratkovskaya 1999). It is worth noting that the BSS thermal photon emission is in the low energy limit, which would thus complement the study of the high-energy photons of relativistic nucleus-nucleus collisions. Future observations using various methods may confirm the existence of BSSs, and in return the observational fit of the thermal spectra from the quark surfaces could be used as a test in checking those phenomenological models for quark gluon plasma in strong magnetic fields.

It should be noted that magnetospheric power-law components of BSSs are also featureless (Xu & Qiao 1998; Xu et al. 2001), but an NS may have magnetospheric line features due to the ions pulled out from NS surface by the space-charge-limited flow mechanism in the open field line region.

4. CONCLUSION AND DISCUSSION

An alternative opinion is proposed for the nature of the sources with featureless X-ray spectra observed by *Chandra* and *XMM-Newton*, which is that these X-ray emitters are simply BSSs. Possible scenarios for the creation of BSSs are studied, and we find that accretion cannot prevent the formation of a BSS unless the accretion rate is much higher than the Eddington one. The cooling and thermal radiation of BSSs are also discussed, indicating that they do not strongly conflict with observations.

There may be indications for one or two lines at about 40 and 20 Å in RX J1856.5–3754 (van Kerkwijk 2002). This is a real challenge to the BSS idea. If future longer observations with *Chandra* and *XMM-Newton* confirm the existence of these lines, then the source is certainly not a BSS but might be a crusted strange star, since stringent constraints on the mass ($M \approx 1 M_\odot$) and radius ($R \approx 6$ km) for RX J1856.5–3754 (Ransom, Gaensler, & Slane 2001) clearly show that it can hardly be modeled by the equations of states of nuclear matter.

The age of PSR J0437–4517 is worth deliberating. A millisecond pulsar could be very hot soon after a recycling phase when the polar heat is transported effectively to the other part of the BSS owing to a small ϵ . However, r -mode instability may spin down a BSS to an initial period of $P_0 \sim 3$ –5 ms (e.g., Andersson & Kokkotas 2001), which can have substantial influence on the age calculation by dipolar radiation braking. However, P_0 is temperature dependent and is thus relevant to the accretion history. The fastest rotating pulsar, PSR 1939+21, might have a slow accretion rate but a long accretion phase. The age of PSR J0437–4517 is much smaller if it has $P_0 \sim 5$ ms soon after accretion and thus has a high temperature today.

This is a critical time in obtaining the thermal spectra from

pulsar-like compact stars. Besides *Chandra* and *XMM-Newton*, more X-ray missions (e.g., *Astro-E* in 2005) may finally reveal the secrets, including whether some of the sources are BSSs. We are looking forward to the discoveries over the coming years.

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APPENDIX

ENERGY REEMITTED ON THE POLAR CAPS

The essential difference between the accretion- or rotation-powered energy deposit processes of NSs and BSSs is that part of the energy should be transported to the outside of the polar caps for BSSs but not for NSs (e.g., Xu et al. 2001), since the coefficient of thermal conductivity of electrons in the NS surface $\kappa^{\text{NS}} = 3.8 \times 10^{14} \rho_5^{4/3} \text{ ergs s}^{-1} \text{ cm}^{-1} \text{ K}^{-1}$ is much smaller than the coefficient of degenerate quark matter $\kappa^{\text{BSS}} = \kappa_q^{\text{BSS}} + \kappa_e^{\text{BSS}}$, with $\kappa_q^{\text{BSS}} = 1.41 \times 10^{21} \alpha_s^{-1} \rho_{15}^{2/3} \exp(-\Delta/T) \text{ ergs s}^{-1} \text{ cm}^{-1} \text{ K}^{-1}$ for quark scattering and $\kappa_e^{\text{BSS}} = 1.55 \times 10^{23} Y_e \rho_{15} T_9^{-1} \text{ ergs s}^{-1} \text{ cm}^{-1} \text{ K}^{-1}$ for electron scattering (e.g., Blaschke et al. 2001), where ρ_5 and ρ_{15} are the densities in units of 10^5 and $10^{15} \text{ g cm}^{-3}$, respectively, α_s is the coupling constant of strong interaction, T the temperature, $T_9 = T/(10^9 \text{ K})$, $\Delta \sim 10\text{--}100 \text{ MeV}$ the energy gap, and $Y_e \sim 10^{-3}$ the ratio of numbers of electrons and baryons. A dimensional argument provides the temperature difference between the polar cap and equator for BSSs,

$$\delta T \sim \frac{L}{\kappa^{\text{BSS}} R}, \quad (\text{A1})$$

where L is the rate of total energy deposit and $R \sim 10^6 \text{ cm}$ is the stellar radius. For $L \sim 10^{36} \text{ ergs s}^{-1}$, one has $\delta T \sim 6.5 \times 10^9 T_9 \text{ K}$, which is on the same order as polar temperature.² This means substantial energy should dissipate to outside the polar cap in BSSs if $L \lesssim 10^{36} \text{ ergs s}^{-1}$. Defining ϵ to be the reemission photon fraction of the total energy deposit, we have $1 > \epsilon > r_p^2/(2R^2) \sim 10^{-4}/P$ if $L \lesssim 10^{36} \text{ ergs s}^{-1}$, where $r_p = 1.45 \times 10^4 P^{-1/2} \text{ cm}$ is the polar cap radius and P is the rotation period. Assuming one-half of the deposited energy is brought away by neutrinos rather than by photons in this case, one obtains modified limits for ϵ : $5 \times 10^{-5}/P < \epsilon < 0.5$, where the upper limit is for $L \rightarrow +\infty$ and the lower limit for $L \rightarrow 0$.

² In case no energy is dissipated (e.g., for NSs), the polar temperature $T = 2.3 \times 10^9 L_{30}^{1/2} P^{1/4}$, where $L_{30} = L/(10^{30} \text{ ergs s}^{-1})$. This temperature is an upper limit for BSSs.

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Note added in proof.—After this Letter was accepted, I was informed by Dr. Drake that he and his co-authors have analyzed 500 ks *Chandra* data on RXJ 1856.5–3754 and that this deeper exposure reveals still no evidence for spectral features (J. J. Drake et al., *ApJL*, in press [2002, astro-ph/0204159]). Their research does not confirm the previous discovery of the possible two lines (56 ks observation; van Kerkwijk 2002).