Hardness-Intensity Correlations in Magnetar Afterglows

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ABSTRACT

We explore the hardness-intensity correlations observed in several AXPs and SGRs within the framework of a thermally emitting magnetar model. Using our detailed atmosphere models and taking into account reprocessing of the surface emission by the magnetosphere, we show that the hardness of the surface spectra increases with increasing temperature and hence the changes in the effective temperatures of the outer layers of the star alone can account for the observed correlations. We conclude that the slow release of the heat deposited in the deep crust during a magnetar burst naturally accounts for the spectral changes during the afterglow. The correlations are further enhanced by changes in the structures of the magnetic currents during or following a burst. However, the additional hardening produced by scattering of the surface photons off the magnetospheric charges saturates at moderate values of the scattering optical depth.

1. Introduction

Anomalous X-ray Pulsars (AXPs) are a class of neutron stars identified by a number of unique characteristics. Rapid secular spindowns ($\dot{P} \sim 10^{-13} - 10^{-10}$ s $^{-1}$), clustered periods ranging between 5 – 12 s, the lack of observable companions, and persistent X-ray luminosities that exceed their rotational energy losses are among the known properties of these sources (see Kaspi 2006 for a review). Soft Gamma-ray Repeaters (SGRs), on the other hand, are a related class of neutron star sources that are primarily defined by recurrent, often highly super-Eddington bursts of soft gamma rays and hard X-rays. Also detected as persistent X-ray pulsars, they share many of the quiescent properties of AXPs (see Woods & Thompson 2006 for a review).

The intense bursts of SGRs lend strong support to the identification of these sources as ultramagnetic ($B \gtrsim 10^{14}$ G) neutron stars, or magnetars (Duncan & Thompson 1992; Kouveliotou et al. 1998). It is again this bursting activity that establishes the most firm connection between AXPs and SGRs (Gavriil, Kaspi, & Woods 2003). In AXPs, numerous bursts have been observed to date in about half of the sources, with strengths ranging from strong outbursts to long term flux...
variations (Kaspi 2006). Some of these bursts accompanied other changes in the sources, such as increases in the pulsed flux, large glitches, and spectral hardening.

Continuous monitoring of SGRs and AXPs following bursting activity has revealed significant clues about the nature of the bursts and the sources themselves. Initially, afterglow studies focused on the variation of the source flux with time in order to measure the total energy release and the cooling timescales (e.g., Kouveliotou et al. 2003). These studies indicate that the location of the energy deposition during bursting events is a few hundred meters beneath the surface. Monitoring the post-flare pulse profiles has shown significant changes that are likely to be related to magnetic field reconfiguration (Woods et al. 2001). This is consistent with the presence of glitches concurrent with the bursts, which also affect the long-term spindown behavior of the sources (Kaspi 2006).

There are still a number of open questions regarding the underlying mechanisms of the bursts and their long-term effects on the properties of the magnetars. One such question is related to the correlation between the hardness of the X-ray spectra and the flux variations that have been recently observed in several sources (Mereghetti et al. 2005; Rea et al. 2006; Tiengo et al. 2006; Campana et al. 2006; Woods et al. 2006). The sudden increase and the subsequent slow decay of the X-ray flux is understood to be the result of heat deposition in the surface layers. The corresponding variations in the spectral index have so far been attributed to the changes in the magnetic field structure and the increase in the density of charges in the magnetosphere, independent of the surface emission. This interpretation has not taken into account that the surface emission spectra have an intrinsic hardness which depends strongly on the atmospheric temperature and thus can change as the magnetar cools.

In this Letter, we show that the changes in the effective temperatures of the outer layers of the star alone can account for the observed correlations. This is further enhanced by changes in the structures of the magnetic currents during or following a burst. However, the additional hardening produced by scattering off the magnetospheric charges saturates at moderate values of the scattering optical depth.

2. The Hardness of Magnetar Spectra

In the following, we calculate the X-ray spectrum emerging from the surface of a fully ionized, hydrogen atmosphere of a magnetar in radiative equilibrium. We take the magnetic field to be locally perpendicular to the neutron star surface. We take into account the effects of vacuum polarization and proton cyclotron scattering as discussed in Özel (2003). The surface emission spectrum is completely defined by the effective temperature $T_{\text{eff}}$ of the atmosphere, the surface magnetic field strength $B$, and the gravitational acceleration $g$ on the stellar surface, which we set to $g=1.9 \times 10^{14} \text{ cm s}^{-2}$.

The surface radiation is reprocessed by the charges in the magnetosphere of the star. The dominant effect is the scattering of photons at radii at which they are resonant with the local elec-
tron cyclotron energy (Thompson, Lyutikov, & Kulkarni 2002; Güver, Özel, & Lyutikov 2006). We calculate this effect using the Green’s function approach described in Lyutikov & Gavriil (2006), assuming that the field in the magnetosphere is spherically symmetric and follows a $1/r^3$ dependence. The emerging spectrum depends on two parameters: the resonant scattering optical depth $\tau$ and the thermal electron velocity $\beta$.

The atmospheric model spectra are broader than a blackbody and have substantial structure in the continuum, even beyond the presence of a proton cyclotron absorption line. In particular, at high photon energies, the model spectra fall off more slowly than a blackbody, which is typically referred to as hard excess. There are three phenomena that determine the amount and hardness of this excess. (i) The frequency dependence of the free-free opacity in a magnetized plasma causes the higher energy photons to originate deeper in the atmosphere, where the temperature is higher. This dependence, however, is weaker than that in a nonmagnetized atmosphere. If this were the only mechanism that generates hard excesses, as is commonly believed, magnetar spectra would be systematically softer than those of nonmagnetic stars. (ii) The presence of a weak proton cyclotron absorption line in the X-ray band significantly alters the continuum spectrum in the nearby energies. As a result, the location of the proton cyclotron line with respect to the peak of the spectrum affects significantly its perceived hardness. This means that, even for a fixed magnetic field strength, changing the effective temperature of the atmosphere and thus whether the peak of the spectrum appears above, at, or below the cyclotron line changes the hardness of the spectrum. (iii) Vacuum polarization resonance produces a depression in the spectrum, which, for the magnetic fields of magnetars, occur at a few keV. Fitting such spectra with a blackbody function leads to blackbody temperatures smaller than or comparable to the effective temperature and significant hard excess.

The effects of all three phenomena discussed above depend strongly on the temperature profile in the atmosphere, which is determined by the effective temperature (i.e., the brightness of the magnetar when the emitting area is constant). This is shown in Figure 1 for a magnetic field strength of $8 \times 10^8$ G and for effective temperatures varying between $0.3 – 0.6$ keV, which is in the range of temperatures inferred for cooling magnetars. Note that while the rest of the calculations presented here incorporate the effects of resonant scattering in the magnetosphere, this figure shows only atmospheric spectra for illustrative purposes.

The effects of magnetospheric scattering on magnetar spectra have been discussed in Lyutikov & Gavriil (2006) and Güver et al. (2006). The non-Planckian tails already present in the surface spectra become even harder due to resonant Compton scattering in the magnetosphere and the equivalent widths of the cyclotron absorption lines are reduced. These models then have all the qualitative features required to fit most quiescent spectra of AXPs and SGRs.

The hardness of the observed spectra of AXPs and SGRs has typically been quantified in terms of the power-law index of a phenomenological blackbody plus power-law fit (e.g., Rea et al. 2006; Woods & Thompson 2006). These studies yield power-law indices that range between $2 – 4$ for
Fig. 1.— The spectra emerging from the atmosphere of a magnetar with a surface magnetic field strength of $8 \times 10^{14}$ G, and different values of the effective temperature in keV. This shows that as the source flux increases, the spectra become harder. When the surface emission is further reprocessed in the magnetosphere, the spectra become harder and the equivalent widths of the cyclotron lines are significantly reduced.
different sources and varying epochs. However, there are two reasons why theoretical spectra cannot bemeaningfully described in terms of these two components. First, the power-law component dominates over the blackbody at low photon energies, which is an unphysical situation. This is particularly problematic for steep power-law slopes often inferred from AXP and SGR spectra. In the case of observations, this is prevented by taking into account the interstellar extinction which attenuates the spectrum at low energies. Similarly, theoretical spectra always cut off exponentially beyond some characteristic energy scale while a phenomenological power-law extends to infinite energies.

To quantify the hard excess theoretically, we instead define hardness as the ratio of the flux in the hard band to the flux in the soft band. We choose the fluxes in the $4 - 10$ keV and $2 - 4$ keV intervals as the hard and soft bands, respectively, as hardness defined in this way mimics the behavior of the power-law index closely for our spectra. Note that the varying response of the detector at different photon energies also has an effect on the hardness of the observed spectra. We do not take into account the detector response in any of the model predictions presented here, and therefore, would exercise caution when performing direct comparisons with data.

3. Spectral Manifestations of Crustal Heating

The energy released in a magnetar burst is thought to have effects on both the neutron star surface and its magnetosphere. The long timescales observed in the afterglows suggest that most of the burst energy is released several hundred meters deep in the crust (Lyubarsky et al. 2002; Kouveliotou et al. 2003), altering the temperature profile of the surface layers. Moreover, the burst can also reconfigure the magnetosphere, change the density of the charged particles there, and accelerate them to higher energies. All of these changes can affect the source spectra following bursting activity.

Observationally, the spectra of SGRs during post-burst cooling and of AXPs during different flux states show a correlated change between the source brightness, the temperature of the phenomenological blackbody component, and the hardness of the spectrum (Mereghetti et al. 2005; Rea et al. 2006; Tiengo et al. 2006; Campana et al. 2006; Woods et al. 2006). Specifically, as the brightness decreases, the inferred blackbody temperature decreases and the spectrum becomes softer. This indicates that independent of the changes that occur in the magnetosphere, the temperature of the surface layers changes with the changing flux of the magnetar. As we discussed in the previous section, this alone alters the hardness of the spectrum emerging from the atmosphere.

In order to disentangle the role of the temperature change in the crust from the scattering optical depth change in the magnetosphere on the hardness of the spectra, we focus on a setup in which only the temperatures of the outer layers of the star increase, without any changes in the magnetospheric configuration. We achieve this by fixing the model parameters that describe the magnetosphere at values that can qualitatively reproduce the quiescent spectra of AXPs and
SGRs: we take a scattering optical depth of $\tau = 3$ and a thermal electron velocity $\beta = 0.3$ (Güver et al. 2006). (We will present the quantitative results obtained from fitting observed spectra with these models in a forthcoming paper.) We model the flux enhancement as a change in the effective temperature $T_{\text{eff}}$ of the atmosphere because the burst energy is deposited well below the photosphere. We vary $T_{\text{eff}}$ over a wide range ($0.2 - 0.6$ keV) in our calculations to model the large flux variations observed in some afterglows (Kouveliotou et al. 2003). However, we do not exceed temperatures above which noncoherent scattering within the atmosphere becomes important or reach low enough temperatures at which the assumption of complete ionization is not valid.

The resulting correlated change in the hardness of the spectrum and the $0.2 - 10$ keV flux is shown in Figure 2. For any magnetic field strength, the hardness of the spectrum changes considerably even with a modest change in the effective temperature. Furthermore, the models follow the same trend as the observed spectra, i.e., they become softer as the source flux decreases. The weak dependence of the hardness on the magnetic field is a result of the various atmospheric and magnetospheric effects discussed in the previous section.

4. Discussion

In this paper, we show that the hardness of the theoretical spectra emerging from the surface of a magnetar is a strong function of its luminosity, as characterized by the effective temperature of the atmosphere. This provides a natural explanation of the observed correlation between the spectral hardness and X-ray flux found in a number of AXPs and SGRs (Mereghetti et al. 2005; Rea et al. 2006; Tiengo et al. 2006; Campana et al. 2006; Woods et al. 2006).

The changes in the charged particle density and energetics in the magnetosphere of a magnetar during a burst can also alter the spectral hardness. This is shown in Figure 3, where the spectral hardness is plotted as a function of the scattering optical depth in the magnetosphere. Contrary to the case of varying the effective temperature of the atmosphere, increasing the scattering optical depth produces a more modest change in the spectral hardness. Moreover, this effect saturates at optical depths $\tau \gtrsim 5$, as is often the case for Compton upscattering studied in different astrophysical settings (Sunyaev & Titarchuk 1980). This is a consequence of our assumption of a nearly constant particle velocity in the magnetosphere. Assuming a multidimensional magnetic field structure and a broad spectrum of particle velocities can further change the shape and hardness of these spectra. Fernandez & Thompson (2006) carried out detailed Monte Carlo simulations of magnetospheric scattering and explored these possibilities.

Our results demonstrate that atmospheres play a significant role in determining the hardness of magnetar spectra and its correlated change with source flux. Therefore, when performing detailed simulations of magnetar spectra or interpreting observational results, the non-Planckian shape of atmospheric spectra need to be considered. Furthermore, the complicated beaming patterns of the radiation emerging from the atmosphere as well as general relativistic effects (Özel 2002) can be used
Fig. 2.— The hardness of the spectra emerging from the atmosphere of a magnetar as a function of the $0.2 - 10$ keV source flux, where hardness is defined as the ratio of the flux in the $4 - 10$ keV band to the flux in the $2 - 4$ keV band. Different curves correspond to different surface magnetic field strengths in units of $10^{14}$ G. The spectral hardness increases with increasing flux, as in the correlations observed for several AXPs and SGRs.
Fig. 3.— The dependence of the hardness of the magnetar spectra on the scattering optical depth in the magnetosphere for different values of the magnetic field strength in units of $10^{14}$ G. The hardness, which is defined in Figure 2, saturates at moderate values of the optical depth.
in conjunction with the magnetospheric models to also predict the evolution of pulse profiles with bursting activity. Comparison of such detailed models with the observations of the spectra, pulse profiles, and cooling timescales of magnetar burst afterglows offers the possibility of disentangling the effects of the burst on the crust and the magnetosphere.

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