A Model for the Optical/Infrared Emission from Magnetars

Feryal Özel

University of Arizona, Departments of Physics and Astronomy
1118 E. 4th St., Tucson, AZ 85721; fozel@physics.arizona.edu

ABSTRACT

A number of Anomalous X-ray Pulsars (AXPs) have recently been detected in the optical/IR wavelengths. We use their inferred brightness to place general constraints on any model for this emission within the magnetar framework. We find that neutron-star surface emission cannot account for the observations and that the emission must be magnetospheric in origin. We propose a model for the optical/IR emission in which a distribution of energetic electrons in the neutron-star magnetosphere emits synchrotron radiation. This model can naturally reproduce the observed brightness and the rising spectra of AXPs as well as the observed pulsations at the stellar spin frequency and the correlation of the IR flux with their bursting activity.

1. Introduction

Magnetars are a class of neutron stars powered by the decay of their ultrastrong magnetic fields (Duncan & Thompson 1992). If they are isolated, magnetars are believed to appear as persistent pulsars in the X-rays, with occasional episodes of bursting activity in the hard X-rays/soft γ-rays. Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) are thought to be the observational manifestations of magnetars: their steady spin-down, quasi-thermal X-ray spectra, bursts, and the absence of binary companions all lend support to this identification (see, e.g., Kouveliotou et al. 1998; Mereghetti, Israel, & Stella 1998; Woods et al. 1999; Özel, Psaltis, & Kaspi 2001; Gavriil & Kaspi 2002; Gavriil, Kaspi, & Woods 2003). The absence, until recently, of detectable emission from AXPs and SGRs in longer wavelengths constrained all such studies to the X-rays and γ-rays.

In the last few years, faint counterparts of four AXPs have been detected in IR and optical wavelengths (Hulleman, van Kerkwijk, & Kulkarni 2000, 2004; Hulleman et al. 2001; Israel et al. 2002, 2003; Wang & Chakrabarty 2002) but no counterparts have yet been observed for SGRs, due at least in part to the high extinction along the line of sight to these sources (Corbel et al. 1997, 1999; Vrba et al. 2000; Kaplan et al. 2001, 2002; Eikenberry et al. 2001; Wachter et al. 2004). The AXP counterparts were found to be variable, with fluxes possibly correlated with the

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bursting activity (Kaspi et al. 2003), had rising spectra in $\nu F_\nu$ (Hulleman et al. 2004; see Fig. 1 below), and showed pulsations at the stellar spin frequency (Kern & Martin 2002). These long-wavelength detections have been used to argue strongly against the presence of accretion disks and companion stars around AXPs (Hulleman et al. 2000; Perna, Hernquist, & Narayan 2000). However, no predictions have been made so far for the expected long-wavelength emission from a magnetar, which can be tested against observations (see Eichler, Gedalin, & Lyubarsky 2002 for a preliminary discussion).

In this Letter, we discuss the strong constraints imposed by the observed IR and optical brightness of AXPs on any magnetar emission model. In particular, we argue that the long-wavelength emission cannot originate from the surface of the neutron star. We suggest that synchrotron emission from energetic particles in the magnetosphere at $\gtrsim 50$ stellar radii is responsible for this emission.

2. Constraints on Emission Models

The brightness and limits inferred from the optical and IR observations of AXPs and SGRs can be used to place stringent constraints on the mechanisms that can give rise to this emission within the magnetar model. The most robust constraint comes from imposing the thermodynamic limit on the surface emission from a neutron star.

If the source of energy that powers the optical/IR emission is in the interior of the neutron star, the emitted radiation will be reprocessed in the thermalized surface layers of the star. For such processes, the maximum flux that can emerge from the star is equal to the flux of blackbody radiation at the temperature $T_{BB}$ at optical depth unity. For a source at a distance of 5 kpc observed at a frequency of $10^{15}$ Hz, the blackbody limit is

$$\nu F_{\nu, BB} = 5 \times 10^{-18} \left( \frac{R_{NS}}{10^6 \text{ cm}} \right)^2 \left( \frac{D}{5 \text{ kpc}} \right)^{-2} \left( \frac{T_{BB}}{0.1 \text{ keV}} \right) \left( \frac{\nu}{10^{15} \text{ Hz}} \right)^3 \text{ erg s}^{-1} \text{ cm}^{-2},$$

where $R_{NS}$ is the radius of the neutron star. Models of magnetar atmospheres indicate that the temperature at the thermalization depth of optical/IR photons is $T_{BB} \approx 0.1$ keV in an atmosphere of $T_{eff} \approx 0.5$ keV, which reproduces the X-ray spectra of AXPs (Özel 2001, 2003).

The constraint imposed on the emission models by equation (1) is illustrated in Figure 1 for the case of AXP 4U 0142+61, which has been detected over the widest range of optical/IR wavelengths. This source has a period of $P = 8.69$ s, a period derivative of $\dot{P} = 2 \times 10^{-12}$ s s$^{-1}$, and an uncertain distance of $D > 1$ kpc or $D > 2.7$ kpc (see Özel et al. 2001 and references therein). For this discussion, we set $D = 2$ kpc.

As Figure 1 shows, the maximum possible flux from the surface of the neutron star 4U 0142+61 is smaller by orders of magnitude than the observed optical flux for any reasonable value of the surface temperature. Indeed, for the blackbody limit to be comparable to the optical flux, the
Fig. 1.— The solid lines show the blackbody limit for different temperatures on the neutron star surface for a source at 2 kpc. The dashed line shows the maximum rotation-powered flux for the timing parameters of 4U 0142+61. The crosses and triangles show the absorbed and unabsorbed fluxes (Hulleman et al. 2000), respectively, inferred for 4U 0142+61, while the squares show the absorbed X-ray flux.

temperature of the emitting layers needs to exceed 1 MeV. At this temperature, the cooling of the neutron star would proceed via neutrino and not photon emission. Moreover, it would yield an X-ray spectrum inconsistent with the observations. These strongly argue against a magnetar surface emission model for the optical/IR emission of AXPs.

An upper limit on the size of the emitting region can be obtained by considering the large amplitude of pulsations at the stellar spin frequency observed at optical wavelengths for 4U 0142+61 (Kern & Martin 2002). For coherent pulsations to be produced at $P = 8.69$ s, the size of the emitting region has to be smaller than the light travel distance $R < cP \simeq 10^5 R_{NS}$, which also coincides with the size of the light cylinder. Therefore, the optical/IR emission of AXPs must be magnetospheric in origin. Note that these limits apply in either the case of emission from or reprocessing of stellar radiation by the magnetosphere.
The source of energy that powers the optical/IR emission is more difficult to constrain. However, contrary to the case of the high-energy emission which requires a source of magnetic energy, it is significant that rotational energy alone is sufficient to account for the observed long-wavelength brightness of AXPs. This is illustrated in Figure 1 for the case of 4U 0142+61, where the horizontal line corresponds to the maximum flux that can be observed at Earth from processes powered by rotational energy losses, i.e.,

$$ \nu F_{\nu,\text{rot}} = \frac{\dot{E}_{\text{rot}}}{4\pi D^2} $$

$$ = 2.7 \times 10^{-13} \left( \frac{I}{10^{45} \text{ g cm}^2} \right) \left( \frac{D}{2 \text{ kpc}} \right)^{-2} \left( \frac{P}{8.69 \text{ s}} \right)^{-3} \left( \frac{\dot{P}}{2 \times 10^{-12} \text{ s s}^{-1}} \right) \text{erg s}^{-1} \text{ cm}^{-2}. $$

In this equation, $\dot{E}_{\text{rot}}$ is the rotational luminosity and $I$ is the moment of inertia of the neutron star. Further observations of AXPs in UV wavelengths may be able to distinguish between the magnetic and rotational energy as the source of the long-wavelength emission.

3. A Magnetospheric Model for Long-Wavelength Emission

In the previous section, we argued that the optical/IR emission from AXPs should originate within their magnetospheres. In this section, we show that synchrotron emission from a Goldreich-Julian density of electrons in a dipole magnetic field geometry at $\gtrsim 50$ neutron star radii can reproduce the observed long-wavelength properties of AXPs.

In the magnetosphere of a rotating neutron star, the quasi steady-state distribution of charges is given by (Goldreich & Julian 1969)

$$ N(r) = \frac{B(r)}{eeD}, $$

where $B(r)$ is the local magnetic field at radius $r$, $e$ is the electric charge, and $c$ is the speed of light. The acceleration mechanism and the resulting energy distribution of these charges is largely unknown. In this section, we will assume a mono-energetic distribution of electrons characterized by a Lorentz factor $\gamma$. We will also assume a magnetic field strength with a dipolar radial profile

$$ B(r) = B_{NS} \left( \frac{R_{NS}}{r} \right)^3 $$

where $B_{NS}$ is the magnetic field strength at the stellar surface.

This distribution of energetic charges in the stellar magnetic field emits synchrotron radiation with an integrated power

$$ P_{\text{tot}} = \frac{4}{3} \sigma T c N(r) \beta^2 \gamma^2 \frac{B^2}{8\pi}, $$
where $\sigma_T$ is the Thompson cross-section and $\beta$ is the velocity of the electrons in units of $c$. In this calculation, we assume that, at each radius, all the power is emitted at the fundamental synchrotron frequency

$$\nu_c(r) = \frac{eB(r)}{\gamma m_e c} = \frac{2 \times 10^{21}}{\gamma} \left( \frac{B}{10^{14} \text{ G}} \right) \left( \frac{R_{\text{NS}}}{r} \right)^3 \text{ Hz},$$

(6)

where $m_e$ is the mass of the electron. Note that the classical expression for the synchrotron emissivity is sufficient for the magnetic field strengths that generate the optical/IR frequencies.

Under these assumptions, the photon-frequency dependent luminosity can be calculated as

$$L_\nu = \int_{R_{\text{NS}}}^{\infty} P_{\text{tot}}(r) \delta[\nu - \nu_c(r)] 4 \pi r^2 dr,$$

(7)

which yields

$$L_\nu = 1.1 \times 10^{16} \beta^2 \gamma^4 \left( \frac{P}{5 \text{ s}} \right)^{-1} \left( \frac{B_{\text{NS}}}{10^{14} \text{ G}} \right) \left( \frac{\nu}{10^{15} \text{ Hz}} \right) \text{ erg s}^{-1} \text{ Hz}^{-1}.$$  

(8)

This luminosity corresponds to a flux at Earth of

$$\nu F_\nu = 3.5 \times 10^{-15} \beta^2 \gamma^4 \left( \frac{P}{5 \text{ s}} \right)^{-1} \left( \frac{B_{\text{NS}}}{10^{14} \text{ G}} \right) \left( \frac{D}{5 \text{ kpc}} \right)^{-2} \left( \frac{\nu}{10^{15} \text{ Hz}} \right)^2 \text{ erg s}^{-1} \text{ cm}^{-2}.$$  

(9)

The predictions of this model for the case of 4U 0142+61 are shown in Figure 2. The optical spectrum of this source, which approximately follows a $\nu^2$ dependence, can be fit very well with a mono-energetic distribution of electrons characterized by

$$\gamma \simeq 3 \left( \frac{B_{\text{NS}}}{10^{14} \text{ G}} \right)^{-1/4}.$$  

(10)

We discuss the effects of relaxing some of the approximations made in this section and its implications for the IR spectra of AXPs in the next section.

4. Discussion

In this Letter, we described a model of the optical/IR emission of AXPs in which a distribution of energetic electrons in the neutron star magnetosphere emits synchrotron radiation. This model can naturally reproduce the observed brightness and the rising spectra of AXPs.

In the calculations reported above, we have made some simplifying assumptions that may affect the quantitative predictions of the model. First, we did not take into account the angular dependence of the magnetic field and of the emitted radiation. Relaxing this assumption will result in a brightness and spectrum that depends on the relative orientation of the magnetic axis and the observer. Moreover, it will naturally give rise to pulsations of the long-wavelength emission.
Fig. 2.— The Optical/IR spectrum for magnetospheric synchrotron emission from a magnetar. Labels 10 and 100 refer to the values for the parameter $\beta^2 \gamma^4 (B/10^{14} \text{G})$. The data points and the dashed line are as in Figure 1.

The source of energy and the mechanism of particle acceleration in the magnetosphere of a magnetar are open questions. The long-wavelength observations of AXPs may provide within this model clues towards distinguishing between various possibilities. If the source of this radiation is dissipation of the rotational energy of the neutron star, then equation (2) provides an upper limit on the flux of magnetospheric synchrotron photons (see the dashed line in Fig. 2). This, in return, sets an upper limit on the frequency of synchrotron radiation at $\simeq 10^{15} \text{Hz}$ for the parameters of 4U 0142+61. Combining this limit with equation (6) and the best-fit value of the parameter $B_{\text{NS}} \gamma^4$ (see Fig. 2) results in a lower limit on the emission radius of $r/R_{\text{NS}} \gtrsim 80(B_{\text{NS}}/10^{14} \text{G})^{5/12}$. The observations of 4U 0142+61, in this framework, require that either the particles do not radiate at smaller radii or that particle acceleration takes place at large distances from the neutron star.
surface, possibly due to the formation of bound positronium states (Leinson & Pérez 2000) at the stronger magnetic fields close to the star.

The inferred IR spectrum of 4U 0142+61 is flatter than its optical spectrum (Hulleman et al. 2004). This can be achieved for a radial distribution of Lorentz factors that rises locally with increasing radius. Such an energy distribution would strongly suggest that the particles are accelerated at $\gtrsim 100R_{\text{NS}}$ and lose energy via synchrotron radiation as they follow field lines back toward the star. If the low-frequency radiation is powered by magnetic energy, such a configuration may naturally arise from the dissipation of Alfvén waves in the magnetospheres of magnetars (Thompson & Duncan 1996). Because of the much larger reservoir of magnetic energy, the optical spectrum may extend to higher frequencies than in the case of rotation power. Observations of AXPs and SGRs in UV wavelengths will be important in distinguishing between different mechanisms. Note also that the optical and IR observations of 4U 0142+61 were not carried out simultaneously and may point to a change in the magnetic field configuration in time. Simultaneous and/or repeat observations may also provide additional clues to the nature of the emission.

This magnetospheric model can also account for a number of other observed properties of the optical/IR emission of AXPs. As mentioned above, the magnetic field geometry and the angular dependence of synchrotron emission gives rise to pulsations at the stellar spin frequency as observed (Kern & Martin 2002). The optical/IR flux is also likely to be polarized due to the strong beaming of synchrotron emission but a quantitative prediction for the degree of polarization requires including in the calculations the angle dependences discussed above. Observations that search for polarization of the optical emission may help further constrain the magnetospheric model. In addition, the optical/IR emission will naturally respond to the changes in the magnetic field strength, configuration, or spin-down rate following an SGR-like burst. The timescale for this flux enhancement will be dictated by the rearrangement of magnetic field lines which are anchored in the neutron star crust and thus will proceed at a slower pace than any characteristic timescale in the magnetosphere. Such correlated changes have been observed following the burst of 1E 2259+586 (Kaspi et al. 2003).

Finally, because of its proposed magnetospheric origin, the low-energy emission of AXPs is expected to correlate with the rate of rotational or magnetic energy losses. The absolute luminosities of AXPs in the IR are very hard to infer observationally because of the unknown distances and the effects of the large interstellar absorption to these sources. To minimize these uncertainties, we have normalized the unabsorbed IR flux in the K band to the unabsorbed persistent X-ray flux at $5\times 10^{17}$ Hz. The intrinsic X-ray luminosities of AXPs are expected to be similar between the sources and not to depend strongly on the magnetic field strength. Even though such a luminosity clustering is difficult to infer from the data, their quasi-thermal spectra with similar color temperatures and the fact that the emitting areas should all be comparable to the surface area of a neutron star point to such a theoretical expectation. The inferred flux ratios are plotted against the observed rate of rotational energy loss in Figure 3 (see Israel et al. 2003 and references therein for the data). The overall correlation provides additional support to the model of magnetospheric optical/IR emission...
Fig. 3.— The ratio of the unabsorbed IR flux in the K band to the X-ray flux at $5 \times 10^{17}$ Hz as a function of the rotational luminosity for four persistent AXPs. Normalizing to the X-ray flux minimizes the differences in distance uncertainties and absorption column between the sources. The positive correlation supports the idea of magnetospheric origin for the long-wavelength emission of AXPs discussed here.

I thank Chryssa Kouveliotou, Peter Woods, and Sandeep Patel for stimulating discussions and their hospitality during my visit to MSFC where this work was initiated, as well as for their detailed comments on the manuscript. I thank Sandeep Patel also for his help with the AXP data files. I am grateful to Dimitrios Psaltis for his help, scientific and otherwise, while completing this work. I acknowledge support by NASA through Hubble Fellowship grant HF-01156 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.
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