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The intriguing thermal emission of isolated neutron stars

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Abstract. The X-ray spectral energy distribution of isolated neutron stars shows no evidence of atmospheric spectral features due to atomic transitions. This unexpected lack of spectral lines, together with the systematic optical excess (with respect to the X-ray best fit extrapolation) observed in several objects, is one of the current paradigms in the theoretical understanding of neutron stars. We investigate the thermal emission from neutron star surfaces in which the cohesive effects of a strong magnetic field have produced the condensation of the atmosphere and the external layers. This may happen for sufficiently cool ($T \leq 10^6$) atmospheres with moderately intense magnetic fields (about 10^{13} G for Fe atmospheres). The thermal emission from such a *bare surface* shows no remarkable spectral features. In addition, since the thermal conductivity is very different in the perpendicular and parallel directions to the magnetic field lines, the presence of the magnetic field is expected to produce a highly anisotropic temperature distribution at the surface of the star, depending on the magnetic field geometry. The observed flux from this objects looks very similar to a blackbody spectrum, but depressed by a nearly constant factor at all energies. More interestingly, if one takes into account the effect of the motion of ions in a crude approximation, combined with the anisotropic thermal distribution, it results in an apparent optical excess. Both facts seem to indicate that some isolated neutron stars are old, cold magnetars.

Key words. stars: neutron - stars: X-ray sources: thermal radiation

1. Introduction

Neutron stars with large magnetic fields ($B \geq 10^{13}$ G), the so-called magnetars, are becoming more and more abundant as new observations reveal phenomena that can only be explained by the action of strong magnetic fields. It is now believed that the small population (4 objects) of soft gamma repeaters (SGRs) are young neutron stars with magnetic fields in the range $\approx 10^{14} - 10^{15}$ G. Another subclass of candidates to be magnetars are the anomalous X–ray pulsars (AXPs), whose high X–ray luminosities and fast spindown rates make them different from isolated radio pulsars or NS in accreting X-ray binaries. The six members of this family (Tiengo et al. 2005; McGarry et al. 2005) exhibit a small range of spin periods (5-12 s), and inferred magnetic fields (from their period derivative) in the same range as SGRs.

A third rare family of NS, the radio-quiet isolated neutron stars share some common features with the standard magnetars (SGRs and AXPs). Almost a decade after the discovery

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Table 1. Properties of isolated neutron stars observed by ROSAT, Chandra, and XMM-Newton (Haberl 2004, 2005; Zane et al. 2005): effective temperature (kT), period (P), period derivative ($\dot{P}$), estimated age (τ), optical/IR magnitude, optical excess flux (with respect to the best X-ray, blackbody fit extrapolation), magnetic field estimation (B_{db}) according to dipole breaking, and magnetic field (B_{cyc}) assuming that reported absorption features correspond to proton cyclotron lines.

Source	kT (eV)	P (s)	$\dot{P}$ 10^{-12} (s s^{-1})	τ 10^6yr	Opt.	Opt. excess	B_{db} 10^{13} G	B_{cyc} 10^{13} G
RX J0420.0−5022	45	3.453	< 9		B= 26.6	< 12	< 18	6.6
RX J0720.4−3125	85	8.391	0.1 – 0.2	0.6-1.5	B= 26.6	5	2.8-4.2	5.2
RX J0806.4−4123	96	11.371	< 2		B> 24		< 14	?
RBS1223	95	10.313	< 6		m_{50ccd} = 28.6	< 5	?	2-6
RX J1605.3+3249	95	–	–		B= 27.2	14	?	9.1-9.7
RX J1856.4−3754	63	–	–	0.5	V= 25.7	5-7	1?	
RBS1774	101	9.437	–		R> 23		?	14

of the first member of the family, the soft X-ray source RXJ185635-3754 (Walter, Wolk, & Neuhäuser 1996), the thermal component associated with the direct emission from a neutron star's surface has been detected in more than 20 X-ray sources. In many cases it is superimposed on a power–law tail, but seven of these objects are well–characterized as simple blackbodies with temperatures ranging between 60 and 100 eV. Using the Hubble Space Telescope, Walter & Matthews (1997) subsequently identified an optical source at 6060 Å and 3000 Å, with a brightness about 7 times brighter than an extrapolation of a 62 eV X-ray blackbody into the optical V band. Remarkably, the other three isolated compact X-ray sources that have been detected in the optical band (RX J0720.4-3125, RX J1308.6+2127, and RX J1605.3+3249) also have a significant optical excess over the extrapolation of the X-ray blackbody (a factor 5 to 14). None of them have yet been detected as 1.4 GHz radio sources. Thus, RXJ185635-3754 is not an uncommon object, for it shares the same general observational properties of other isolated neutron stars (blackbody spectrum in X-ray, no evident spectral features, optical excess), except for the fact that four of them have pulsating X-ray signals with fairly long periods (8-22 s), while RXJ185635-3754 is not variable, with a reported upper limit on the pulse amplitude of < 1.3% (Burwitz et al. 2003).

It must be mentioned that, although the broadband spectrum is well reproduced by a simple blackbody spectrum, some broad absorption features (broader than atomic spectral lines predicted by heavy element atmospheric models) have been reported. Their origin is unclear, but they have been sometimes interpreted as proton cyclotron resonances (Zane et al. 2005), which, if confirmed, permits to infer the magnetic field strength. In Table 1 we summarize the properties of known isolated neutron stars.

2. The metallic surface model

Having established that there is increasing evidence of the existence of neutron stars with strong magnetic fields, a natural alternative to standard atmospheric models that explains the absence of spectral features is the emission from a solid surface. This was a common idea 20-30 years ago (Ruderman 1971; Brinkmann 1980) until the existence of a thin gaseous atmosphere was appreciated and model atmospheres became more popular. However, at sufficiently low temperatures, highly magnetized neutron stars may undergo a phase transition that turns the gaseous atmosphere into a solid (Ruderman 1971; Lai 2001). The critical temperature below which the atmosphere condensates depends on the composition and the magnetic field. For example, for typical magnetic field strengths of 10^{13} G, a Fe atmosphere will condensate for $T < 100$ eV while a H atmosphere needs temperatures lower than 30 eV to undergo the phase transition to the *metallic* state (Lai 2001). Notice that effective temperatures of the observed isolated neutron stars fall in this temperature range, therefore they should plausibly be in the solid state if the dominant element in the atmosphere is Fe. In such a metallic neutron star surface made of nuclei with atomic number Z and atomic weight A, the pressure vanishes at a finite density

$$\rho_s \approx 560\, A Z^{-3/5} B_{12}^{6/5}\, \mathrm{g\,cm^{-3}} \tag{1}$$

The two main features of the *metallic surface* model are, first, an almost featureless spectrum, and second, an overall flux smaller than that of a BB at the same temperature, especially at low energies (Pérez–Azorín, Miralles & Pons 2005a). However, the fact that the condensed surface is strongly magnetized makes the thermal conductivity very different in the directions perpendicular and parallel to the magnetic field lines. Similar effects have been pointed out to be relevant in the envelope (Greenstein & Hartke 1983; Page 1995) or in the crust, where a very recent study (Geppert, Küker, & Page 2004) finds that the anisotropy in the temperature distribution depends very strongly on the particular geometry of the internal magnetic field, resulting in variations of temperature of up to a factor 5. In a recent work (Pérez–Azorín, Miralles & Pons 2005b), we report results from a detailed study of the temperature distribution obtained from 2D diffusion calculations for different magnetic field geometries. For the purpose of understanding qualitatively the effects on the observed spectrum, in this paper we will limit our analysis to the case in which the temperature distribution has the following angular dependence

$$T = T_p \left[\cos^2\theta_B + \chi \sin^2\theta_B\right]^{1/4}, \tag{2}$$

where θ_B is the angle between the field and the radial direction, χ is the ratio between the thermal conductivities normal and parallel to the magnetic field, and T_p is the polar temperature (where $\theta_B = 0$). The origin of this distribution has been discussed in previous works on neutron star envelopes (Greenstein & Hartke 1983; Page 1995). Note that for a dipolar magnetic field χ is a function of the polar angle because the magnetic field strength varies with the latitude.

In Fig 1 we plot the observed flux (dashes) from a model with a polar magnetic field of $B_p = 5 \times 10^{13}$, and the anisotropic temperature distribution given by Eq. (2) with $T_p = 10^6$. The symmetry axis of the magnetic field forms and angle of $\theta_o = 90°$ with the observer, and we have taken into account interstellar medium absorption with $n_H = 1.4 \times 10^{20}$ cm^{-2}. This model is compared with a uniform temperature, blackbody model that fits the X-ray part of the spectrum (solid line). The parameters of the BB model are: $T = 10^6$ K, $n_H = 1.3 \times 10^{20}$ cm^{-2}, and a relative normalization factor of $1/5$. Therefore, the apparent estimated value of the R_∞/d is 2.23 times lower than that of the "real" model, despite the X–ray spectrum being very similar.

When the effect of the motion of ions (considered as free particles) is included (dotted line) the observed flux in the optical changes significantly. Notice that the optical flux of this model is a factor 3 larger than the BB fit prediction, similarly to what has been observed in isolated neutron stars. Nevertheless, it must be stressed that this is just a crude approximation, with no pretension of being the real answer to the observed optical excess, but it serves to illustrate how important it is to understand details about the magnetic field structure, the properties of the solid lattice, and the temperature distribution, before one is able to make robust estimates of the neutron star properties (e.g. radius).

3. Conclusions

The *metallic neutron star surface* model, first studied in detail in the 80s, is becoming popular again and attracting the attention of several groups (Lai 2001; Turolla, Zane, & Drake 2004; Pérez–Azorín, Miralles & Pons 2005a; van Adelsberg, Lai, & Potekhin 2005). The theoretical emission models with uniform tem-

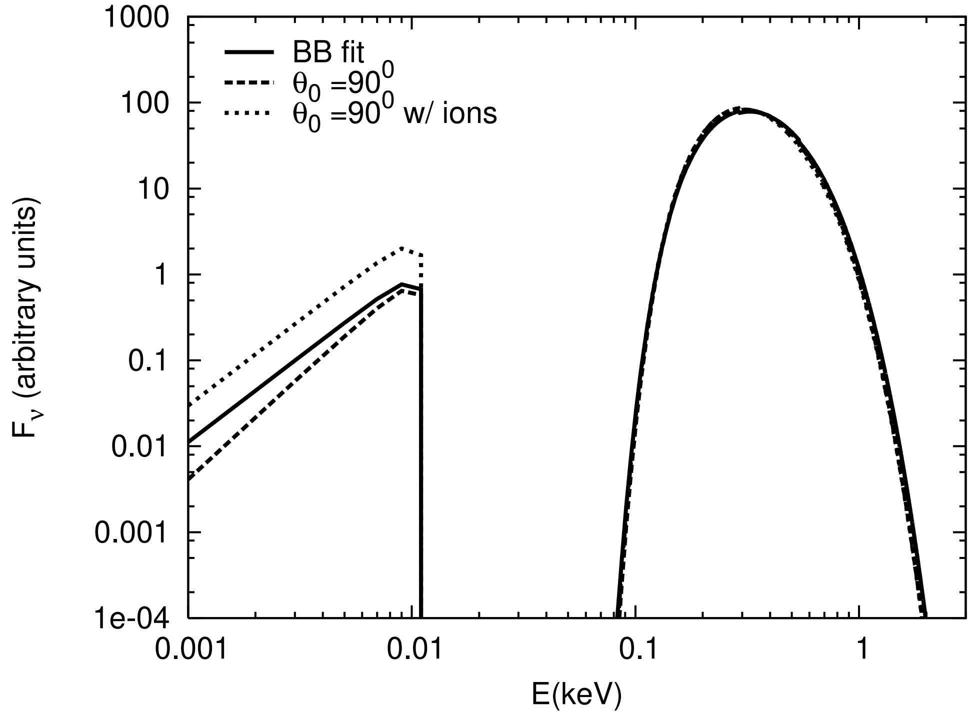

Fig. 1. Observed flux, F_ν, (in arbitrary units) for the anisotropic temperature distribution described in Eq. (2) with $T_p = 10^6$K and $\theta_o = 90°$, as it would be seen after taking into account interstellar medium absorption with $n_H = 1.4 \times 10^{20}\mathrm{cm}^{-2}$. We show results with (dots) and without (dashes) including the effect of ions. A uniform temperature, blackbody fit of the X-ray part of the spectrum is also depicted with solid lines ($T = 10^6$K, $n_H = 1.3 \times 10^{20}\mathrm{cm}^{-2}$) but corrected by a factor 1/5, that is, the apparent estimated value of the R_∞/d is 2.23 times lower than that of the "real" model.

perature show a broadband spectrum that is very close to Planckian at energies $E > \omega_p^2/\omega_B$, where ω_p is the plasma frequency and ω_B is the electron cyclotron frequency, but significantly depressed (up to a factor 10) in the optical band. The spectrum is almost featureless, except for relatively broad cyclotron resonances and minor spectral features at energies where the interstellar medium absorbs the emitted flux. However, in the crust and the condensed outer layer, the assumption of a homogeneous temperature distribution is inconsistent because magnetic fields of the order of or even larger than 10^{13} G imply some degree of anisotropy in the thermal conductivity. Preliminary results (Pérez–Azorín, Miralles & Pons 2005b) predict the existence of large meridional variations in the surface temperature when the magnetic field is confined to the crust. Notice that, if in the inner core of neutron stars we have superconducting protons, as seems to be the case, this situation is very likely. Before engaging in more detailed numerical simulations of multidimensional radiative transfer, one can guess what sort of changes to expect by looking at the emitted spectrum produced by an *ad–hoc* temperature distribution, as we discussed in this paper. This example was very illustrative of one fact: the observed flux of such an object is very close to a BB spectrum, but we might be underestimating the area of the emitter (and therefore its size) by a large factor. In addition, depending on the strength of the magnetic field, and including the effects of ions, we could even obtain an optical flux larger (relative to the BB case) than that in the X-ray band, which is commonly found in all radio-quiet isolated neutron stars with an optical counterpart.

In conclusion, isolated neutron stars are just beginning to reveal the nature of neutron star outer layers, and there are important indications that magnetic fields do influence significantly their thermal emission properties. Perhaps in the near future we can add isolated neutron stars to the family of magnetars, since they could be just older versions of the other two rare classes of magnetars, AXPs and SGRs.

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