17. Y. Nozaki, Y. Horibe, H. Tsubota, *Earth Planet. Sci. Lett.* **54**, 203 (1981).
18. M. P. Bacon and R. F. Anderson, *J. Geophys. Res.* **87**, 2045 (1982).
19. Y. Nozaki and T. Nakanishi, *Deep-Sea Res.* **32**, 1209 (1985).
20. C.-H. Huh and M. P. Bacon, *Nature* **316**, 718 (1985).
21. L. Guo, P. H. Santschi, M. Baskaran, A. Zindler, *Earth Planet. Sci. Lett.* **133**, 117 (1995).
22. M. R. Scott, *ibid.* **4**, 245 (1968).
23. H. G. Östlund, G. Possnert, J. H. Swift, *J. Geophys. Res.* **92**, 3769 (1987).
24. R. W. Macdonald, E. C. Carmack, D. W. R. Wallace, *Science* **259**, 103 (1993).
25. M. P. Bacon, *Philos. Trans. R. Soc. London Ser. A* **325**, 147 (1988).
26. R. L. Edwards, H. Cheng, M. T. Murrell, S. J. Goldstein, *Science* **276**, 782 (1997).
27. R. F. Anderson and A. P. Fleer, *Anal. Chem.* **54**, 1142 (1982).
28. Y. Nozaki, H.-S. Yang, M. Yamada, *J. Geophys. Res.* **92**, 772 (1987).

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Is GRO J1744-28 a Strange Star?

K. S. Cheng,* Z. G. Dai, D. M. Wei, T. Lu

The unusual hard x-ray burster GRO J1744-28 recently discovered by the Compton Gamma-Ray Observatory can be modeled as a strange star with a dipolar magnetic field of $\leq 10^{11}$ gauss. According to this model, when the accreted mass of the star exceeds some critical mass, its crust breaks, resulting in the conversion of the accreted matter into strange matter and a release of energy. Subsequently, a fireball forms and expands relativistically outward. The expanding fireball interacts with the surrounding interstellar medium, causing its kinetic energy to be radiated in shock waves and producing a burst of x-ray radiation. The burst energy, duration, interval, and spectrum derived from such a model are consistent with the observations of GRO J1744-28.

GRO J1744-28 is a previously unknown type of x-ray transient source that was discovered on 2 December 1995 by the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory (GRO) (*1*). The bursts were detected up to energies of ~75 keV with intervals between bursts of ~200 s initially. After 2 days, the burst rate dropped to ~1 per hour (*2*). However, by 15 January 1996 the burst rate had increased to ~40 per day. The burst durations were ~10 s. The burst fluences (25 to 60 keV) ranged from 1.7×10^{-7} to 6.8×10^{-7} ergs cm^{-2}; the average fluence $\overline{S} = 2.7$ $(\pm 0.9) \times 10^{-7}$ ergs cm^{-2}. The position of the source is near the galactic center. For a distance of ~7.5 kpc, the average peak luminosity was $\sim 2 \times 10^{38}$ ergs s^{-1}, with a flux of $\sim 3 \times 10^{-8}$ergs cm^{-2} s^{-1}.

Analysis of the BATSE data indicated that the source is a binary pulsar with a pulsation period of 0.467 s, a companion with a mass of 0.22 to 1.0 $M_{\odot}$ (where $M_{\odot}$ is the mass of the sun) and a binary orbital period of 11.8 days (*3*). Because the x-ray mass function is small ($\sim 1.31 \times 10^{-4}$ $M_{\odot}$), the system must be nearly face-on to an observer from Earth, with an inclination angle of ~18° (*3–5*). Furthermore, for the measured rotation period derivative to be consistent with standard accretion torque theory (*6*), the persistent luminosity of the source at its peak should be close to the Eddington limit (*4*) and the surface dipole magnetic field of the pulsar should be $\leq 10^{11}$ G (*3–5*). From the observed pulsed fraction and the pulsar's x-ray spectrum, the strength of the local surface magnetic field is estimated to be several teragauss (*4*). In addition, the proportional counter array (PCA) experiment (2 to 60 keV) on the Rossi X-ray Timing Explorer (RXTE) (*7*) had detected GRO J1744-28 during the period 18 January to 10 May 1996. The observations showed that after the earlier large bursts, the flux dipped below the preburst level by as much as 25 to 30% and then made a slow quasi-exponential recovery back toward the preburst level. The observed recovery period lasted up to ~1000 s for some bursts, but most bursts recovered in a few hundred seconds.

The properties of the hard x-ray bursts (HXRBs) from GRO J1744-28 differ from those of other known high-energy bursts—x-ray bursts, soft γ-ray bursts, and γ-ray bursts. First, the HXRBs are probably not type I x-ray bursts (*8*). Thus, thermonuclear flashes in matter accreted onto the surface of a neutron star may not produce HXRBs. Second, the durations of the HXRBs are several hundred times those of the three soft γ-ray repeaters, even though these two kinds of bursts have similar repeat times and spectra. Third, the HXRBs are different from γ-ray bursts, because γ-ray bursts do not have fast repeat times and their spectra are much harder. On the other hand, the repeat times and spectra of the HXRBs are somewhat similar to those of type II x-ray bursts from the rapid burster (*2, 8*). This suggests that some accretion instability may be a mechanism for producing HXRBs. Cannizzo (*9*) studied the global, time-dependent evolution of the Lightman-Eardley instability, which might account for some observational features of the HXRBs. Here, we propose an alternative model in which a strange star accretes matter from its low-mass companion.

Strange matter (bulk quark matter) is conjectured to be more stable than hadronic matter (*10*). The existence of strange matter is allowable within uncertainties inherent in a strong-interaction calculation (*11*); thus, strange stars may exist in the universe. Strange stars have crusts with masses of $\sim 10^{-5} M_{\odot}$ (*12*). However, the postglitch behavior of pulsars can be described by the neutron-superfluid vortex creep theory (*13*), which requires a crustal mass of $\geq 10^{-3} M_{\odot}$. The conversion of a neutron star to a strange star may require the formation of a strange matter seed, which is produced through the deconfinement of neutron matter at a density of ~7 to 9 ρ_0 (where ρ_0 is the nuclear matter density), much larger than the central density of a $1.4 M_{\odot}$ neutron star with a moderately stiff to stiff equation of state (*14*). These two features suggest that strange stars may be formed in low-mass x-ray binaries (*15*) because when the neutron star in a low-mass x-ray binary accretes sufficient mass (perhaps $\geq 0.4 M_{\odot}$), its central density can reach the deconfinement density and the whole star will then undergo a phase transition to become a strange star. The phase transition from nuclear matter to strange matter under the condition of conserved charge rather than constant pressure may occur at a density as low as 2 to 3 ρ_0 (*16*). If so, strange stars may be formed during the evolution of protoneutron stars (*17*). Some arguments against the existence of strange stars should be kept in mind; for example, the disruption of a single strange star may contaminate the entire galaxy, and

K. S. Cheng, Department of Physics, University of Hong Kong, Hong Kong, China.
Z. G. Dai, Department of Astronomy, Nanjing University, Nanjing 210093, China.
D. M. Wei, Purple Mountain Observatory, Nanjing 210008, China.
T. Lu, Department of Astronomy, Nanjing University, Nanjing 210093, China, and Chinese Center for Advanced Science and Technology (World Laboratory), Post Office Box 8730, Beijing 100080, China.

*To whom correspondence should be addressed.

essentially all neutron stars may be strange stars (18). In view of these uncertainties, we should regard strange stars only as possible stellar objects. According to standard accretion torque theory (6) and Daumerie *et al.* (4), the binary system of GRO J1744-28 is nearing the end of the mass transfer phase. If this is true, then the companion has transferred mass of $\geq 0.4 M_\odot$ to the pulsar and now has a mass of ~ 0.22 to $0.5\ M_\odot$.

We next discuss the burst mechanism. We assume that at large distances from the proposed strange star, the magnetic field is purely dipolar and the accretion flow is spherically symmetric. We consider the simple case of a pulsar with mass $M_{\rm pulsar} = 1.8 M_\odot$ and radius $R_{\rm pulsar} = 10^6$ cm. The Alfvén radius for spherical accretion, obtained by balancing accretion and magnetic pressure, is given by $R_A = 1.8 \times 10^7 L_*^{-2/7} B_*^{4/7}$ cm, where L_* is the total accretion luminosity of $\sim 2 \times 10^{38}$ ergs s^{-1} (the Eddington limit) and B_* is the surface dipolar magnetic field strength (in units of 2×10^{10} G), which is close to the B_* derived in (5). For an assumed dipolar magnetic field geometry, $\sin^2 \theta_m / r$ is a constant, where θ_m is the magnetic colatitude and r is the distance to the star. Thus, at the stellar surface near a pole, the cross-sectional area of the accretion column is $A_p \approx 1.8 \times 10^{11} L_*^{2/7} B_*^{-4/7}$ cm^2, and the corresponding radius of the accretion column is $r_p \approx 2.4 \times 10^5 L_*^{1/7} B_*^{-2/7}$ cm.

As the strange star accretes matter from its companion, pressure is formed at the base of the accreted matter near the polar cap, because of the gravitational attraction of the compact strange star. When this pressure exceeds the critical stress of the star's thin crust, the crust may break. The condition under which a crust-breaking event takes place is given by $\rho h g = \mu\theta$, where ρ is the density at the base of the accreted matter, h is the height of the accretion column, g is the surface gravity, μ is the shear modulus, and θ is the shear angle of the crust. For neutron stars in low-mass x-ray binaries, θ should be $\sim 10^{-3}$ to explain the bimodal magnetic field distribution of binary pulsars (19). We expect that θ for strange stars in low-mass x-ray binaries is close to this value, because in both cases the stellar crust is replaced by accretion material. From (20), $\mu \approx 2.5 \times 10^{27}$ dyne cm^{-2}, and hence the column density of the accreted matter is $\sigma = \rho h \approx 1.0 \times 10^{10}\ \theta_{-3}$ g cm^{-2}, where $\theta_{-3} = \theta/10^{-3}$. The interval between crust-breaking events, τ_1, can be written as

$$\tau_1 \approx \frac{\sigma A_p}{\dot{M}} \approx 2.2 \times 10^3\ \theta_{-3}\ L_*^{-5/7}\ B_*^{-4/7}\ \mathrm{s} \tag{1}$$

where $\dot{M}$ is the mass accretion rate. As the luminosity attributable to accretion decreases or the magnetic field decays, τ_1 increases. This time scale is consistent with the typical observed intervals between the HXRBs. However, the accreted matter may diffuse away from the polar cap area A_p before it builds up enough pressure to break the crust. We can estimate the diffusion time of the accreted matter across the local surface magnetic field of the polar cap, B_s, which is assumed to be dominated by the multipole field component and is stronger than that of the dipolar field component. The transverse velocity resulting from collisional diffusion in the presence of a pressure gradient (∇P) is approximated by $v_d \sim 1.3 \times 10^2\ Z T_8^{-3/2} B_s^{-2}\ \nabla P$ cm s^{-1} (21), where $Z = 1$ hydrogen and T_8 is the matter temperature (in units of 10^8 K). In the present case, $\nabla P \sim \mu\theta/r_p$, so the diffusion velocity is

$$v_d \sim 2 \times 10^{-4}\ T_8^{-3/2} \times L_*^{-1/7}\ B_*^{2/7} \left(\frac{B_s}{10^{12}\ \mathrm{G}}\right)^{-2} \mathrm{cm\ s^{-1}} \tag{2}$$

Thus, the time scale for the accreted matter to diffuse over a length of ~ 1 km is at least 10^9 s, which is much longer than τ_1.

After the crust has been broken, the accreted matter will fall into the strange-matter core within ~ 1 ms. Two kinds of energy are subsequently released: (i) gravitational energy (~ 2 MeV per nucleon), because of the movement of the accreted matter from the stellar surface to the base of the crust, and (ii) deconfinement energy (~ 30 MeV per nucleon), because of the conversion of the accreted matter to more stable strange matter (22). The total released energy is $E_{\rm tot} \sim 5.5 \times 10^{40}\ \theta_{-3}\ L_*^{2/7} B_*^{-4/7}$ ergs. Because the total volume of the strange-matter blobs formed during the conversion of accreted matter is small ($\sim 10^6$ cm^3), most of $E_{\rm tot}$ will be radiated through photons from the surfaces of the blobs. However, a fraction of the radiation energy may be absorbed and then reradiated as neutrinos, which pass almost freely through the crust. Thus, it is expected that about half of the total released energy may be finally radiated in photons that form a fireball of volume $\sim A_p l$ (where l is close to the crustal thickness, $\sim 10^4$ cm). Assuming that ξ is the ratio of the fireball energy to the total released energy, we obtain the fireball energy

$$E_\gamma \sim 2.8 \times 10^{40}\ \xi_{1/2}\ \theta_{-3}\ L_*^{2/7}\ B_*^{-4/7}\ \mathrm{ergs} \tag{3}$$

where $\xi_{1/2} = 2\xi$. Let T_0 be the initial temperature of the fireball. By using the expression $^{11}\!/_4\ a T_0^4\ A_p l \sim E_\gamma$ (where $a = 7.6 \times 10^{-15}$ ergs cm^{-3} K^{-4} is a constant), we obtain

$$T_0 \sim 5.2 \times 10^9\ \xi_{1/2}^{1/4}\ \theta_{-3}^{1/4}\ \mathrm{K} \tag{4}$$

The fireball must be contaminated by baryons, and we can estimate the amount of contamination. The radiation-dominated outflow begins when the radiation energy density $u_\gamma = {}^{11}\!/_4\ a T_0^4$ is equal to the gravitational energy density $u_g = GM\rho/r$ (where G is the gravitational constant), or $\rho = 8.7 \times 10^5 [T_0/(10^{10}\ \mathrm{K})]^4$ g cm^{-3}. From (23), the column density for the radiation-dominated surface layer is given by $\sigma' \approx 3 \times 10^8\ \mu_e^{-1/3} [\rho/(10^6\ \mathrm{g\ cm^{-3}})]^{4/3}$ g cm^{-2}, where μ_e is the mean molecular weight per electron ($\mu_e = 1$ for hydrogen). Therefore, the amount of the baryons loaded with the fireball is approximated by

$$\Delta M \approx \sigma' A_p \sim 1.4 \times 10^{18} \times \xi_{1/2}^{4/3}\ \theta_{-3}^{4/3}\ L_*^{2/7}\ B_*^{-4/7}\ \mathrm{g} \tag{5}$$

Thus, the ratio of the initial fireball energy to the rest energy of the contaminating baryons is defined as

$$\eta \equiv \frac{E_\gamma}{\Delta M c^2} \sim 21 \xi_{1/2}^{-1/3}\ \theta_{-3}^{-1/3} \tag{6}$$

The fireball will expand outward because of the large optical depth of photon-electron scattering. Because $\Delta M/M_\odot > 1.7 \times 10^{-16} (E_\gamma/10^{41}\ \mathrm{ergs})$ (24), most of the initial fireball energy will be converted into the bulk kinetic energy of the baryons during the expansion. When the optical depth reaches a value of 1, therefore, the rest radiation energy becomes negligibly small. Fortunately, as suggested by Mészáros and Rees (25), the expanding shell (having a relativistic factor $\Gamma \sim \eta$) will interact with the surrounding medium, and its kinetic energy will be converted into the random energy of the shell by shock waves and finally radiated through nonthermal processes in these shock waves. The time scale for radiation is approximated by

$$\tau_2 \approx 0.1 E_{\gamma,40}^{1/3} (\Gamma/10^2)^{-8/3}\ n_0^{-1/3}\ \mathrm{s} \sim 9.0 \xi_{1/2}^{11/9}\ \theta_{-3}^{11/9}\ L_*^{2/21}\ B_*^{-4/21}\ n_0^{-1/3}\ \mathrm{s} \tag{7}$$

(25), where $E_{\gamma,40}$ is the fireball energy (in units of 10^{40} ergs) and n_0 is the interstellar density (~ 1 cm^{-3}). This time scale is consistent with the typical observed durations of the HXRBs.

Electrons can be accelerated by shock waves to high energy with the minimum Lorentz factor $\gamma_{\rm min} \sim (m_p/m_e)\Gamma$ (where m_p and m_e are the masses of the proton and electron, respectively), assuming that all particles behind the shock waves have the same energy. If the shock waves can produce approximate equipartition between the magnetic field energy density and the particle energy density, then the strength of the magnetic field is $B \simeq 0.3 \Gamma n_0^{1/2}$ G (25).

The typical synchrotron photon energy ε_p emitted by electrons with the Lorentz factor γ_{min} at the observer's frame is

$$\varepsilon_p \simeq 1\xi_{1/2}^{-4/3}\,\theta_{-3}^{-4/3}\,n_0^{1/2}\ \mathrm{KeV} \quad (8)$$

The diffusion shock wave acceleration can produce a power-law electron spectrum, $dN_e/d\gamma \sim \gamma^{-p}$, $\gamma_{min} \leq \gamma \leq \gamma_{max}$, where N_e is the electron number and the spectral index p is typically between 2 and 3 (*26*). For photon energies greater than ε_p, the synchrotron radiation for electrons with such a distribution has a spectrum with a power-law form and a photon index of $\alpha = -(p + 1)/2$ (*27*). Hence, the theoretical value of α may be in the range –1.5 to –2.0. This result is consistent with observations by the Oriented Scintillation Spectrometer Experiment (OSSE) (*28*) and by RXTE (*7*), which gave $\alpha = -(2.0 \pm 0.6)$ and $\alpha \sim -1.3$, respectively.

The bursting spectrum for our radiation model is similar to the spectrum of the persistent emission observed in (*7*, *28*). Theoretically, the radiation processes at the surface near a magnetic pole of the accreting strange star are complicated, and these processes are beyond the scope of this report. Some models of the radiation processes of an accreting neutron star with a rather strong magnetic field may give power-law spectra with an index near –1.5 (*29*). In addition, the spectrum does not evolve during the bursting period, because the spectral index for the electron distribution behind the shock wave during the shell's expansion is unlikely to change (*30*).

We can estimate the recovery time scale as follows. When a burst occurs, the huge radiation pressure will push the accreted matter outward over a distance $\Delta r \sim (E_\gamma R_A v_r)/(LR_{pulsar})$, where L is the accretion luminosity and v_r is the radial velocity of the accreted matter. After a burst, the accreted matter will fall back toward the strange star over a time $\tau_3 \sim \Delta r/v_r \sim 2.4 \times 10^3\, \xi_{1/2}\, \theta_{-3}\, L_*^{-1}$ s, which is consistent with the typical observed recovery time scale (*7*).

We can compare other characteristics determined from Eqs. 1, 3, and 7 with the observations. First, the RXTE observations on GRO J1744-28 between 29 January and 26 April 1996 (*7*) indicate that the data for the nonbursting flux from this source can be approximately fitted with the straight-line flux (measured in units of 10^{-3} of the flux from the Crab Nebula) = 2703.3 – 23.0D, where D is the day number in 1996. If this expression can be extrapolated to December 1995, the ratio of the persistent flux on 5 December 1995 to the persistent flux on 30 January 1996 is ~1.6. Because the interval time scale is proportional to $L_*^{-5/7}$ (Eq. 1), the ratio of the typical interval time scale for the HXRBs on 30 January 1996 to that on 5 December 1995 is ~1.4. The observations from RXTE on 30 January 1996 (*7*) and BATSE on 5 December 1995 (*2*) showed that this ratio is ~1.38. Therefore, Eq. 1 is consistent with the observations. Second, for our model, the bursting flux is obtained by dividing Eq. 3 by Eq. 7, and this flux is proportional to $L_*^{4/21}$. This means that the bursting flux is weakly dependent on the persistent flux, in agreement with the observations from BATSE (*2*, *8*) and OSSE (*28*).

The surface radiation in the crust-breaking region during the bursts should show pulsations whose amplitude is close to that of pulsations during the nonbursting periods. This model agrees with the observations from OSSE (*28*) and RXTE (*31*). However, the RXTE results indicate that the bursting flux seems approximately linearly proportional to the persistent flux (*32*, *33*). On the other hand, accretion instability models indicate that during this instability, a great deal of matter falls onto the surface near a magnetic pole of the pulsar, and subsequently a large amount of gravitational energy is released and an HXRB is formed. If this is correct, pulsations during the bursts should be detected whose amplitude is much larger than that of pulsations during the nonbursting periods.

A similar strange star model was recently proposed to explain the soft γ-ray repeaters (*34*). There are several key differences between the soft γ-ray repeater model and our model: (i) The crust cracking of the soft γ-ray repeater model results from the spindown of the strange star instead of accretion. (ii) The amounts of energy released from these two mechanisms differ by two orders of magnitude. (iii) The strengths of the dipolar magnetic fields in these two kinds of sources also differ by two orders of magnitude. (iv) The time scales of energy release are different by at least one order of magnitude. These differences make the magnetic energy density of the soft γ-ray repeaters stronger than the radiation energy density, and therefore the fireball mechanism cannot be developed.

REFERENCES AND NOTES

1. G. Fishman *et al.*, *IAU Circ. 6272* (1995). The Physics and Astronomy Classification Scheme (PACS) numbers for GRO J1744-28 are 97.80Jp, 13.38Mh, 95.30Gv, and 97.60Gb.
2. C. Kouveliotou *et al.*, *Nature* **379**, 799 (1996).
3. M. H. Finger *et al.*, *ibid.* **381**, 291 (1996).
4. P. Daumerie, V. Kalogera, F. K. Lamb, D. Psaltis, *ibid.* **382**, 141 (1996).
5. S. J. Sturner and C. D. Dermer, *Astrophys. J.* **465**, L31 (1996).
6. P. Ghosh and F. K. Lamb, *ibid.* **234**, 296 (1979).
7. A. B. Giles *et al.*, *ibid.* **469**, L25 (1996).
8. X-ray bursts are sudden increases in the x-ray flux of x-ray sources, with rise times of ≤1 s, and subsequent decay with characteristic times ranging from 10 s to a few minutes. They are classified as type I or type II. Type I x-ray bursts are characterized by the relatively long burst intervals (hours to days) and the significant spectral softening during the burst decay relative to their type II counterparts. The differences between type I (and type II) bursts and the HXRBs are discussed by W. H. G. Lewin, R. E. Rutledge, J. M. Kommers, J. van Paradijs, C. Kouveliotou, *Astrophys. J.* **462**, L39 (1996).
9. J. K. Cannizzo, *ibid.* **466**, L31 (1996).
10. Pure hadronic matter can exist inside compact stars, for example, neutron stars in which most stellar masses are in the form of free protons and neutrons. In conditions of extremely high density, the smaller constituents (quarks) inside the protons and neutrons are no longer confined and a new phase of matter (that is, quark matter) can occur. For discussions of the possibility of such a phase of matter in compact stars, see A. R. Bodmer, *Phys. Rev. D* **4**, 1601 (1971); E. Witten, *ibid.* **30**, 272 (1984).
11. R. L. Jaffe and E. Farhi, *ibid.*, p. 2379.
12. C. Alcock, E. Farhi, A. Olinto, *Astrophys. J.* **310**, 261 (1986); P. Haensel, J. L. Zdunik, R. Schaeffer, *Astron. Astrophys.* **160**, 121 (1986); N. K. Glendenning and F. Weber, *Astrophys. J.* **400**, 647 (1992).
13. Glitches refer to the sudden spin-up of pulsars. Generally, the new rotation curve will relax back to the original spin-down curve. Such a process is called postglitch relaxation. For a discussion of the physical mechanism of postglitch relaxation, see D. Pines and M. A. Alpar, *Nature* **316**, 27 (1985).
14. G. Baym, in *Neutron Stars: Theory and Observation*, J. Ventura and D. Pines, Eds. (Kluwer, Dordrecht, Netherlands, 1991), pp. 21–36.
15. K. S. Cheng and Z. G. Dai, *Phys. Rev. Lett.* **77**, 1210 (1996).
16. N. K. Glendenning, *Nucl. Phys. B (Proc. Suppl.)* **24**, 110 (1991); *Phys. Rev. D* **46**, 1274 (1992); H. Heiselberg, C. J. Pethick, E. F. Staubo, *Phys. Rev. Lett.* **70**, 1355 (1993); V. R. Pandharipande and E. F. Staubo, in *Proceedings of the 2nd International Conference on Physics and Astrophysics of Quark-Gluon Plasma,* B. Sinha, Y. P. Viyogi, S. Raha, Eds. (World Scientific, Singapore, 1994), pp. 56–69.
17. M. Prakash, J. R. Cooke, J. M. Lattimer, *Phys. Rev. D* **52**, 661 (1995).
18. R. R. Caldwell and J. L. Friedman, *Phys. Lett. B* **264**, 143 (1991); W. Kluzniak, *Astron. Astrophys.* **286**, L17 (1994).
19. K. S. Cheng and Z. G. Dai, *Astrophys. J.* **476**, L39 (1997).
20. G. Baym and D. Pines, *Ann. Phys.* **66**, 816 (1971).
21. L. Spitzer, *Physics of Fully Ionized Gases* (Interscience, New York, ed. 2, 1962), p. 42.
22. G. Baym, E. W. Kolb, L. McLerran, T. P. Walker, J. L. Jaffe, *Phys. Lett. B* **160**, 181 (1985).
23. P. Mészáros and M. Rees, *Astrophys. J.* **397**, 570 (1992).
24. A. Shemi and T. Piran, *ibid.* **365**, L55 (1990).
25. P. Mészáros and M. Rees, *ibid.* **405**, 278 (1993).
26. R. Blandford and D. Eichler, *Phys. Rep.* **154**, 1 (1987).
27. K. S. Cheng and D. M. Wei, *Mon. Not. R. Astron. Soc.* **283**, L133 (1996).
28. M. S. Strickman *et al.*, *Astrophys. J.* **464**, L131 (1996).
29. P. Mészáros, *High Energy Radiation from Magnetized Neutron Stars* (Univ. of Chicago Press, Chicago, 1992).
30. E. Waxman, *Astrophys. J.* **491**, L19 (1997); *ibid.* **485**, L5 (1997); *ibid.* **489**, L33 (1997).
31. M. J. Stark, A. Baykai, T. Strohmayer, J. J. H. Swank, *ibid.* **470**, L109 (1996).
32. K. Jahoda, M. J. Stark, T. E. Strohmayer, W. Zhang, paper presented at the symposium "The Active X-ray Sky," Rome, 1997.
33. For a detailed discussion of the discrepancies between experimental results and model predictions, see K. S. Cheng, Z. G. Dai, T. Lu, *Int. J. Mod. Phys. D.*, in press.
34. K. S. Cheng and Z. G. Dai, *Phys. Rev. Lett.* **80**, 18 (1998).

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