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Magnetar spectra and twisted magnetospheres

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Abstract

The huge potential drop between the footpoints of the closed field lines in the twisted magnetospheres of magnetars may accelerate electrons up to very high energies, $\gamma \gg 10^6$. On the other hand, the comparison between the observed spectra of magnetars and spectra obtained by accurate theoretical models seems to favor of a picture in which the magnetosphere is filled by "slow" electrons ($v \lesssim 0.8c$), rather than by ultra-relativistic particles.

Actually, two different processes may limit the effective velocity of charges in the innermost part of the magnetosphere, both related to the resonant behavior of the Compton scattering in strong magnetic field. Near the stellar surface, where the magnetic field B exceeds the quantum limit $B_Q \simeq 4.4 \times 10^{13}$ G, scattering between fast electrons and $\sim$1 keV seed photons generates high-energy gamma rays that immediately convert to electron/positron pairs via one-photon pair production. This runaway process limits the value of γ to the threshold value for pair production $\gamma \approx 1000$. At larger distance the magnetic field weakens, and pair creation is strongly depressed for the impossibility of resonant scattering to generate high-energy photons. We discuss the possibility that, in the intermediate region $5R_* \lesssim r \lesssim 20R_*$ (with $R_* = 10$ km), intense Compton losses are effective in reducing the acceleration of electrons even in presence of a very high potential drop.

Keywords: Pulsars; Magnetars; X-ray spectra

1. Introduction

Soft-gamma ray repeaters, SGRs, and anomalous X-ray pulsars, AXPs, are the most magnetized bodies known, with a superstrong magnetic field $B \gtrsim 10^{14}$ G, hence their name is magnetars. They are characterized by quiescent, bursting and flaring X-ray emission powered by ultra-strong magnetic field. Their luminosity, in fact, greatly exceeds the spin-down power and the energy released is higher then the rotational energy.

There is a widespread consensus about the role played by the huge magnetic energy stored both inside and outside the neutron star. Less obvious is the interpretation of the physical mechanisms that converts magnetic energy into the observed radiation.

Among the alternative models discussed in the literature (Chatterjee et al., 2000; Alpar, 2001; Ertan et al., 2007; Kaminker et al., 2009), the magnetar model originally proposed by Duncan and Thompson (1992), Thompson et al. (2002), Thompson and Beloborodov (2005), Beloborodov and Thompson (2007) seems to better account for the complex phenomenology of AXPs/SGRs. In particular, it seems to contain all the necessary ingredients that permit to explain most of the energetic and spectral peculiarities of these extraordinary stellar objects.

Spectra of magnetars in the soft X-ray range ($\sim$0.1–10 keV) are well described by a combination of a soft X-ray thermal emission with $kT \approx 0.5$ keV, and a power-law with a photon index $\Gamma \approx 2$–4. Some cases are known in which the hard tail extends up to 100–200 keV (Mereghetti, 2008; Zane et al., 2009, see also Mereghetti and Zane, this

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issue). The most natural interpretation of the tail formation is given in terms of repeated scattering of the thermal radiation emitted by (part of) the stellar surface. In twisted magnetospheres the large optical depth to electron-scattering arises for two concomitant factors: the presence of intense electric currents required to sustain the magnetic twist and the resonant character of the magnetic Thompson cross-section.

2. The twisted magnetosphere model

The basic idea of the twisted magnetosphere model (TMM) is that the dipole magnetic field of the neutron star (NS) is suddenly twisted because of a deformation of the stellar crust caused by strong magnetic internal stresses. The presence of non-vanishing toroidal components of the magnetospheric field induces the formation of large scale currents, $J \propto \nabla \times B$, flowing along the field lines, with charge densities largely in excess to the Goldreich–Julian value. The charges flowing in the current play a fundamental role in the Comptonization process.

It is important to note that in intense magnetic fields electron-scattering is strongly enhanced if compared with the classical Thomson limit. In fact, as shown in Fig. 1, the magnetic cross-section, corrected for quantum effects, manifests a characteristic resonant behavior where (in the electron rest frame [ERF]) the frequency ω of the incoming photon is equal to the cyclotron frequency $\omega_B = eB/m_ec$, or (in the non-relativistic limit) to multiple integers of this quantity for higher harmonics (Daugherty and Harding, 1986, 1991, see e.g.).

Expressed in terms of the adimensional photon energy $\varepsilon = \hbar\omega/m_ec^2$, in the ERF the resonant condition reads

$$\varepsilon = B/B_Q, \tag{1}$$

where $B_Q = m_e^2c^3/e\hbar = 4.4 \times 10^{13}$ G is the critical QED field at which the fundamental cyclotron energy $\hbar\omega_B$ equals

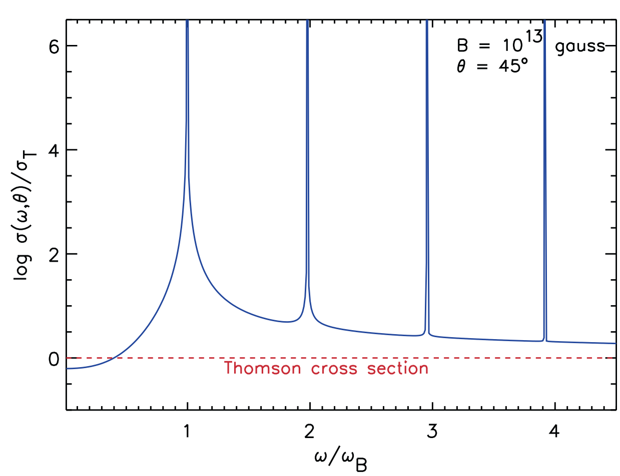

Fig. 1. The (magnetic) scattering cross-section is shown as a function of the incident photon frequency (in unit of the cyclotron frequency eB/m_ec) for a field strength $B = 10^{13}$ G and a photon angle $\theta = 45°$ between the photon direction and the magnetic field line.

the electron rest mass energy. In very strong field ($B \gtrsim 0.1B_Q$) Eq. (1) must be corrected to account for relativistic effects (Nobili et al., 2008).

When moving in an inhomogeneous magnetic field $B(\mathbf{r})$, a photon has a very high probability to *meet* somewhere in the magnetosphere a resonant peak, and then to scatter. As a consequence, the magnetosphere becomes effectively optically thick even in relatively rarefied plasma.

The spectral formation in twisted magnetosphere was investigated by Lyutikov and Gavriil (2006) using a phenomenological approach, and by Fernandez and Thompson (2007) and Nobili et al. (2008) with a 3D–Monte Carlo method. Recently, we have upgraded our code (Nobili et al., 2008) inserting the fully relativistic Klein–Nishina (resonant) cross-section. This allows to model spectra in a wider range of energies (Zane et al., 2009, see also Zane, this issue).

3. The resonant condition

Eq. (1) is valid only in the ERF. Taking into account for the Doppler effect, it is straightforward to generalize Eq. (1) to a different frame. In particular, if a photon of energy ϵ scatters onto an electron with a velocity $v = \beta c$, both measured in the stellar frame (LAB), the resonant condition (1) becomes

$$\gamma(1 - \beta\cos\theta)\epsilon = B/B_Q, \tag{2}$$

where θ is the angle between electron and photon directions of propagation and $\gamma = (1 - \beta^2)^{-1/2}$ is the electron Lorentz factor.

In the theory of magnetars it is generally assumed that most of the seed photons are emitted by the hot stellar surface with a typical energy of 1 keV (i.e. $\epsilon \approx 1/511$). In this hypothesis the resonant condition (2) expresses a relation between the local value of the magnetic field strength $B(\mathbf{r})$ and the energy of the "resonant" electron

$$\gamma_{res} \approx 10^3 B/B_Q. \tag{3}$$

In deriving this expression we have assumed a random distribution of the photon propagation. Since in near dipole configurations it is $B(r) \approx B_s(r/R_*)^{-3}$, where R_* is the stellar radius and B_s the surface magnetic strength, it is evident from Eq. (3) that a photon can scatter resonantly only with electrons whose local energy $\gamma(r)$ decreases with increasing radial distance, as shown qualitatively by the heavy (blue) line of Fig. 2, upper panel.[1] An important consequence of this result is that photons propagate freely unless the region does contain a population of charge carriers with the "right" velocity depending on the value of $B(r)$, as indicated by Eq. (3).

For example, near the stellar surface, in a region extending up to ~2 to $3R_*$, it is $B \gtrsim 2B_Q$. From Eq. (3) it follows that resonant scattering can occur only if there a popula-

[1] Actually, the curve is smeared because (i) the energy of seed photons is distributed around 1 keV; (ii) photons have different angle of propagation.