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GEMINGA'S SOFT X-RAY EMISSION AND THE STRUCTURE OF ITS SURFACE

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Instituto de Astronomía, UNAM, Apdo Postal 70-264, 04510 México D.F., México; page@astroscu.unam.mx
YU. A. SHIBANOV
Ioffe Physical-Technical Institute, St. Petersburg 194021, Russia; shib@ammp.ioffe.rssi.su
AND
V. E. ZAVLIN
Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany; zavlin@rosat.mpe-garching.mpg.de
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ABSTRACT

We present a model to explain the decrease in the amplitude of the pulse profile with increasing energy observed in Geminga's soft X-ray surface thermal emission. We assume the presence of plates surrounded by a surface with very distinct physical properties: these two regions emit spectra of very distinct shapes which present a crossover, the warm plates emitting a softer spectrum than the colder surrounding surface. The strongly pulsed emission from the plates dominates at low energy while the surrounding's emission dominates at high energy, producing naturally a strong decrease in the pulsed fraction. In our illustrative example, the plates are assumed to be magnetized, while the rest of the surface is field free.

This plate structure may be seen as a schematic representation of a continuous but very nonuniform distribution of the surface magnetic field or as a quasi-realistic structure induced by past tectonic activity on Geminga.

Subject headings: pulsars: general — pulsars: individual (Geminga) — stars: neutron — X-rays: stars

1. INTRODUCTION

Despite the large amount of observational data available on radio pulsars, and more recently on X-ray and γ-ray pulsars, the structure of neutron stars still remains elusive. Not only is the interior a puzzle, but even the structure of the very surface is a mystery: in the low-density–low-temperature region near the surface the effects of the magnetic field on the structure of matter and the equation of state still defy any conclusive description. Early work on this question claimed that an iron surface should be a magnetic solid (Ruderman 1974) instead of an atmosphere. Improved calculations in this direction showed that the problem is extremely delicate and the situation is not yet clearly resolved (see, e.g., Neuhauser, Langanke, & Koonin 1986 and Kössl et al. 1988). However, the surface itself, or the atmosphere, is not necessarily made of iron but probably consists of light elements. A few grams per cm^2 of hydrogen at the surface are sufficient to give an optical depth of unity and could be present due to accretion from the interstellar medium or produced on site from the original iron layer by the bombarding of highly energetic particles generated in the magnetosphere. Moreover, fallback of matter after the supernova explosion can also cover the surface, and its magnetic field, by a layer of light elements (Chevalier 1989; Muslimov & Page 1995). If hydrogen is present, the heavier elements will sediment owing to the enormous gravitational field: this would reduce the study of the surface to the comparatively simpler case of a magnetized hydrogen atmosphere. However, hydrogen may aggregate into molecules (Lai, Salpeter, & Shapiro 1992) because of the magnetic field, and convection within the atmosphere at low temperature ($T \lesssim 10^5$ K; Zavlin, Pavlov, & Shibanov 1995a) may mix the hydrogen with the heavier elements lying beneath it, complicating again the problem.

Thank to deep *ROSAT* observations, we now have strong evidence that thermal radiation from four nearby neutron stars has been detected (Ögelman 1995): we are at long last *seeing* the surface of a neutron star. Fitting of these observed thermal spectra with theoretical spectra raised the hope of allowing us to select the correct atmosphere or surface model(s) for these neutron stars. Unfortunately, the energy resolution of the *ROSAT* PSPC detector and unsolved problems in the calibration of this detector at low energy prevented this hope from materializing since analyses with various spectra have given equivalent results: *spectral fits by themselves are not sufficient to discriminate clearly among the various atmosphere models* (Page 1995b; Meyer, Pavlov, & Mészáros 1994) with the present observational capability. On the other hand, the strong modulation of the observed pulsed profiles can be interpreted as being due to magnetic field effects inducing large surface temperature differences (Page 1995a, b; Page & Sarmiento 1995) and/or anisotropy of the atmospheric emission (Shibanov et al. 1994; Zavlin et al. 1995b). These works thus showed that the shape of the light curves and their energy dependence contain crucial information.

Presently, the most intriguing and unexplained observed feature is found in Geminga (Halpern & Ruderman 1993): the amplitude of the pulsations (or pulsed fraction, *Pf*) in the PSPC channels 8–28 (i.e., roughly at energies below 300 eV) is much larger than in channels 28–53: 33% versus 20%. No matter what the assumed surface temperature distribution, unless the temperature is uniform, blackbody emission *always* gives an increase of *Pf* with energy below 0.5 keV (Page 1995a; Page & Sarmiento 1995). This "Geminga effect" thus requires the inclusion of magnetic effects on the emitted spectrum and not only on the surface temperature distribution. The preliminary results of Shibanov et al. (1994) showed that realistic atmospheric models are able to produce a slight decrease of *Pf*

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with increasing energy, but still much smaller than what is observed.

Due to the low resolution of the PSPC and uncertainties in its calibration at energies below 0.5 keV, as well as the low statistics, doubts can be cast on the magnitude or even the reality of this "Geminga effect." We take here the option, and the risk, to consider this effect as real and propose a model that can explain it in a natural way. Our work is also an example of the type of information that can be obtained from the analysis of the energy dependence of the light curves, and the mechanism we propose will also have implications for other pulsars, by either its presence or its absence.

We present in § 2 our model that assumes that the surface of Geminga consists of regions with very distinct physical properties. The results are presented in § 3. We discuss in § 4 some possible reasons for such a surface structure and conclude in § 5.

2. THE MODEL

We model the surface of the Geminga pulsar as made of two uniformly magnetized plates, containing the "north" and "south" magnetic poles, surrounded by a nonmagnetized crust. This can be considered either as a quasi-realistic structure within the scenario of plate tectonics (see § 4) or as a schematic representation of a continuous but very nonuniform distribution of surface magnetic field. It has the advantage of simplicity, requiring only two models of atmosphere. On these large plates should be located the small polar caps: if heated at sufficiently high temperatures, these could be responsible for the hard tail observed above 0.5 keV (but we do not attempt to model this part here). If Geminga is considered to be an orthogonal rotator (Halpern & Ruderman 1993), the two magnetic plates are located near to the rotational equator. If the surface temperature is determined by the heat flow from the hot interior through the crust, the magnetized plates must be warmer than the remainder of the surface (Page 1995a), and the presence of a single peak in the observed soft X-ray light curves imply that the plates are close to each other. We assume that the whole stellar surface is covered by a hydrogen atmosphere, magnetized on the plates. The plates and the off-plate region have thus very distinct emission properties: the off-plate region has a much harder spectrum, i.e., a large excess in the Wien tail, compared to the plate spectrum due to the different frequency dependence of the opacity (Shibanov et al. 1992). We use the emission spectra calculated by Pavlov et al. (1994) which are similar to the spectra used to perform spectral fit for Geminga by Meyer et al. (1994).

The parameters of our model are thus the following: (1) Diameter and position of the two magnetic plates; (2) temperature of the off-plate region $T_{\rm op}$ and magnetic field B_p and temperature T_p of the plates; (3) mass M and radius R of the star; and (4) distance D of the star, interstellar column density $N_{\rm H}$, and orientation of the observer with respect to the star's rotation axis ζ. We fix M at 1.4 $M_\odot$ and R at 10 km and take $\zeta = 90°$. The temperature $T_{\rm op}$ (and to some extent T_p) as well as D and $N_{\rm H}$ are determined by fitting the spectrum, while the size and location of the plates and B_p and T_p are determined mainly by fitting the shape of the light curves.

3. RESULTS

The values of the parameters are found in Figure 1, which shows the partial spectra from the plate and off-plate regions

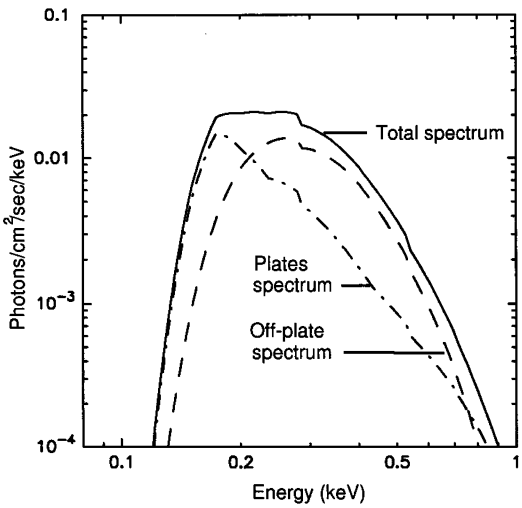

FIG. 1.—Total spectrum and partial spectra from the two plates and the off-plate region. The plate spectrum is much softer than the surrounding's spectrum and dominates at low energy: this results in a strong decrease in the pulsed fraction with increasing photon energy as shown in Fig. 2. The circular magnetized plates have diameters of 60° and 85°, and their centers are located on the rotational equator at a distance of 140° from each other. The magnetic field strength on both plates is 4.7×10^{12} G. The temperature of the plates is $T_p = 4.17 \times 10^5$ K, while the main surface is at $T_{\rm op} = 2.18 \times 10^5$ K. The star is at a distance of 15 pc, and the effective hydrogen column density is $N_{\rm H} = 3 \times 10^{20}$ cm^{-2}. (The two absorption edges at 0.284 and 0.532 keV are due to interstellar C and O, respectively).

and the resulting spectrum: the dominance of the plate emission at low energy is clearly seen. Since the plate emission is the cause of the pulsations, this naturally implies that the pulsed fraction is strongly decreasing with increasing photon energy as can be seen in Figure 2. This result depends critically on the presence of (at least) two different emitting regions with a *crossover* in their spectra (i.e., the partial spectra cross each other at photon energy ≈ 0.2 keV). This crossover is due here to the effect of the magnetic field on the plate spectrum that is absent off-plate, but other mechanisms providing the same spectral properties would give the same results. The most interesting point is that the warm region (the plates) must have

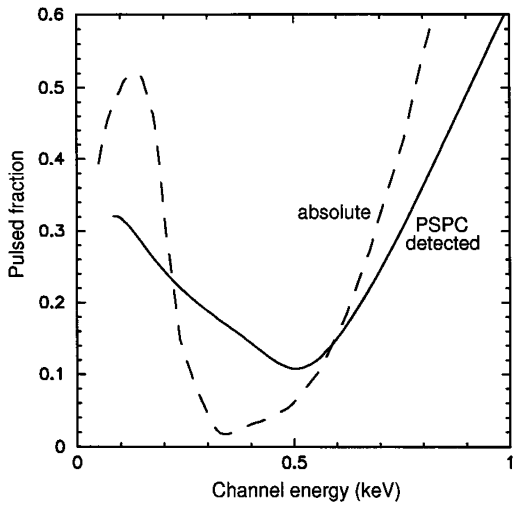

FIG. 2.—Pulsed fraction of the model as detected through the *ROSAT* PSPC and as would be recorded by a perfect spectrometer. We used the 1992 March 19 version of the PSPC's response matrix.

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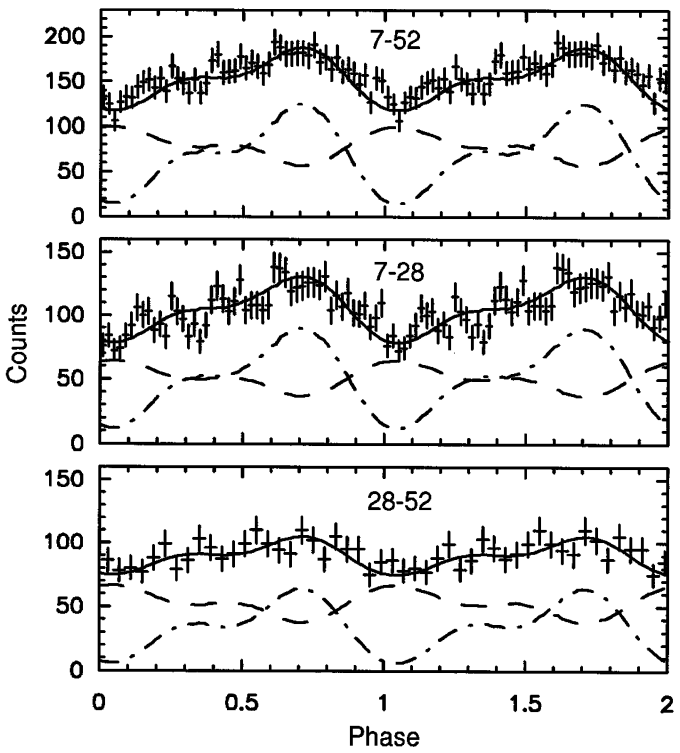

FIG. 3.—Comparison of the theoretical light curves with the observed pulse profiles of Geminga (Halpern & Ruderman 1993). Line styles are as in Fig. 1. Notice the strong decrease in the pulsation amplitude in the channel range 28–53 compared to 7–28.

a softer spectrum than the cold one. This is the contrary to what one would expect if the whole surface of the star were homogeneously magnetized or nonmagnetized: the cold atmosphere would show more intense absorption and have a softer spectrum than the warm region. Our result thus requires a drastic difference in the physical properties of the warm region compared to the cold one, here the presence or absence of the magnetic field.

We show finally in Figure 3 our fit to the light curves in three channel ranges: the decrease of the amplitude of the pulsations with increasing channel number is clearly seen again in bands 7–28 versus 28–53. The higher channel band 53–256 (not shown in the figure) corresponds to the hard tail that has a different origin than the thermal emission from the whole surface (Halpern & Ruderman 1993), and we do not attempt to model it. It was proposed by Halpern & Ruderman (1993) that the decrease in the pulsed fraction of the surface thermal component may be caused by contamination from this hard tail, whose pulses are 105° off-phase with respect to the thermal component. However, the contribution of the hard tail in the channel range 28–53 is one to two orders of magnitude below the contribution from the thermal component, depending on whether the hard tail is modeled as a power law or blackbody spectrum (see Figs. 3 and 6 in Halpern & Ruderman 1993) and cannot possibly be responsible for the decrease in the pulsed fraction (Page & Sarmiento 1995). The origin of this hard tail is not yet definitely established; it is probably thermal emission from the hot polar caps, but a purely magnotespheric origin cannot be excluded to date.

The above results also give us a clue to the behavior of the pulsed fraction in other models. The increase in *Pf* obtained with blackbody spectra (Page 1995a; Page & Sarmiento 1995) is most certainly due to the fact that the blackbody hardness increases with temperature. The small decrease in *Pf* obtained with magnetized hydrogen spectra and a dipolar surface field (Shibanov et al. 1994) is itself due to the slight softening of these spectra with increasing field strength and the fact that the regions with stronger field have a higher temperature.

4. DISCUSSION

4.1. *The Parameters of the Model*

The parameters used in our model for the figures are given in the legend of Figure 1. We have obtained similar results using a larger field strength ($\sim 10^{13}$ G) or even by using a blackbody spectrum for the plates: both give the same crossover with the nonmagnetic spectrum at roughly the same energy. The distance D is then larger ($\sim$30 pc), with the same $N_{\rm H}$. The distance D and $N_{\rm H}$ we obtain are comparable to the ones obtained by Meyer et al. (1994) to whom we refer for a discussion of this aspect of the problem. The exact values of the parameters depend, moreover, on the detector's response. We have used the 1992 March 19 response matrix, and the 1993 January 12 version implies, e.g., changes of the order of 5% in temperature and and an increase of about 15% in $N_{\rm H}$. We did not attempt to perform an accurate spectral fit but tried only to show the main possible mechanism able to produce the "Geminga effect" as observed in the first set (1991 March) of *ROSAT* observations. Our spectral fit does have an excess in the channel range 50–90: spectra softer than the nonmagnetized hydrogen one are needed for a more complete study. A detailed fit of *both* the spectrum and the energy-dependent light curves impose very strong constraints on the atmosphere models, and models presently available are apparently not sufficient.

The ratio of the on-plate to off-plate temperatures we need is within the predicted range from models of heat transport in magnetized and nonmagnetized neutron star envelopes (Van Riper 1988). However, at such low surface temperatures, the envelope models are extremely uncertain owing to the dominating effect of the magnetic field on the equation of state; magnetized atmosphere models are also not very reliable, since the effect of the atomic motion in the magnetic field has not yet been included (Pavlov & Mészáros 1993).

4.2. *Reasons for Surface Inhomogeneity*

The large inhomogeneity needed in our model could be attributed to chemical changes at the surface if the surface is solid. If the surface is gaseous or liquid (covered or not by an atmosphere), then meridional flows, induced by the rotation and/or the magnetic field gradient, would very probably homogenize the chemical composition; in this case, only magnetic field inhomogeneity could be invoked to produce the needed spectra.

Magnetic field inhomogeneity is thus most probably the major agent in inducing large variation in the emitted spectrum. In our example we invoked regions with and without magnetic field. Other possibilities are the formation of a magnetic solid surface or the presence of magnetic molecules, both of which depend on the local field strength and temperature (which itself depends on the strength of the underlying field). The strong magnetic inhomogeneity may be due, e.g., to the upraising of the interior field by ohmic diffusion (Muslimov & Page 1995) or to early tectonic activity of the pulsar.

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The theory of plate tectonics (Ruderman 1991) stipulates that fast-spinning pulsars can be expected to break their crust due to the spindown-induced stresses. As a consequence, neutron stars born with high spin rate can be expected to have undergone a phase of crust braking and thus should keep on their surface the marks of the previous platelets' motion (toward the rotational equator) and formation of a new crust between the moving platelets. Thus the "marks" left by the tectonic activity should affect the properties of the pulsar surface and its thermal emission, i.e., *they should be visible*. The model we have presented here finds a natural explanation within this theory of plate tectonic, and the "Geminga effect" may be such a sign of past tectonic activity on Geminga.

5. CONCLUSIONS

We have shown that the energy dependence of the amplitude of the observed pulse profile of Geminga's soft X-ray thermal emission can be naturally explained by using a superposition of two very different spectra: a soft component that dominates at energies below 200 eV and a harder component that dominates at higher energies (at energies above ~500 eV, the surface thermal emission is hidden behind the hard tail of different origin). The soft component produces the pulsations, i.e., it is emitted by a smaller area than the hard component, and hence the pulsed fraction naturally decreases with increasing photon energy. Since the soft spectrum is emitted by a smaller region than the hard spectrum, it very probably implies a higher temperature in this small area to produce the required crossover of these two spectra.

This postulated surface structure may be simply seen as an idealized representation of a smooth but highly nonuniform distribution of the surface magnetic field or as a quasi-realistic structure resulting from a past era of tectonic activity on Geminga.

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Note added in proof.—Measurement of the distance of Geminga has been announced by P. Caraveo at the Third Compton Symposium, Munich, 1995 June, with the *Hubble Space Telescope*: 160 ± 40 pc. This strengthens our statement that presently available atmosphere models are not able to fit both the spectrum and the light curves: our spectral fit needs a distance of ~20 pc!

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