Emerging Spectra in Neutron Stars with Ultra-Strong Magnetic Fields

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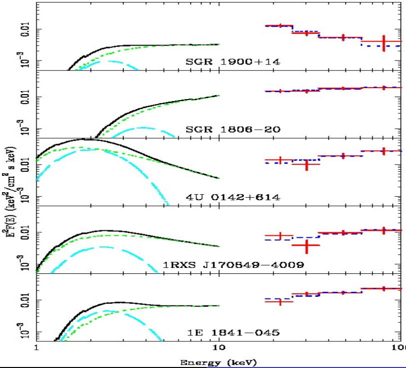
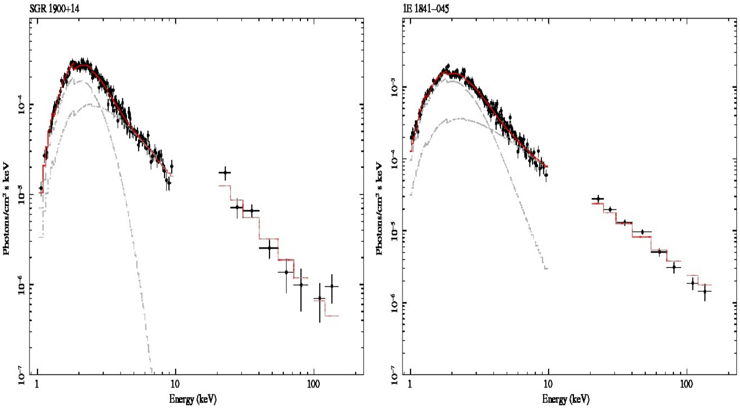
Outline

Who are Magnetars?

There are evidences of ultra-strong magnetic fields ($B \gtrsim 10^{13}$G) from a class of objects called magnetars. Magnetars are divided into two subclasses: Soft Gamma Repeaters (SGRs) and Anomalous X-Ray Pulsars (AXPs).



Persistent Emission from SGR 1900+14 and 1E1841-045 (Zane et al. 2008)



Burst Emission from SGR 1900+14 (Israel et al. 2008)

Best fit models

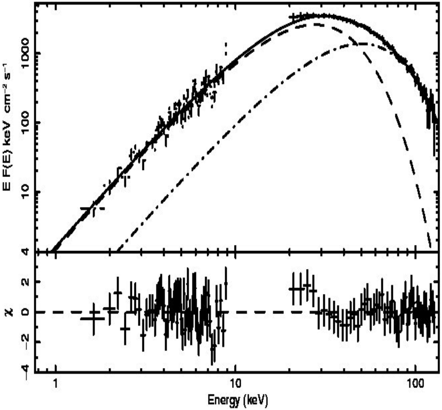
$BB_1 + BB_2$

$kT_{BB,1} \sim 12$ keV

$R_{BB,1} \sim 15$ Km

$kT_{BB,2} \sim 7$ keV

$R_{BB,2} \sim 40$ Km



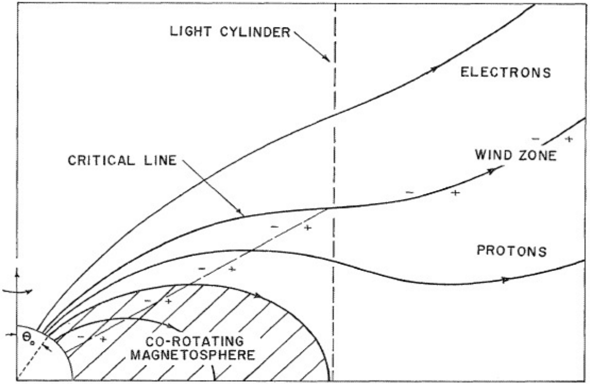
Inverse Compton Model

$kT_{BB} \sim 5$ keV

$\tau \sim 5$

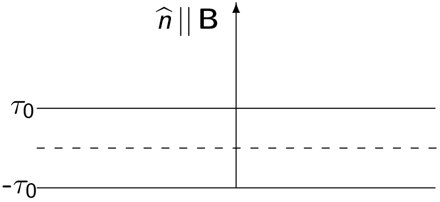
$kT_e \sim 15$ keV

General Scheme



Assumptions and Geometry

The geometry assumed for the thermal plasma is that of an infinite plane-parallel slab, with the magnetic field oriented along the normal to the plane. Photons are assumed to propagate from the base of the slab.



Polarization Modes

The magnetic field induces photons to be splitted into two modes of polarization, with different cross-sections.

Ordinary Mode photons have the electric field parallel to $\mathbf{k} \wedge \mathbf{B}$

Extraordinary Mode photons have the electric field perpendicular to $\mathbf{k} \wedge \mathbf{B}$

Ordinary photons have the stronger interactions (inverse Compton scattering) with the electron plasma, hence they dominate the spectrum at high energy.

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Radiative Transfer for Ordinary Mode Photons (Lyubarskii, 1987)

The equation for the ordinary mode photons reads

$$c(\vec{l}\nabla)n_{\mathrm{O}}(\vec{l},\nu,\vec{r}) = \int d\Phi dw\{n_{\mathrm{O}}(\vec{l'},\nu',\vec{r})N(\epsilon + h\nu - h\nu') - n_{\mathrm{O}}(\vec{l},\nu,\vec{r})N(\epsilon)\} - c\sigma_{\mathrm{OE}}N_{\mathrm{e}}n_{\mathrm{O}}(\vec{l},\nu,\vec{r})$$

On the lhs there is the directional derivative of the photon occupation number.
On the rhs there is a term that describes the energy exchange with electrons and a term describing transitions between the two modes of polarization.

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Space and Energy Operators

Using $x \equiv h\nu/kT$ as the energy variable and the optical depth τ as the space variable, it is possible to write the equation in the more compact form

$$L_x n_{\mathrm{O}}(x,\tau) + L_\tau n_{\mathrm{O}}(x,\tau) = 0$$

where L_x is the energy operator and L_τ is the space operator.
We look for a solution in which energy and space dependences are decoupled:

$$n_{\mathrm{O}}(x,\tau) = \sum_{\mathrm{k}=1}^{\infty} c_{\mathrm{k}} T_{\mathrm{k}}(\tau) Z_{\mathrm{k}}(x)$$

Separation of Variables

We find two equations, one for the energy operator L_x and the other for the spatial operator L_τ:

$$\frac{2}{15}\frac{kT}{m_e c^2}\frac{1}{x^2}\frac{d}{dx}x^4\left(\frac{dZ}{dx}+Z\right)-\frac{1}{4}\left(\frac{x}{x_g}\right)^2 Z-\lambda^2 Z=S(x)$$

$$\left(1-\frac{3}{4}\lambda^2\right)T(\tau)=\int_{-\tau_0}^{\tau_0}K(|\tau-\tau'|)T(\tau')d\tau'$$

where $x = h\nu/kT$ and Z(x) is

$$Z(x)=\frac{J(x)}{x^3}=\frac{1}{4\pi x^3}\int I(x,\Omega)d\Omega$$

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Seed Photons

Seed photons $S(x)$ are assumed to be distributed as a blackbody

$$S(x) = 5.05 \times 10^{22} \left(\frac{kT_\mathrm{e}}{keV}\right)^4 \frac{x^3}{e^x - 1}$$

The fraction of E-photons that change their polarization (becoming O-photons) enters the equation as an additional source term, namely

$$\frac{3}{8}\sigma_\mathrm{T}\left(\frac{x}{x_\mathrm{g}}\right)^2 \cos^2\theta \int n_\mathrm{E}(\theta')d(\cos\theta')$$

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Radiative Transfer for Extraordinary Mode Photons

We need one more equation to couple in order to solve completely the radiative transfer problem. This equation is a diffusion equation that describes extraordinary photons

$$\mu \frac{dn_{\mathrm{E}}}{d\tau}(\mu) = \left(\frac{x}{x_{\mathrm{g}}}\right)^2 \left[-n_{\mathrm{E}}(\mu) + \frac{3}{8}\int_{-1}^{1} n_{\mathrm{E}}(\mu')d\mu' + \frac{1}{4}n_{\mathrm{O}}\right]$$

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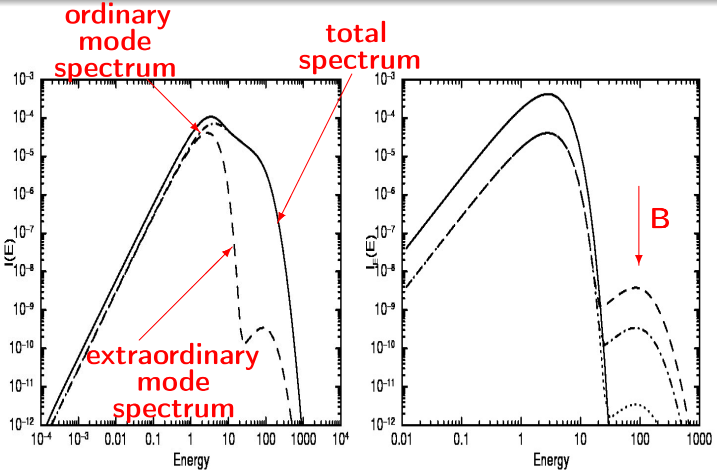
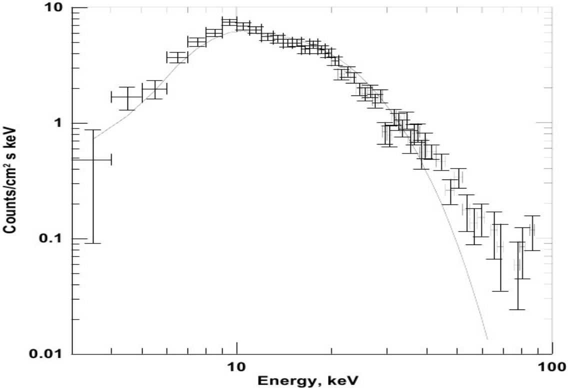
Theoretical spectra



Bright Flare from SGR 1806-20 (Hurley et al.2005)



Eddington Limit with Ultra-Strong Magnetic Fields

The Eddington limit sets the maximum accretion rate allowed. In absence of magnetic fields this is

$$L_{\mathrm{EDD}} = 4\pi c \frac{GMm_{\mathrm{p}}}{\sigma_{\mathrm{T}}} \simeq 1.3 \times 10^{38} \left(\frac{M}{M_{\odot}} \right) \ \mathrm{erg/s}$$

In presence of strong magnetic fields, the radiation pressure decreases due to smaller cross-sections, allowing larger accretion rates. With $B \sim 10^{14}$G, the limit luminosity can increase up to 4 orders of magnitude.

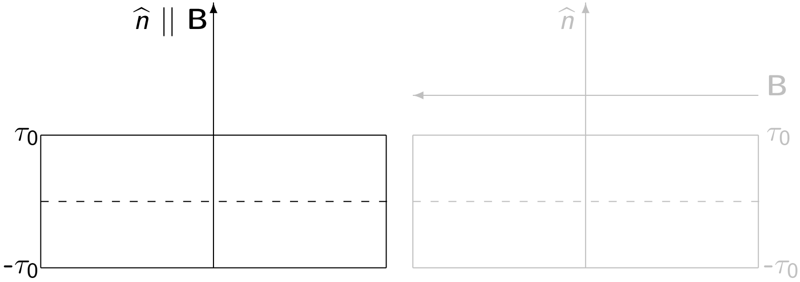
Introducing Montecarlo Code

The introduction of MonteCarlo techniques can lead to a clear improvement in finding solutions without facing many problems of numerical calculus.
We are developing a code based on the algorithm described by Nobili et al.(2008) and Fernandez & Thompson (2005).
Initially, we still consider an infinite plane slab, but with more complex magnetic field configurations.

Geometry of the System: Slab

We have considered two different cases for the magnetic field:

- magnetic dipole having its axis perpendicular to the slab
- uniform magnetic field parallel to the slab



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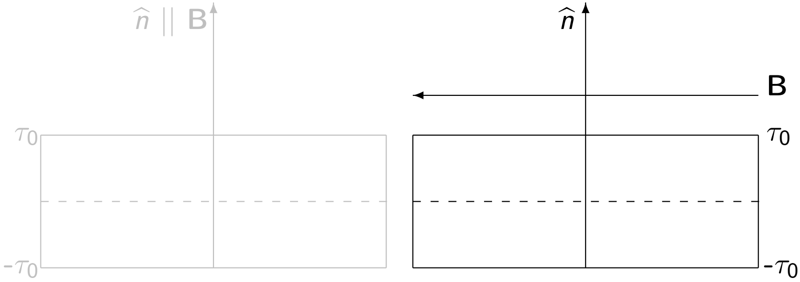
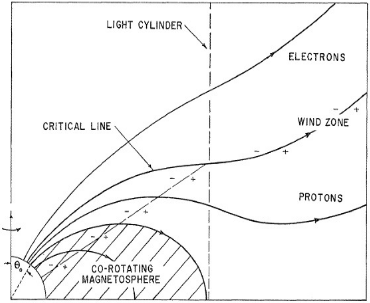


Geometry of the System: Equatorial Regions

In order to achieve a more accurate description of the emission, one should consider not only the polar cap but also the equatorial regions. Plasma geometry, rotation and magnetic field shape heavily complicate the problem. The complete code is currently being developed.



Conclusions

- The semi-analytical approach gives emerging spectra that are compatible with the burst emission of the magnetars
- We obtain a modified Eddington limit in the presence of ultra strong magnetic field which is larger than the ordinary Eddington limit and in agreement with the observed luminosity ($\approx 10^{40-41}$erg/s, Israel et al.2008)
- We are now developing a MonteCarlo code which will take into account also more realistic geometries