Surface Temperature of Magnetized Neutron Stars

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Abstract. We show that the expected inhomogeneous temperature distribution induced at the surface of a neutron star by the anisotropy of heat transport in the magnetized envelope allows us to understand quite well the observed pulse profiles of the four nearby pulsars for which surface thermal emission has been detected. However, due to gravitational lensing, dipolar magnetic fields are not adequate and the observed high pulsed fractions force us to include a quadrupolar component.

1. INTRODUCTION
The definite detections of surface thermal emission from four nearby neutron stars by ROSAT (Ögelman 1995) opened up a new era in the study of these objects: we are at the long last seeing an isolated neutron star (Page 1995b). All four objects: PSR 0833-45 (Vela; Ögelman, Finley, Zimmermann 1993), PSR 0656+14 (Finley, Ögelman, Kızıloğlu 1992), PSR 0630+178 (Geminga; Halpern, Holt 1992) and PSR 1055-52 (Ögelman & Finley 1993), show a two component spectrum with surface thermal emission in the soft band and a hard tail. Most important is that the soft thermal component is pulsed at the 10 – 30% level for all four stars. The hard tail is pulsed except maybe in the case of Vela (Ögelman 1995). The origin of the hard tails is not clear yet although thermal emission from the hot polar caps seems to be presently getting the preference over a power-law emission.

A natural interpretation of the observed pulsations, in the soft X-ray band, is that the surface temperature is not uniform: if it is determined by the heat flow from the hot interior through the envelope then the presence of a strong magnetic field will a fortiori induce large temperature inhomogeneities (see, e.g., Yakovlev & Kaminker 1994). For a given field structure, the temperature at any point of the neutron star surface can then be easily calculated (Page 1995a), as a function of the local field strength and of its angle $\Theta_B$ with the normal, and the distribution of surface temperature can be generated.

2. RESULTS
Magnetic field effects in the atmosphere are also extremely important but as a first step we neglect them and restrict ourselves to consider only blackbody (BB) emission. Inclusion of these effects is in process and results will be reported later.

An important role is played by gravity through lensing: the observable amplitude of the pulsations is very strongly reduced and if we assume a simple dipolar field geometry, with reasonable neutron star masses and radii, the resulting amplitudes are smaller than what is observed (Page 1995a). It is doubtful that inclusion of atmospheric effects will significantly alter the conclusion: dipolar fields are totally insufficient to explain the observations (Page 1995a, b). Moreover, the predicted shapes of the light curves are also very distinct from what is observed. A similar conclusion has been reached by Possenti et al. (1995) who performed a more detailed analysis of PSR 0656+14 along the same lines.

There are of course no strong a priori reasons for the surface field to be dipolar and the previous conclusion is not really surprising. The next obvious step is the inclusion of a quadrupolar component. In general, this component will induce a very complicated surface temperature distribution and will actually even reduce the amplitude of the pulsations. However, if the orientation of the quadrupole with respect to the dipole is adequately chosen then it is possible to increase substantially the pulsations, even with very strong lensing (e.g., $1.4 M_\odot$ star with 8 km radius). With dipole+quadrupole magnetic fields it is possible to reproduce both the spectrum and the pulse profile of the four pulsars we study (Page & Sarmiento 1996). The needed strength of the quadrupole is slightly lower than the dipole one: if much lower, the quadrupole has no effect but if larger it will dominate over the dipole and produce several distinct warm regions (where $\Theta_B \sim 0^\circ$), flattening thus the light curves. Possible evidence for the presence of a significant quadrupole has already been brought up by high frequency radio observations of several pulsars (Kuz’min 1992). The four pulsars with detected surface thermal emission have, to our knowledge, unfortunately not been observed at high radio frequencies and it is thus not possible to compare the quadrupole we need with radio observations.

We show in Fig. 1 an example of surface temperature distribution induced by a dipole+quadrupole field and the resulting fit of the observed spectrum and light-curves of Geminga: $M = 1.4 M_\odot$, $R = 12$ km ($R^\infty = 14.82$ km) at a distance $D = 185$ pc and an effective temperature $T^\infty = 4.3 \times 10^5$ K. Two hot polar caps are added to fit the hard tail. Both caps have a temperature $T^\infty = 2.7 \times 10^6$ K and diameters of 0.55 and 0.40 degree: the positions of the polar caps (dots on panel A) have been chosen to fit the light curve in channel band 53 – 150. Pulsations of the observed amplitude can be reproduced despite of gravitational lensing in this model of $1.4 M_\odot$ star with a radius of 12 km; at smaller radii fits are still possible but very restrictive on the quadrupole component. The data are from Halpern & Ruderman (1993).
Fig. 1. A model for Geminga’s soft X-ray emission (see text). A) Surface temperature distribution induced by a dipole+quadrupole field. (Equal area mapping with $\theta$ vertically and $\phi$ horizontally). B) Spectral fit (surface thermal emission + hot polar caps). C) Fit of the pulse profiles in three channel bands. The rotation axis is along $\theta = 0$ and the observer is at 90° as well as the dipole. In B & C: main surface emission in dashed, polar caps emission in dotted and total emission in continuous. C1 and C2 show that the polar caps make almost negligible contribution to the low energy range and dominate the high energy range (as is also obvious from B).

An important feature of BB emission is that the pulsed fraction always increases with photon energy in the energy range where surface emission is detected, no matter the surface temperature distribution (Page & Sarmiento 1996). This feature does not correspond to what is observed in the case of Geminga: in Fig 1 the decrease in pulse amplitude in channel band 28 – 53 (C2) with respect to the band 7 – 28 (C1) is not reproduced by this model and may require a very different model (Page, Shibanov & Zavlin 1995).

3. CONCLUSIONS

Reasonable surface magnetic field configurations (dipole + quadrupole) allow us to interpret the observed pulse profiles as due to surface temperature inhomogeneities induced by anisotropy of heat transport in the neutron star magnetized envelope. We used only BB spectra but the energy dependence of the observed pulsed fraction in Geminga is already an indication that BB spectra are not adequate. Another indication is the BB fit of the Vela spectrum which requires a distance of $\sim 1,500$ pc instead of the $\sim 500$ pc pulsar distance (Ögelman et al. 1993) while magnetized hydrogen atmosphere spectra are quite successful (Page, Shibanov & Zavlin 1996). A complete study will definitely need the inclusion of magnetic effects both in the envelope and the atmosphere but our conclusion about the need of a quadrupolar component will certainly not be altered by the use of realistic atmosphere models.

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