GENERAL RELATIVISTIC EFFECTS ON MAGNETAR MODELS OF AXPS

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General relativistic bending of light dramatically alters the variability of X-ray emission originating from the surfaces of ultramagnetic neutron stars. We construct radiative equilibrium models of such strongly magnetic cooling neutron stars with light-element atmospheres to compute the angle- and energy-dependent intensity emerging from their surfaces and find that the beaming of surface emission is predominantly non-radial. The combination of this radiation pattern with the calculations of light bending yields pulse amplitudes that vary non-monotonically with the neutron star compactness and the size of the emitting region. The significant suppression of the pulse amplitude for large emitting areas provides very strong constraints on the mechanisms that can simultaneously produce high periodic variability and X-ray luminosity. We apply these results to the thermally-emitting magnetar models of anomalous X-ray pulsars (AXPs), which are bright slowly-rotating X-ray sources with large pulse amplitudes. We use the observed fluxes and pulse amplitudes for all known AXPs and show that thermal emission from two antipodal regions on their surfaces, as predicted by some magnetar models, is inconsistent with these observed properties.

Since their identification as a class in 1995, Anomalous X-ray Pulsars (AXPs), distinguished primarily by their X-ray brightness, by pulsations with 6-12 s periods and by the lack of radio or optical counterparts [1], have been elusive sources challenging our current theoretical understanding. The combination of their soft spectra (with color temperatures of ~ 0.5 keV), their X-ray luminosities of $10^{34}-36$ erg s$^{-1}$ and their large pulse amplitudes ranging between 15% – 70%, have also been important properties to account for within the current models of AXPs.

One such class of models, commonly referred to as the magnetar models, relies on anisotropic thermal emission from the surface an ultramagnetic ($B \gtrsim \text{few} \times 10^{13}\text{G}$) neutron star (NS) as the source of the modulated X-ray emission of AXPs, powered either by the decay of this strong field in the crust or by the latent heat from the young NS core. This surface emission is thought to give rise to the soft and dominant component in the spectra of AXPs and, therefore, primarily determines the spectral and timing properties of these sources.

We carried out the first angle- and energy-dependent radiative transfer calculations at ultrastrong magnetic fields and constructed radiative equilibrium models of cooling NSs [2]. We assume that the NS atmosphere is a fully ionized H plasma with an ideal gas equation of state in plane-parallel geometry, and that the magnetic field is normal to the surface. The problem then consists of solving the angle- and energy-dependent equation of radiative transfer coupled to the equation of hydrostatic balance and subject to the constraint of radiative equilibrium. We take into account bremsstrahlung and fully angle-dependent conservative scattering processes at high magnetic fields. We employ a modified Feautrier method for the solution of the radiative transfer problem to allow for the two polarization modes of the
photons in the plasma, and a partial linearization scheme based on a Unsöld-Lucy temperature correction method to determine the thermodynamic structure of the atmospheres in radiative equilibrium. Figure 1 shows the beaming of emerging radiation at photon energies of 0.1, 1, 5, and 10 keV. At almost all magnetic field strengths and photon energies, the beaming has a radial (pencil) and prominent broad non-radial (fan) component. At $B \sim > 10^{14}$ G, the radial component is significant only at high photon energies. The X-ray spectra of the emerging radiation (not shown) are broader than blackbody spectra and, allowing for hard excess, can be fit with a blackbody of color temperature $T_c \approx 1.2 - 1.8 T_e$, where $T_e$ is the effective temperature of the atmosphere.

General relativistic (GR) effects dramatically alter the observable modulation of X-ray emission originating from a NS surface due to the curved photon paths in strong gravitational fields. For radially peaked beaming patterns, the result is a significant suppression of the pulse amplitude because the curved trajectories effectively allow a larger fraction of the NS surface to be visible to the observer at any pulse phase. Taking into account such effects and considering an antipodal emission geometry, it was shown that the $\gtrsim 50\%$ pulse amplitudes observed in 3 AXPs limit the angular sizes of the surface emitting areas to $\rho \lesssim 20$ degrees for strongly radially-peaked beaming of the emerging radiation [3].

The case of the non-radial beaming that is relevant for surface emission from a magnetar is significantly more complex, and in particular the pulse amplitude varies non-monotonically with the neutron star compactness and may also not be monotonic with the size of the emitting area (Fig. 2). This is due to several reasons. First, the peak of the non-radial beams appear broader and at an angle further away from the surface normal due to GR effects. The emission reaching the observer

![Figure 1. The beaming of radiation emerging from a NS atmosphere with $B = 10^{14}$ G and $T_e = 0.3$ keV at photon energies 0.1, 1, 5, and 10 keV.](image-url)
from two antipodal emitting regions can therefore add at a phase \( \phi \) away from the direction of the magnetic field to yield the highest flux at \( \phi = \pi/2 \). This effect is present for a range of curvatures of photon paths, corresponding to a range of neutron star compactnesses, as well as for a range of spot sizes. In addition, neutron stars of different compactness give rise to different redshifts so that the 1–10 keV range detected by an observer at infinity corresponds to an increasingly higher photon energy range on the neutron star surface for increasing compactness. Therefore, for strongly energy-dependent beaming of radiation as in the case of magnetars, the resulting pulse amplitude over an observed energy range is strongly affected by the NS compactness.

Figure 2 (left panel) shows the pulse amplitude from a \( B = 10^{14} \) G NS as a function of \( R/2M \) which specifies the stellar compactness. Note that a smaller \( R/2M \) represents a more compact NS. The two angles \( \alpha \) and \( \beta \) which correspond, respectively, to the position of the emitting region and of the observer with respect to the rotation axis are fixed at 90°, the orthogonal rotator geometry. As \( R/2M \) decreases, we first obtain the more commonly known suppression of pulse amplitudes until the bending of photon paths is strong enough to give the maximum observed flux at \( \phi = \pi/2 \). This increase in the pulse amplitude typically starts at \( R/2M \lesssim 2.8 - 3.8 \) depending on the size of the emitting region. For very compact NSs, nearly the entire surface becomes visible to the observer and thus the behavior is again reversed. Figure 2 (right panel) shows the dependence of the pulse amplitude on the size of the emitting region, for \( R/2M = 4.0 \) and \( \alpha = \beta = 60^\circ \). All other model parameters are as before. The non-monotonic variation of the pulse amplitude with increasing size of the emitting region is due to similar reasons.

The significant overall suppression of the pulse amplitude at large emitting areas has important consequences for thermal emission from the surface of a neutron star.
This is because for thermally emitting sources at a given effective temperature, a natural anticorrelation arises between the maximum luminosity of the source and the maximum observable pulse amplitude. This introduces a limiting curve in the luminosity-pulse amplitude space, above which no thermally emitting system is allowed [4].

Combining the results of the radiative transfer calculations with general relativistic photon transport, we show in Figure 3 the maximal curve allowed by the thermal emission models on the pulse amplitude-luminosity space. In obtaining this curve, we vary all model parameters including the magnetic field strength, effective temperature, and the NS compactness. On the same diagram, we also show the observed fluxes and pulse amplitudes for the five AXPs, making use of the best distance estimates to these sources to calculate source luminosities. Four out of the five sources for which data are available lie well outside of the region allowed by thermal magnetar models, rendering surface emission from ultramagnetic NS with two antipodal regions inconsistent with observations.

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