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LETTER

Letter to the Editor

On the persistent X-ray emission from the soft γ-ray repeaters

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Abstract. It is suggested that the persistent X-ray emission from the soft γ-ray repeaters is the thermal radiation of neutron stars which is enhanced by a factor of 10 or more due to the effect of a very strong magnetic field on the thermal structure of the neutron star envelope. For the thermal luminosity to be consistent with the persistent X-ray luminosity, the field strength at the neutron star surface has to be of the order of 10^{15} G. If it is confirmed that the soft γ-ray repeaters are neutron stars with negligible accretion, then the presence of such a strong magnetic field is inevitable.

Key words: gamma-rays: bursters - stars: neutron - magnetic fields - radiation mechanisms: thermal

1. Introduction

The soft γ-ray repeaters (SGRs) are a small, enigmatic class of γ-ray transient sources (Norris et al. 1991). There are three known SGRs: 0526-66, 1806-20 and 1900+14. All these repeaters have been associated with young supernova remnants. The first, SGR 0525-66, which is the source of the well-known 1979 March 5 burst, is associated with the N49 supernova remnant (SNR) in the Large Magellanic Cloud (Cline et al. 1982). The second, SGR 1806-20, is located toward the Galactic Center, and is associated with SNR G10.0-0.3 (Kulkarni et al. 1994). The age of both N49 and G10.0-0.3 is about 5×10^3 yr. The third, SGR 1900+14, is associated with SNR G42.8+0.6, and its age is $\sim 10^4$ yr (Vasisht et al.1994). The positions of SGRs are offset from the centers of their SNRs. This implies a very high velocity, up to $\sim$ 1200 km s^{-1} or even more, for SGRs. Accepting these SGR - SNR associations, the corresponding burst peak luminosities were estimated. If the burst radiation is more or less unbeamed, these luminosities are a few orders higher than the standard Eddington value for a star with the mass of $M_\odot$. For example, SGR 1806-20 has produced events that are $\sim 10^4$ times the Eddington luminosity (Fenimore, Laros & Ulmer 1994). The durations of these events range between 0.1 s and 200 s. In addition to short bursts of both hard X-rays and soft γ-rays, the persistent X-ray emission was detected from SGRs as well. (Rothschild, Kulkarni & Lingenfelter 1994; Murakami et al.1994; Visisht et al. 1994; Hurley et al. 1996). The luminosity of the persistent X-ray sources is $\sim 7 \times 10^{35}$ erg s^{-1} for SGR 0525-66, $\sim 3 \times 10^{35}$ erg s^{-1} for SGR 1806-20, and $\sim 10^{35}$ erg s^{-1} for SGR 1900+14. In combination, these results support the preposition that SGRs can be firmly identified as neutron stars. High velocities of SGRs imply that the neutron stars are single. It was argued (Usov 1984; Duncan & Thompson 1992; Paczyński 1992; Thompson & Duncan 1993, 1995; Podsiadlowski, Rees & Ruderman 1995) that not very young, single neutron stars may be a source of strong bursts of high-frequency, hard X-ray and γ-ray emission only if their magnetic fields are very high, $B \sim 10^{14}$ G or more (maybe, up to $\sim 10^{16}$ G).

Calculations for the cooling of neutron stars predict (e.g., Nomoto & Tsuruta 1987) that after $(0.5-1) \times 10^4$ yr the bolometric luminosities will be at least an order less than the X-ray luminosities of the persistent X-ray sources which are identified with SGRs. At first sight, a source of heating, such as accretion of gas, is necessary to account for the higher thermal luminosities (e.g., Rothschild et al. 1994). But this is not always a prerequisite. In this letter, it is argued that a very strong magnetic field, $\sim 10^{14} - 10^{16}$ G, can influence the physical conditions in the surface layers of SGRs so that the thermal luminosities of the neutron stars may increase up to observed luminosities of the persistent X-ray sources.

2. Surface structure

The structure of matter in the surface layers of neutron stars with the surface field $B \gg \alpha^2 B_{\rm cr} \simeq 2.35 \times 10^9$ G is largely determined by the magnetic field, where $\alpha = e^2/\hbar c = 1/137$ is the the fine structure constant and $B_{\rm cr} = m^2c^2/e\hbar \simeq 4.4 \times 10^{13}$ G (Ruderman 1971; Flowers et al. 1977; Fushiki, Gudmundsson and Pethick 1989; Abrahams & Shapiro 1991; Rögnvaldsson et

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al. 1993). It has been suggested that the surface of neutron stars with such a strong magnetic field consists of magnetic metal in which atoms form chains aligned along the field lines (Chen, Ruderman & Sutherland 1974).

The strength of a magnetic field on an atom of atomic number Z is characterized by the following dimensionless parameter (Ruderman 1971):

$$\eta = \left(\frac{B}{2\alpha^2 B_{\rm cr} Z^3}\right)^{1/2} = \left(\frac{B}{4.7 \times 10^9 Z^3\,{\rm G}}\right)^{1/2} . \qquad (1)$$

In the case of very strong magnetic fields, $\eta \gg 1$, as it is applied to SGRs, some simplifying assumptions can be made about the electronic structure of atoms and condensed matter. In this case, the *adiabatic approximation* is valid: the magnetic field completely determines the transverse electron motion. This motion is quantized into Landau levels, and only the lowest Landau level is populated (this assumes temperatures such that $kT \ll \Delta\varepsilon_{01}$, where $\Delta\varepsilon_{01} = mc^2[\sqrt{1+(2B/B_{\rm cr})} - 1]$ is the energy difference between the first excited Landau level and the lowest one).

The surface of a neutron star with a very strong magnetic field, $\eta \gg 1$, is probably a magnetic metal, provided that the surface temperature is smaller than the melting temperature (Usov & Melrose 1995 and references therein). The density of the magnetic metal phase is insensitive to the atomic geometry. At the neutron star surface, this density is (Flowers et al. 1977)

$$\rho_{\rm s}(B) \simeq 4 \times 10^3 \left(\frac{A}{56}\right)\left(\frac{Z}{26}\right)^{-3/5}\left(\frac{B}{10^{12}\,{\rm G}}\right)^{6/5} {\rm g\,cm^{-3}}, \quad (2)$$

where A is the mass number of atoms.

The composition of the neutron star surface is uncertain and depends on the star's history. If the neutron star has never accreted matter onto its surface, it is natural to expect that the neutron star surface consists almost entirely of ^{56}Fe, $A = 56$ and $Z = 26$ (e.g., Usov & Melrose 1995). In this case, the surface field is very strong, $\eta \gg 1$, when its strength is much higher than 8×10^{13} G.

For intermediate magnetic fields, $Z^{-3/2} \ll \eta \ll 1$, the qualitative result of Cheng et al. (1974), that chains are energetically favoured over individual atoms, is questionable. The calculations of Neuhause, Koonin & Langanke (1987) indicate that at $B \lesssim 10^{13}$ G free atoms of ^{56}Fe are preferred over chains, and iron does not form a magnetic metal (however, see Abrahams & Shapiro 1991). In this case, the stellar surface is usually identified with the base of the photosphere which is at an optical depth $\tau = \frac{2}{3}$. The photon spectrum mainly forms at this depth. Strong magnetic fields significantly influence the transport properties of neutron-star atmospheres (e.g., Hernquist 1985). For example, such a field can strongly reduce the opacity. As a result, at $B \gg \alpha^2 B_{\rm cr}$ the surface density found by the radiative boundary condition, $\tau = \frac{2}{3}$, increases many orders because of the effect of a strong magnetic field (e.g., Van Riper 1988). Hence, the density $\rho_{\rm s}(B)$ at the surface of neutron stars with strong magnetic fields is much higher than the surface density $\rho_{\rm s}(B = 0) \sim 0.1 - 0.01$ g cm^{-3} in the zero-field case regardless of formation of the magnetic metal phase.

All mentioned studies of iron matter in the field $B \gg \alpha^2 B_{\rm cr}$ were based on nonrelativistic quantum mechanics. For $B \gtrsim B_{\rm cr}$, the transverse motion of electrons becomes relativistic. However, as noted earlier, in very strong magnetic fields, $\eta \gg 1$, the motion of electrons perpendicular to the field is frozen into the lowest Landau level, which is rather insensitive to relativistic corrections. These corrections to the matter parameters are small at $B > B_{\rm cr}$ as long as the electron motion remains nonrelativistic along the field direction (Angelie & Deutsch 1978; Lai & Salpeter 1995). In the instance of condensed iron matter, the electron motion along the field may be roughly considered as nonrelativistic at least up to the field strengths of a few $\times 10^{15}$ G (Glasser & Kaplan 1975).

3. Thermal luminosity

If neutron stars are not too young (age $t \gtrsim 10^2$ yr), for consideration of the thermal structure and photon radiation, it is convenient to divide the stellar interior into two regions: the isothermal core with density $\rho > \rho_e$ and the outer envelope with $\rho < \rho_e$, where $\rho_e \sim 10^{10}$ g cm^{-3} (Gudmundsson, Pethick & Epstein 1983). At $t \simeq (0.5 - 1) \times 10^4$ yr, for a typical neutron star [$M \simeq 1.4 M_\odot$, $R \simeq 1.6 \times 10^6$ cm, and the bulk of neutrons in the core is superfluid] with $B = 0$ at the surface *standard* cooling calculations yield that the temperature decreases by a factor of 2×10^2 in the envelope, from $T_c \simeq 4 \times 10^8$ K at the inner boundary of the envelope to $T_{\rm s} \simeq 2 \times 10^6$ K at the neutron star surface (Nomoto & Tsuruta 1987). (By *standard* cooling we mean cooling without such exotic particles as charged pion condensates and quarks which might prove to be very fast cooling agents.) In this case the expected photon luminosity is $L_{\rm ph}(B = 0) \simeq 10^{34}$ erg s^{-1} within a factor 2 or so.

At $B \gg \alpha^2 B_{\rm cr}$ the surface density increases in comparison with $\rho_{\rm s}(B = 0)$. Besides, the effect of quantization of electron orbits increases the longitudinal thermal conductivity of degenerate electrons. Both these effects may result in an increase of the surface temperature (and the photon luminosity) when the neutron star is not too old ($t < 3 \times 10^5$ yr) and cools mainly via neutrino emission from the stellar interior (e.g., Van Riper 1988, 1991; Shibanov & Yakovlev 1996).

The effect of a strong magnetic field on neutron-star cooling has been considered by a number of authors (e.g., Tsuruta 1979; Van Riper & Lamb 1981; Yakovlev & Urpin 1981; Nomoto & Tsuruta 1987; Schaaf 1990; Page 1995; Shibanov & Yakovlev 1996). According to early calculations of Tsuruta (1979), Van Riper & Lamb (1981), Yakovlev & Urpin (1981) and others, the magnetic field effect can be quite significant even if the field strength is not very high, $B \lesssim B_{\rm cr}$. For example, at the core temperature $T_c = 10^8$ K the predicted enhancements in the flux of radiation (which are the same as the luminosity enhancement) are factors ~ 10 for $B \simeq 0.1 B_{\rm cr}$ and $\sim 10^2$ for $B \simeq B_{\rm cr}$. However, the effect of strong magnetic fields has been overestimated in these calculations (Hernquist 1985). This is because the thermal conductivities which have been used are not accurate, and the tensor nature of the photon transport has been ignored. Besides, all early calculations have been performed under the simplified assumption that the magnetic field is radial everywhere over the stellar surface. Using more realistic heat-transport coefficients it was shown that for a fixed core temperature and a purely radial field of $B \sim 0.1B_{\rm cr}$ the effects of strong magnetic fields increase the heat flux (relative to the zero-field case) by a factor $\lesssim 3$. In turn, at $B \gtrsim 10^{12}$ G the electron thermal conductivity across the field is strongly suppressed, and for a realistic field geometry the mean heat flux is reduced by a factor $2-3$. Thus, it was concluded that at the neutrino cooling stage of neutron stars with intermediate magnetic fields, $B \sim 0.1B_{\rm cr}$, the enhancement in the heat flux due to the magnetic field effects will be approximately cancelled by the suppression of the heat flux due to the overall field geometry (Hernquist 1985). This is reasonably congruent with the *standard* cooling calculations of Shibanov & Yakovlev (1996) for a typical neutron star with a dipole magnetic field. At $t \simeq (0.5-1) \times 10^4$ yr, the enhancement in the photon luminosity (relative to the zero-field case) is a factor ~ 2 for $B = 10^{13.5}$ G, $L_{\rm ph}(B = 10^{13.5}\ {\rm G}) \simeq 2L_{\rm ph}(B = 0)$ (Shibanov & Yakovlev 1996). When the strength of the surface magnetic field changes from $B = 10^{13.5}$ G to $B = 10^{14}$ G, the surface temperature changes by a factor ~ 1.2 (Van Riper 1988). Hence, at $t \simeq (0.5-1) \times 10^4$ yr and $B = 10^{14}$ G the expected enhancement in the photon luminosity is a factor ~ 4, $L_{\rm ph}(B = 10^{14}\ {\rm G}) \simeq 4L_{\rm ph}(B = 0)$. The enhancement in the photon luminosity is more or less the same irrespective of whether the formation of magnetic metal is at the neutron star surface or not (Van Riper 1988).

In all available numerical calculations the thermal structure of magnetized neutron stars were studied for $B \leq 10^{14}$ G. However, the input physics for such calculations does not qualitatively change up to the field strengths of $B \simeq$ a few $\times 10^{15}$ G. Therefore, the tendency of the photon luminosity to increase with increase of B has to be held at least up to $B \simeq$ a few $\times 10^{15}$ G. The maximum photon luminosity, $L_{\rm ph}^{\rm max}(t)$, of a magnetized neutron star with the age t may be estimated in the following way. As noted earlier, the photon luminosity can be enhanced by the effect of strong magnetic fields only at the neutrino cooling stage. At this stage, for a typical neutron star with the *standard* neutrino energy losses, the neutrino luminosity is (Nomoto & Tsuruta 1987)

$$L_\nu(t) \simeq 10^{36} \left(\frac{t}{5 \times 10^3\ {\rm yr}} \right)^{-4/3} \ {\rm erg\,s^{-1}}\,. \qquad (3)$$

The photon luminosity may be enhanced by the field effect up to the neutrino luminosity, i.e., $L_{\rm ph}^{\rm max}(t) \simeq L_\nu(t)$. This may be done because the enhancement in the photon luminosity may be, in principle, as high as a factor $\sim (T_c/T_{\rm s})^4 \sim 10^8$. For all SGRs, $L_{\rm ph}^{\rm max}(t)$ is more than the observed luminosities of the persistent X-ray sources. Let us estimate the minimum photon luminosity of a magnetized neutron star at the neutrino cooling stage.

From the calculations of Van Riper (1988) it follows that the temperature change, $T_c/T_{\rm s}$, through the envelope is strongly reduced at $T_{\rm s} < T_0$, where

$$T_0 \simeq 2.2 \times 10^5 \left(\frac{B}{10^{12}\ {\rm G}} \right)^{1/3} \ {\rm K}\,. \qquad (4)$$

At the neutrino cooling stage, $T_{\rm s}$ cannot be essentially smaller than T_0. Indeed, at this stage the core temperature does not depend on $T_{\rm s}$ (e.g., Nomoto & Tsuruta 1987). If, in the process of the neutron star cooling, the surface temperature $T_{\rm s}$ becomes smaller than T_0, the ratio $T_c/T_{\rm s}$ has to be strongly reduced. However, it is possible only if T_c is strongly reduced too. In turn, such a reduction of T_c is possible only at the photon cooling stage. Hence, for a typical neutron star with the field B at the surface the photon luminosity at the neutrino cooling stage cannot be essentially smaller than

$$L_{\rm ph}^{\rm min} \simeq 4\pi R^2 \sigma T_0^4 \simeq 3 \times 10^{35} \left(\frac{B}{4 \times 10^{15}\ {\rm G}} \right)^{4/3} \ {\rm erg\,s^{-1}}, \quad (5)$$

where σ is the Stefan-Boltzmann constant. Certainly, this estimate may be used only if $L_{\rm ph}^{\rm min} < L_\nu$.

4. Conclusions and discussion

It is suggested in this letter that the persistent X-ray emission from SGRs is the thermal radiation of neutron stars which is enhanced by the effects of a very strong magnetic field on the thermal structure of the neutron star envelope. Since for a nonmagnetic neutron star at $t \simeq (0.5-1) \times 10^4$ yr we have $L_{\rm ph}(B = 0) \lesssim 2 \times 10^{34}$ erg s^{-1}, the field $B = 10^{14}$ G, for which the expected enhancement in the photon luminosity is a factor ~ 4, is a firm lower limit on the field strength at the surface of SGRs. The enhanced luminosity in thermal X-rays may be as high as the neutrino luminosity. At $t \simeq (0.5-1) \times 10^4$ yr, for a typical neutron star the neutrino luminosity obtained from the *standard* cooling theory is more than the persistent X-ray luminosities of SGRs. If our extrapolation of a strong decrease of the temperature change, $T_c/T_{\rm s}$, through the envelope at $T_{\rm s} < T_0$ into the region of very strong magnetic fields, $\sim 10^{14} - 10^{16}$ G, is correct, we have the following upper limit on B: $B \lesssim 7 \times 10^{15}$ G (see, equation (5)). Hence, the strength of the field at the surface of SGRs is somewhere between a few $\times 10^{14}$ G and a few $\times 10^{15}$ G. This is consistent with the estimates of Thompson & Duncan (1995) for the magnetic field at the surface of SGRs.

Some effects are ignored in our consideration. One of them is the effect of strong magnetic fields on the energy losses via neutrino emission from the core of the neutron stars, which may be essential at $B \gtrsim 10^{15}$ G (Cheng, Schramm & Truran 1993). Another is the magnetic field decay. The field strength required to power the persistent X-ray emission for $\sim 10^4$ yr is $\sim 10^{15}$ G or more (Thompson & Duncan 1995). If accretion onto the neutron stars is negligible, both the thermal energy and the magnetic field energy could be a source of energy for the persistent X-ray emission. In both these cases the field strength has to be $B \gtrsim 10^{15}$ G.

The presence of *exotic* particles such as a pion condensate in the core of neutron stars can result in extremely rapid cooling (e.g., Richardson 1982). For such *nonstandard* rapid cooling, at $t \simeq (0.5 - 1) \times 10^4$ yr the expected neutrino luminosity is many orders smaller than L_ν given by equation (3), that excludes the thermal radiation from the neutron star surface as a source of the persistent X-ray emission from SGRs.

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