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Consequences of Interstellar Absorption for Models of Anomalous X-ray Pulsars

Rosalba Perna^{1,3}, Jeremy Heyl² & Lars Hernquist³

ABSTRACT

We examine properties of thermal radiation emitted by strongly magnetized neutron stars (NSs). In particular, we show that the pulsation amplitudes of the energy-integrated flux are an increasing function of the absorption column density to the source. This is especially important for the interpretation of the Anomalous *X*-ray Pulsars (AXPs) as cooling neutron stars with high magnetic fields. We show that the high-pulsation amplitudes observed in these objects are consistent with cooling models, if the large amount of absorption to these sources is taken into account. We also show that cooling models imply inferred radii of the emitting regions on the order of $\sim 5 - 6$ times smaller than the actual NS radii, again in agreement with observations.

Subject headings: stars: neutron — *X*-rays: stars

1. Introduction

In the past few years, *X*-ray observations have revealed a new class of *X*-ray sources, the so-called anomalous *X*-ray pulsars (AXPs) (Mereghetti & Stella 1995; van Paradijs, Taam & van den Heuvel 1995). AXPs are sources of pulsed *X*-ray emission, with persistent luminosities $L_x \sim 10^{35} - 10^{36}$ erg s⁻¹ and soft spectra. Their periods lie in a very narrow range, between 6 and 12 seconds, and their characteristic ages are of order $10^3 - 10^5$ years. Their distances are usually very large, as inferred from the typically large column densities to them ($N_H \sim 10^{22}$ cm⁻²).

Due to the long period of these objects, it is clear that their *X*-ray luminosity cannot be rotation-powered. Two broad classes of models have emerged to explain their *X*-ray emission. In one, the radiation is assumed to be powered by accretion from binary companions of very low mass (Mereghetti & Stella 1995), from the debris of a disrupted high mass companion (van Paradijs, Taam & van den Heuvel 1995; Ghosh, Angelini & White 1997), from the interstellar medium

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(Wang 1997), or from the debris falling back after the supernova explosion (Chatterjee, Hernquist & Narayan 2000; Alpar 1999, 2000; Marsden et al. 1999). In the second class of models, AXPs are hypothesized to be isolated, ultramagnetized neutron stars, with field strengths in the range $10^{14} - 10^{15}$ G, a.k.a. “magnetars” (Duncan & Thompson 1992). The X -ray luminosity could then be powered by either magnetic field decay (Thompson & Duncan 1996; Heyl & Kulkarni 1998) or by residual thermal energy (Heyl & Hernquist 1997a,b).

There are several observational constraints that can be used to discriminate among various models. The presence of an optical counterpart and observable Doppler shifts in the frequency of the X -ray pulses would suggest the presence of an optical counterpart, but this has not been observed so far. Optical and longer wavelength emission (Hulleman et al 2000; Perna, Hernquist & Narayan 2000) would indicate the presence of an accreting fossil disk. Any viable model, however, must also be consistent with the observed high pulse fractions and small emitting areas inferred for the X -ray radiation from these objects.

In this *Letter* we examine whether the observed pulse fractions and inferred emitting areas are consistent with a model for AXPs in which their X -ray emission is powered by thermal radiation from highly magnetized neutron stars. We show that the amplitudes of the pulsations for the total flux observed in a given band are strongly sensitive to the amount of absorption to the source, and, more specifically, increase with it. To understand this point, one first needs to notice that, for typical local blackbody (BB) emission, the energy-dependent pulse fractions increase with energy, as a consequence of the fact that the hardness of the blackbody spectrum becomes larger at higher energies. This point was well elucidated by Page (1995) and Page & Sarmiento (1996): the ratio of the BB fluxes emitted at energy E by two regions of areas A_1 and A_2 with respective temperatures T_1 and T_2 is

$$\frac{F_{\text{BB}}(E, T_1)}{F_{\text{BB}}(E, T_2)} = \frac{A_1 \exp(E/kT_2) - 1}{A_2 \exp(E/kT_1) - 1}, \quad (1)$$

which is an increasing function of E if $T_1 > T_2$. This property remains valid for atmospheric models with beaming $\propto (\cos \theta)^n$, and, furthermore, the increase of the pulse fractions with energy becomes stronger with increasing n .

Absorption by the intervening interstellar medium (ISM) does not affect the energy dependent pulse fractions (though this is rigorously true only for a perfect detector), as photons emitted at a given energy are reduced by the same amount independently of the phase of the rotation. However, pulse fractions measured from flux which is integrated over a given band do depend on absorption. Absorption, in fact, reduces the low-energy part of the flux with respect to the high-energy one. As a result, the main contribution to the pulse fractions is weighed more and more by the high energy component as the amount of absorption is increased.

We compute the expected pulse fractions and inferred areas for typical parameters of AXPs and a thermal cooling model for their emission, which includes processing through an atmosphere. We show that the inferred properties are consistent with observations.

2. Model

Our model is that of a neutron star (NS) cooling through an accreted envelope and with an intense, dipolar magnetic field. Heyl & Hernquist (1998b) showed that, for $B_p \gtrsim 10^{14}$ G, the flux transmitted through the envelope is well described by $F \propto \cos^2 \psi$, where ψ is the angle between the radial direction and the magnetic field. For a dipolar field, $\cos^2 \psi = 4 \cos^2 \theta_p / (3 \cos^2 \theta_p + 1)$ (Greenstein & Hartke 1983), with θ_p being the magnetic colatitude (angle between radial direction and magnetic pole). It is given by

$$\cos \theta_p = \cos \theta \cos \alpha + \sin \theta \sin \alpha \cos \phi, \quad (2)$$

where α is the angle that the magnetic pole makes with the line of sight, and (θ, ϕ) are the usual colatitude and longitude in spherical coordinates. In our calculation, we assume $\alpha = 90^\circ$ (orthogonal rotator). Therefore our results on the pulsation amplitudes must be interpreted as upper limits. We assume that the local emission, $n(E, T)$, is a blackbody spectrum modified by the presence of an atmosphere, for which we adopt the semianalytical model of Heyl & Hernquist (1998a), but with the inclusion of limb darkening⁴. This leads to a beaming of the radiation $\propto \cos \delta$, with δ being the angle between the normal to the NS surface and the direction of the photon trajectory. We will also consider cases with a more intense beaming $\propto (\cos \delta)^n$, but not extreme (i.e. we restrict our attention to $n \leq 2$). Static general relativistic effects (i.e. light deflection and gravitational redshift) are fully taken into account in our calculations.

Let us define $e^{-\Lambda_s} = \sqrt{1 - R/R_s}$, where R is the radius of the NS star, and $R_s = 2GM/c^2$ its Schwarzschild radius. Here we assume $M = 1.4M_\odot$, and consider the range of radii $2 \leq (R/R_s) \leq 4$, all compatible with the currently available models for the NS equation of state. Let D be the distance from the star to the observer, and N_H the intervening column density. The flux measured by an observer at infinity is then given by

$$f(E; N_H) = \frac{\pi R_\infty^2 \sigma T_{p,\infty}^4}{4\pi D^2} \frac{1}{k T_{p,\infty}} e^{-\sigma(E)N_H} \int_0^1 2x dx \int_0^{2\pi} \frac{d\phi}{2\pi} I_0(\theta, \phi) n[Et^{-\Lambda_s}; T_s(\theta, \phi)], \quad (3)$$

in units of $\text{phot cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$. Here $x = \sin \delta$, $R_\infty \equiv R e^{\Lambda_s}$, and $T_{p,\infty} \equiv T_p e^{-\Lambda_s}$, where T_p is the temperature at the pole. The general relativistic effects of light deflection are taken into account through the ray-tracing function $\theta = \theta(x)$, as described in Page (1995). The function $I_0(\theta, \phi)$ sets the normalization of the flux at each point (θ, ϕ) of the NS surface

$$I_0(\theta, \phi) = \frac{4 \cos^2 \theta_p}{3 \cos^2 \theta_p + 1} (\cos \theta_p)^{0.4}, \quad (4)$$

where, following Heyl & Hernquist (1998b), we have assumed a further dependence of the flux on $B^{0.4}$. The local temperature on the star is given by $T_s(\theta, \phi) = T_p [I_0(\theta, \phi)]^{1/4}$, while for the

⁴The model is that of an accreted atmosphere with a magnetized iron envelope, but note that the composition of the envelope does not really affect any of the points made here.

photoabsorption cross section $\sigma(E)$ we use the analytical fit provided by Morrison & McCammon (1988).

Let now $E_{\min}$ and $E_{\max}$ define the boundaries of the band of observation, and let us define $F(N_H) = \int_{E_{\min}}^{E_{\max}} dE f(E; N_H)$. Then, if the column density to the source is N_H , the pulse fraction in that given band is

$$pf(N_H) = \frac{F^{\max}(N_H) - F^{\min}(N_H)}{F^{\max}(N_H) + F^{\min}(N_H)}. \quad (5)$$

In Figure 1, we plot this function for fixed values of $T_p \equiv T_{eff}(\psi = 0)$ and n , while exploring the dependence on R/R_s . Our results agree with those of DeDeo, Psaltis & Narayan (2000) in the limit of $N_H \rightarrow 0$. However, for large column densities, our plots show that the pulsation amplitudes can significantly increase. Therefore, neglecting this effect can lead to misleading interpretations.

In Figure 2, we consider a typical range of column densities inferred for AXPs and show, for an intermediate value of R/R_s , the dependence of pulse fractions on temperature and degree of beaming. We have considered a range of temperatures that is typical for AXPs, if one accounts for the fact that processing through the atmosphere typically results in an overestimate of the effective temperature by a factor of $\sim 2 - 3$. Note that the pulsation amplitudes in a given energy band increase as T_p decreases. This is due to the fact that, as T_p decreases, the spectrum is shifted towards lower energies. This in turn leads, for the same amount of absorption, to a larger suppression of softer photons, and hence to an increase of the pulse fractions. Figure 2 clearly shows that a thermal model for highly magnetized NSs can produce pulsation amplitudes which are consistent with those observed so far (see Chakrabarty et al. 2000 for a summary).

Another property that must be accounted for by any viable model for AXPs is the inferred size of the emitting region. To estimate the effective emitting areas that an observer would deduce for an highly magnetized, cooling neutron star as in our model, we generated a spectrum using Equation (3). We then used the software XSPEC to convolve it with the instrument response (we used *CHANDRA*) and generate a set of simulated data. These were then fitted using a blackbody function. For a star of radius $R = \{2, 3, 4\}R_s$ (corresponding to $R = \{8.25, 12.37, 16.4\}$ km), we found, respectively⁵, $R_\infty \simeq \{1.3, 2.3, 3.5\}$ km, significantly smaller than the stellar radius, but comparable to the parameters inferred for AXPs.

3. Conclusions

We have examined the properties of a model in which the *X*-ray emission of AXPs is thermal radiation from highly magnetized cooling neutron stars. We have shown that the amplitudes of the pulsations in a given energy band are an increasing function of the column density to the

⁵These values are not very dependent on T_p and n , within the range of values considered for the AXPs.

source. If the typically high column densities inferred for AXPs are taken into account, then even a moderate beaming can lead to pulse fractions comparable to those observed so far.

We have used the software XSPEC to generate simulated data from our model and then used these data to find the best-fit blackbody spectrum. We find that the best fit implies an effective radius of the star which is typically $\sim 5 - 6$ times smaller than the actual radius. This is again in agreement with the radii of the emitting regions inferred from the observations of AXPs.

Our results have clear implications for efforts to discern the nature of a variety of X-ray point sources. AXPs have variously been interpreted either as accreting sources, or as isolated, strongly magnetized neutron stars. If interstellar absorption is not taken into account, then the large observed pulse fractions appear to be inconsistent with those predicted by thermal cooling models, as found in recent work by DeDeo et al. (2000). However, as we have demonstrated, interstellar absorption is able to boost the pulsed fraction measured by a distant observer relative to that which would be seen otherwise to the point that a thermal cooling model can easily accommodate the pulsed fractions associated with observed AXPs, if the high inferred column densities to these sources are properly taken into account. Consequently, we do not believe that pulsed fractions discriminate between thermal models for AXP emission from those on which the X-ray luminosity is accretion-powered.

Likewise, interstellar absorption complicates efforts to constrain the sizes of thermally emitting areas on the surfaces of neutron stars. The spectrum of the X-ray point source discovered at the center of the Cas A supernova remnant (Tannanbaum 1999) has now been discussed separately by a number of groups (Pavlov et al. 1999; Umeda et al. 1999; Chakrabarty et al. 2000). Blackbody fits to the observed spectra yield emitting areas that are only a small fraction of a neutron star surface. These results cannot be explained by other models which interpret the spectra using hydrogen atmospheres, but which ignore both the non-uniform temperature distribution expected for a strongly magnetized neutron star and the consequences of interstellar absorption. As we have indicated, when all these various effects are accounted for, there does not appear to be a discrepancy between the effective emitting area of a strongly magnetized neutron star and the values which have been derived for objects like Cas A and the AXPs.

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Fig. 1.— Dependence of the pulsation amplitudes on the absorption column density to the source, for different values of the NS radius. The flux here is assumed to be observed in the (0.1-10) KeV band, the temperature at the magnetic pole is $T_p = 10^6$ K, and the degree of beaming is $n = 2$. It can be seen that a large amount of absorption can significantly increase the observed pulse fractions.

Fig. 2.— Pulsation amplitudes in the range of temperatures and column densities corresponding to those typically inferred for AXPs. The flux is taken in the (1-10) KeV band, and the NS radius is assumed to be $R = 3R_s$. These values of the pulse fractions are consistent with those observed.