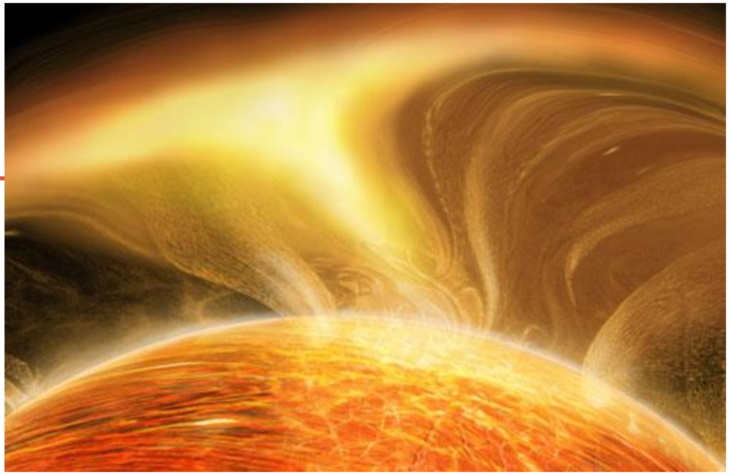
MAGNETARS: A BIASED (RE)VIEW



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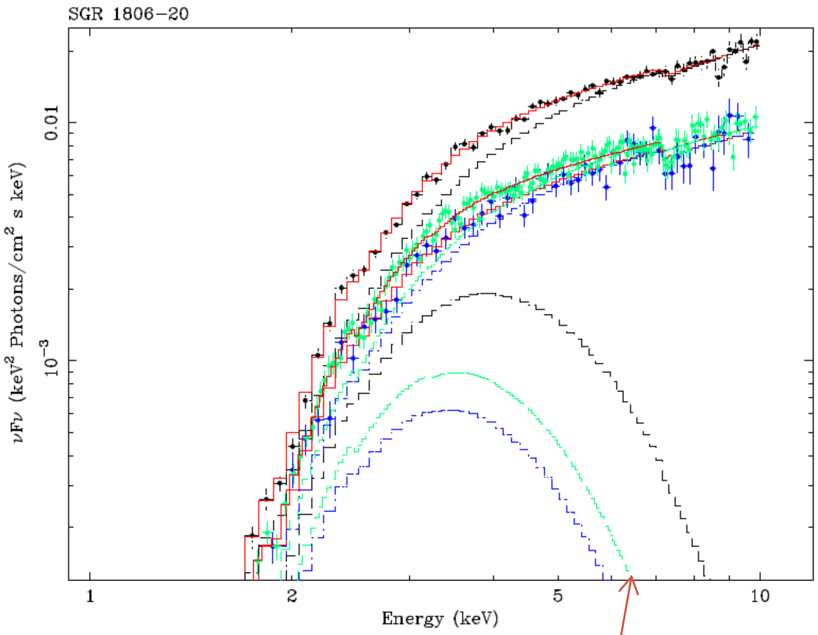
with lot of help from P. Esposito, G.L. Israel, S. Mereghetti, L. Nobili, J. Pons, N. Rea, L. Stella, A. Tiengo, S. Zane and many others

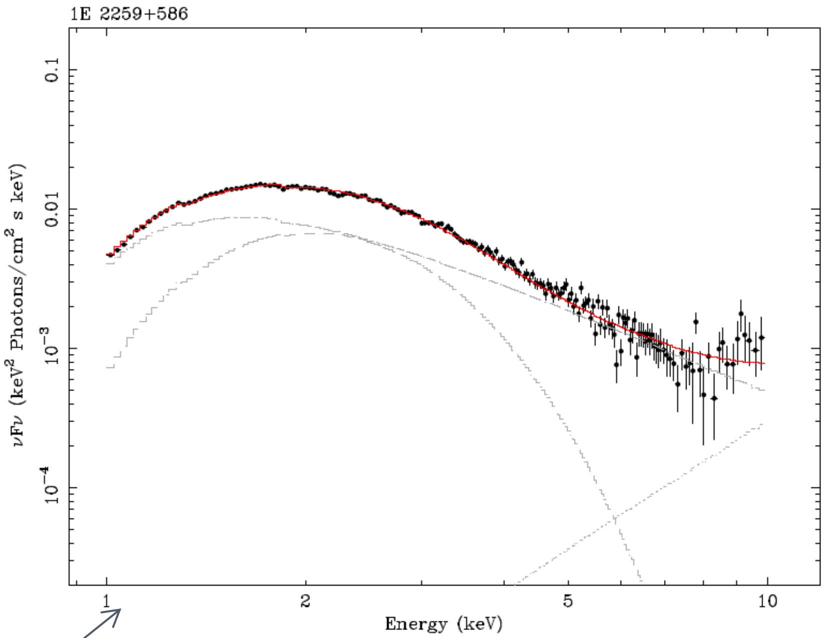
Outline

- Magnetar persistent emission
  - The twisted magnetosphere model
  - The current distribution
  - Soft+hard X-ray spectrum ?
- Transient magnetars & “low-field” sources
  - Outburst models
  - Magneto-thermal evolution
  - “Low-$\dot{P}$” sources
- Bursts & Flares
  - Burst phenomenology
  - Burst triggers and emission

SGRs and AXPs X-ray Spectra

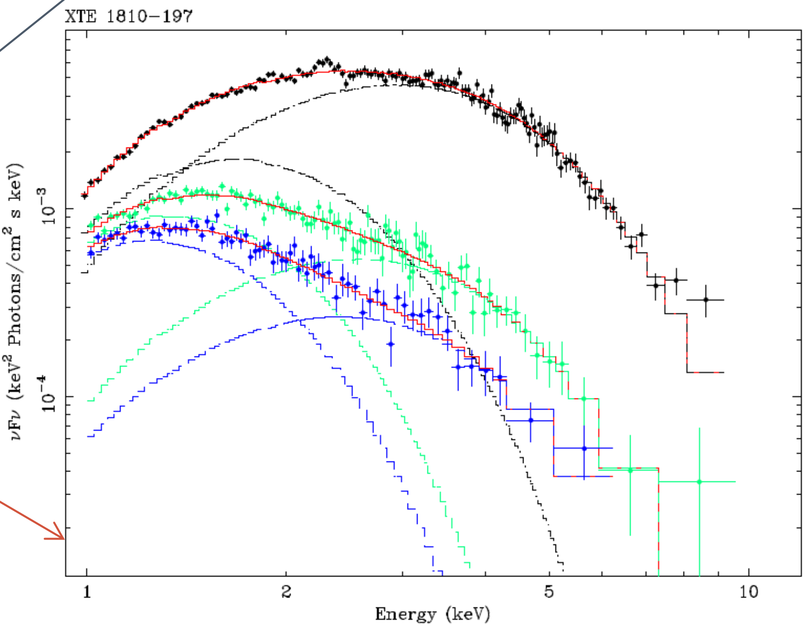
- 0.5 – 10 keV persistent emission well represented by a blackbody plus a power law
- kT_{BB} ~ 0.5 keV, does not change much in different sources
- Photon index $\Gamma \approx 1 - 4$, AXPs tend to be softer
- SGRs and AXPs are variable (days/months; much more dramatic in “transients”)
- Variability mostly associated with the non-thermal component
- Transient spectra can be BB+BB, T_{BB} and R_{BB} decrease in time





SGR 1806-20 at different epochs (BB+PL)

AXP 1E 2259-586 (BB+PL)



Transient AXP XTE 1810-197 at different epochs (BB+BB)

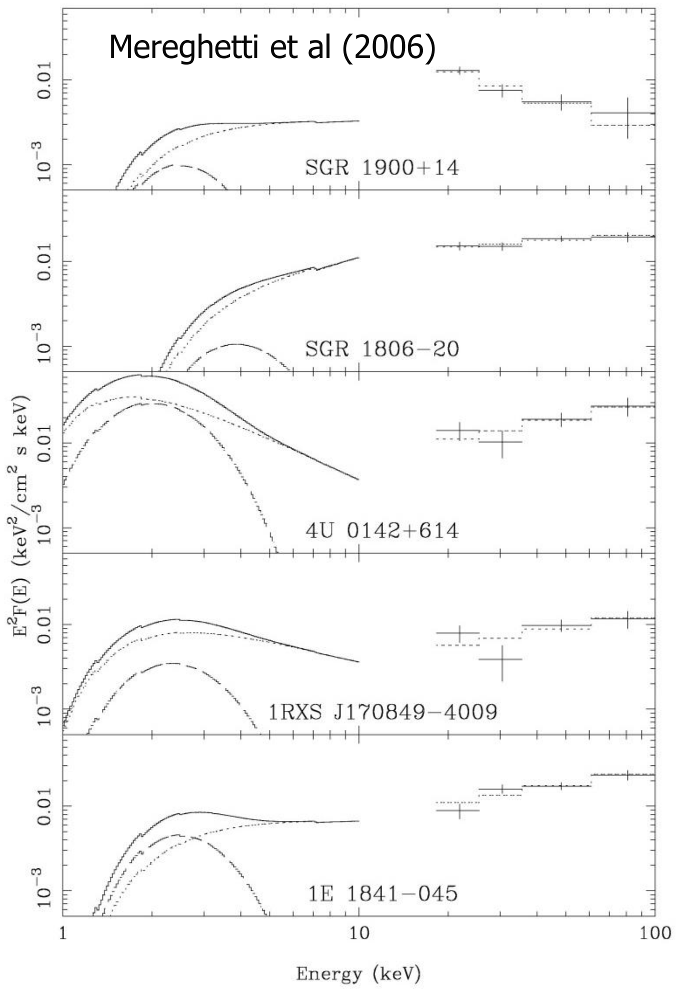
XMM Epic-pn data (Rea el al. 2008)

Hard X-ray Emission

INTEGRAL revealed substantial emission in the 20 -100 keV band from SGRs and AXPs

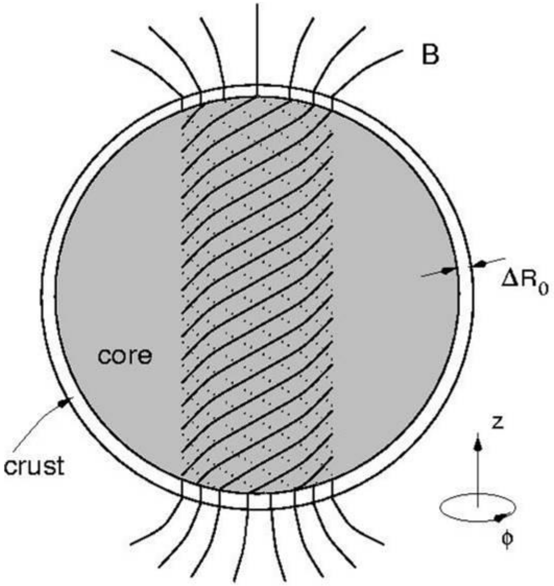
Hard power law tails with Γ ≈ 1-3, hardening wrt soft X-ray emission required in AXPs

Hard emission highly pulsed

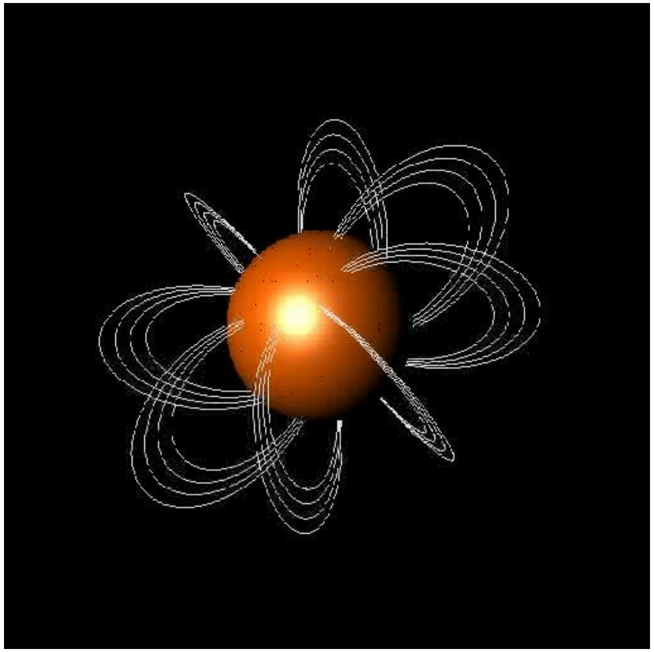


Twisted Magnetospheres

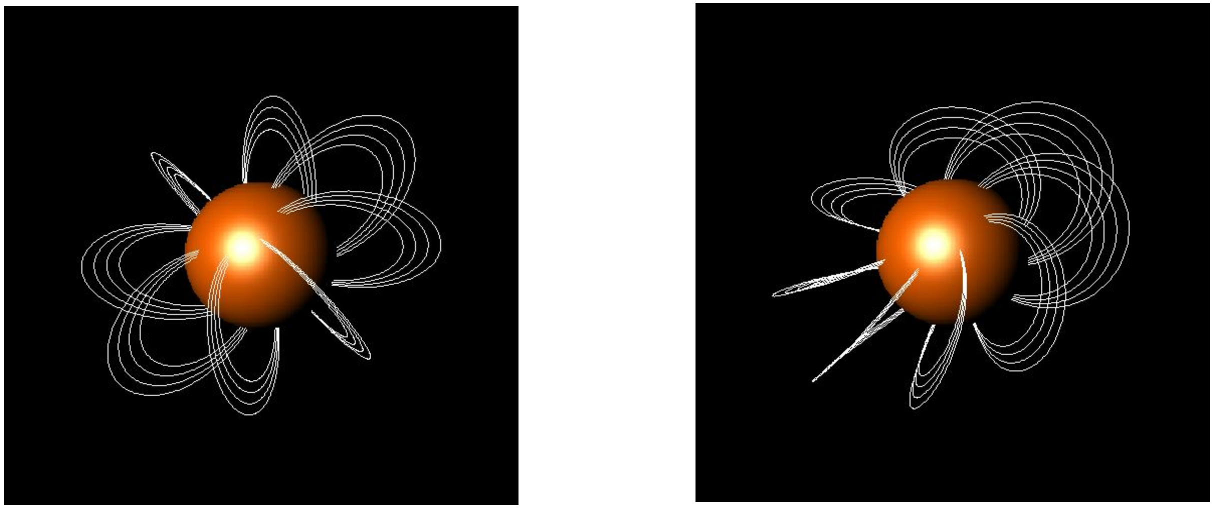
- The magnetic field inside a magnetar is “wound up”
- Magnetic stresses deform/rupture the crust
- The external field twists up (Thompson, Lyutikov & Kulkarni 2002)



Thompson & Duncan (2001)



Magnetospheric Currents



$$\vec{\nabla} \times \vec{B} = 0$$

$$\vec{j} = \frac{c}{4\pi} \vec{\nabla} \times \vec{B}$$

Contrary to PSRs, currents flow (also) along the closed field lines and $j \gg j_{GJ}$

Resonant Compton Scattering

- The current flowing along the closed field lines is

$$\vec{j} = \left(\frac{c}{4\pi}\right)\vec{\nabla}\times\vec{B} \Rightarrow n_e = \frac{p+1}{4\pi e}\frac{B_\varphi}{B_\theta}\frac{B}{r|\langle\beta\rangle|} \approx 10^{14}\ \mathrm{cm}^{-3}$$

- The optical depth for Thomson scattering is low, $\tau_T \approx n_e\sigma_T r \approx 10^{-4}$
- Contrary to a non-magnetized medium, magnetic scattering is energy- and mode-dependent
- Resonances at the cyclotron harmonics

$$E_n = n\hbar\omega_B = n\frac{eB}{mc}$$

Moving electron → $\omega_D = \dfrac{\omega_B}{\gamma(1-\beta\cos\theta)}$

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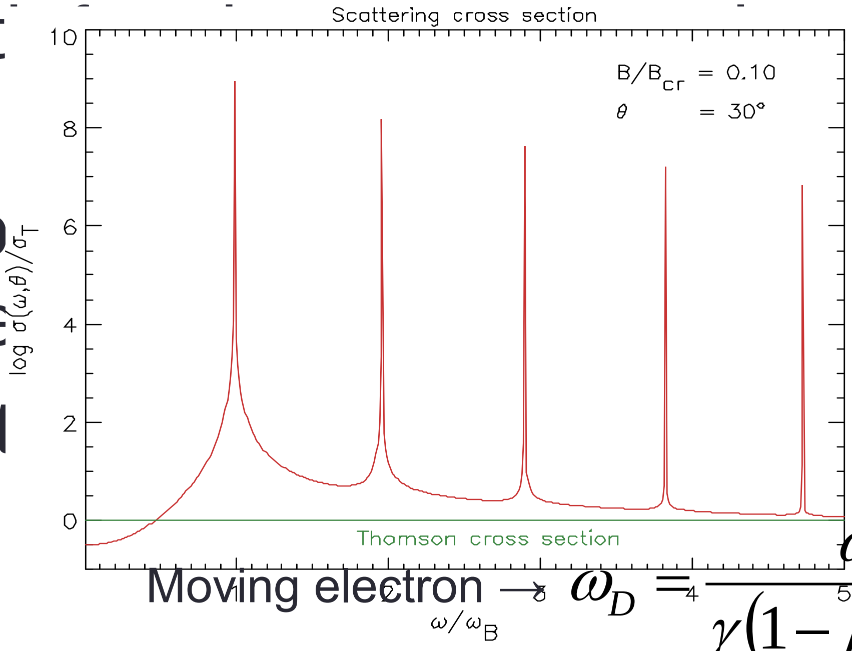
- The optical dept is low, $\tau_T \approx n_e\sigma_T r \approx 10^{-4}$
- Contrary to a no agnetic scattering is ene t
- Resonances at t



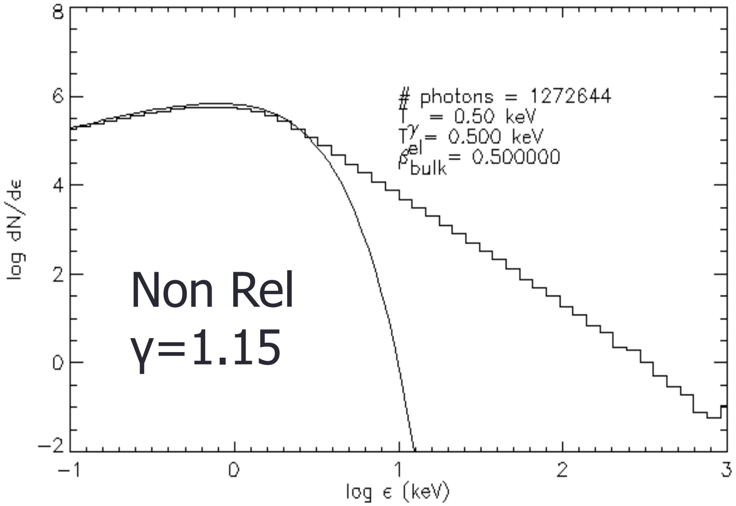
$$E_n = n\hbar\omega_B = n\frac{eB}{mc}$$

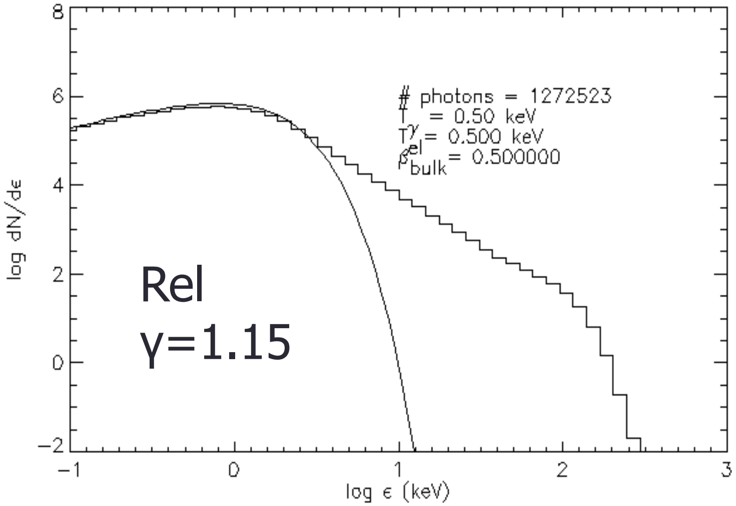
Moving electron → $\omega_D = \dfrac{\omega_B}{\gamma(1-\beta\cos\theta)}$

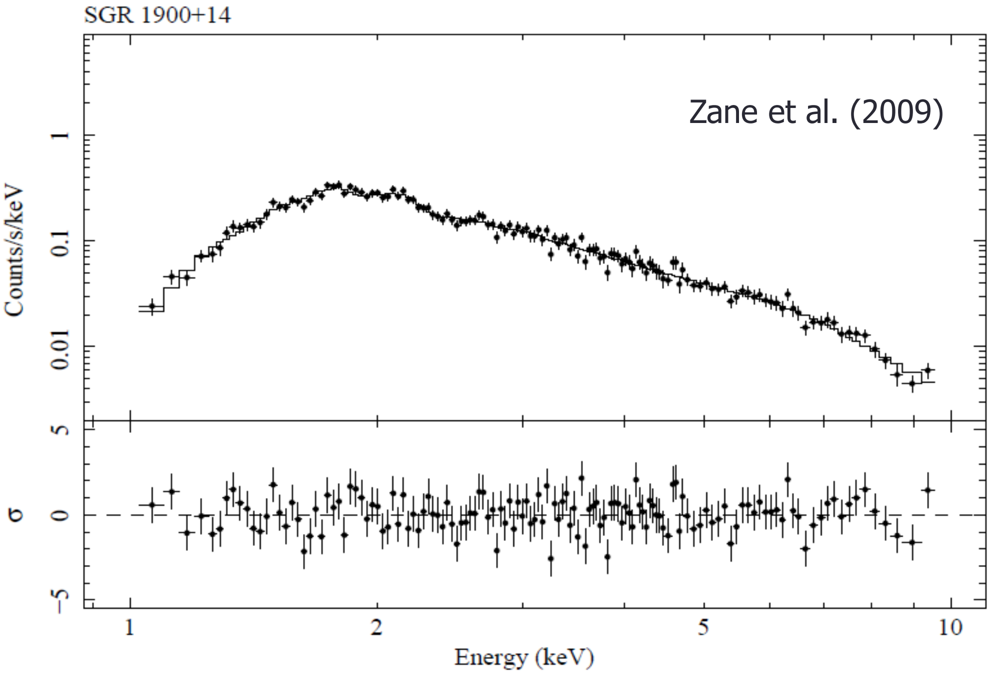
At resonance $\sigma \approx 10^5 \sigma_T \rightarrow$ large optical depth to resonant cyclotron scattering (RCS)

Repeated scatterings lead to the formation of a power-law tail because $\omega_D = \omega_D(r,\theta)$ and $r_{current} > R_{NS}$

Spectral formation in twisted magnetospheres investigated quite in detail using Montecarlo methods (Lyutikov & Gavriil 2006; Fernandez & Thompson 2007; Nobili, Turolla & Zane 2008a, b)







RCS models quite successful in explaining magnetars soft X-ray spectra (~ 0.5 – 10 keV) and also high-energy tails (no spectral break, SGRs)

Spectral fits provide information on the physical state of the star/magnetosphere (twist angle, charge velocity, surface temperature, etc)

Unidirectional electron flow !

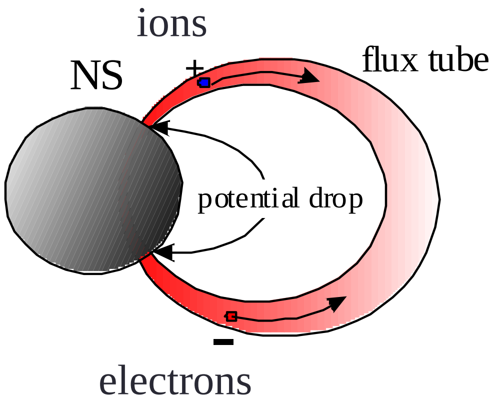
Magnetospheric Currents - II

The twist must decay to support its own currents. A parallel electric field develops which accelerates the charges along the flux tube (Beloborodov & Thompson 2007; Beloborodov 2009)

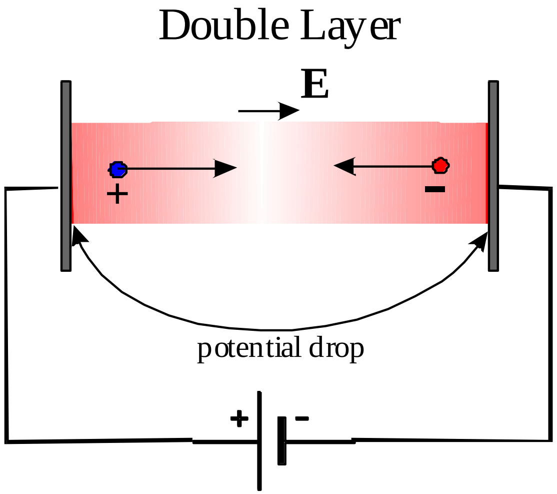
$$\frac{\partial(B_\phi^2/8\pi)}{\partial t} = -E_\parallel j \qquad \frac{\partial E_\parallel}{\partial t} = 4\pi(j_B - j)$$

The electric field is self-regulated to ensure that the required current flows in the circuit

A potential drop Φ is maintained between the footpoints j = j(Φ) depends on the nature of the discharge and this fixes the duration of the twist



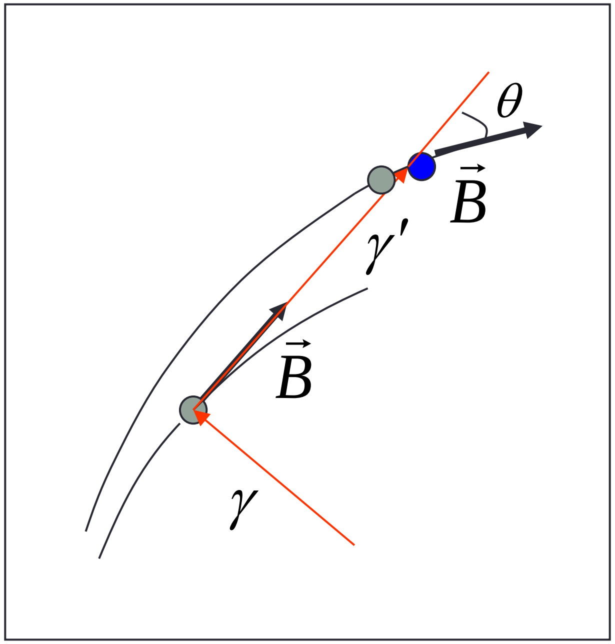
A simple analogue



In a relativistic double layer $$j \propto \frac{m_e}{m_i}\Phi^2, \gamma_e \approx 1 + \frac{e\Phi}{m_e c^2}$$

Φ (and $E_{\|}$) must be huge ($\approx 10^{12}$ GeV) in order to produce j_B: $\gamma_e \approx 10^9$ and the twist decays immediately

Where B > $2B_Q$, 1 keV photons scatter onto γ > 1000 electrons
Scattered photons have energy ε’ in the MeV range and initially propagate along B



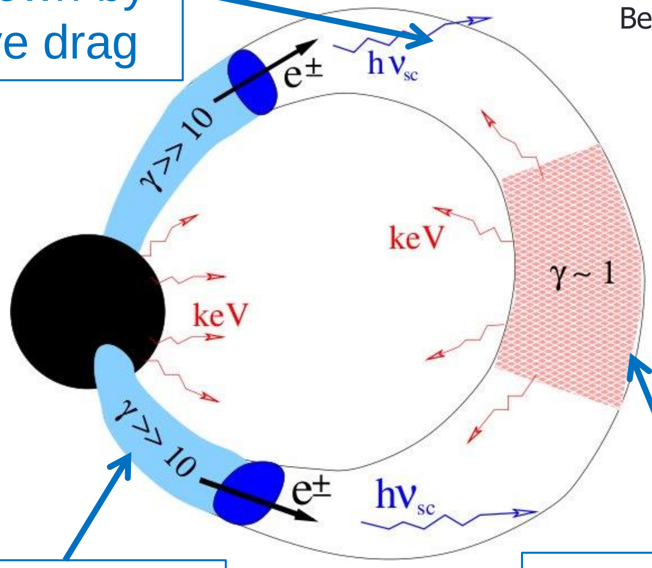
They quickly convert into pairs via

$$\gamma + B \rightarrow e^{+} + e^{-} + B$$

as soon as $\varepsilon' > \frac{2m_e c^2}{\sin\theta}$

Pair production along the circuit screens the potential: j_B can be conducted with $\Phi \ll \Phi_{DL}$

Bidirectional pair flow !

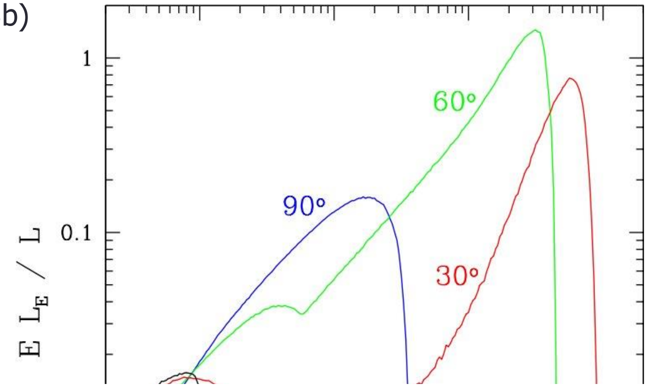


Slow-down by radiative drag

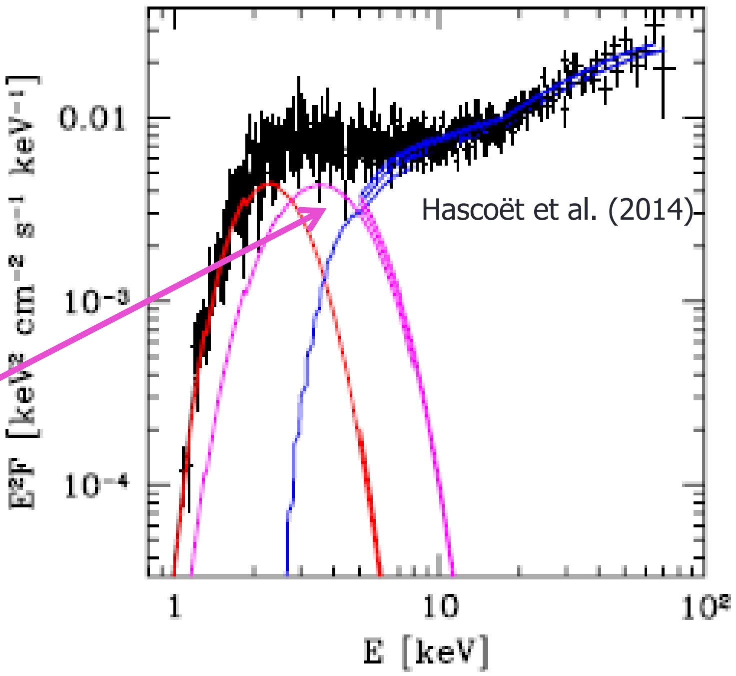
pair creation

pair annhilatio

Beloborodov (2013b)



1E 1841−045



Hascoët et al. (2014)

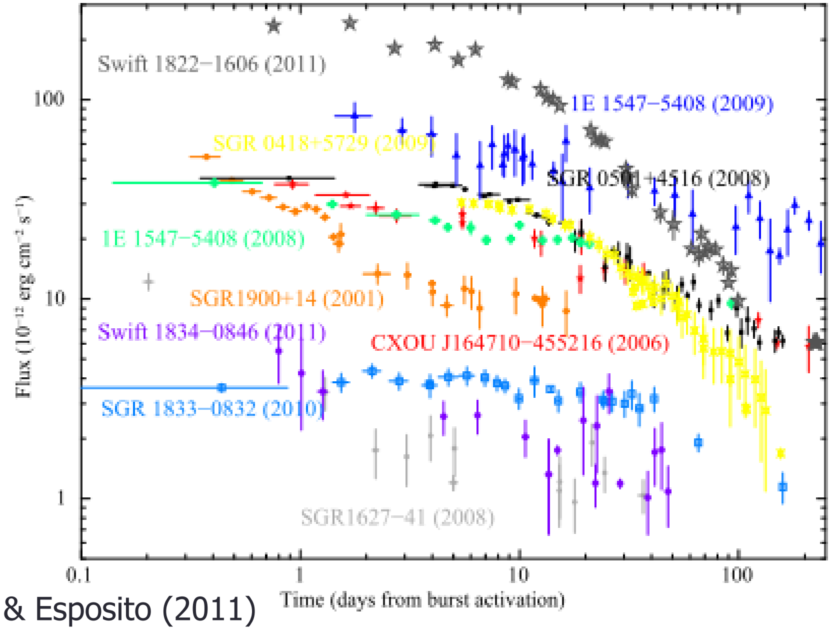
Pairs are still rather fast

All right to explain the hard tails
Needs another component to account for the soft X-rays

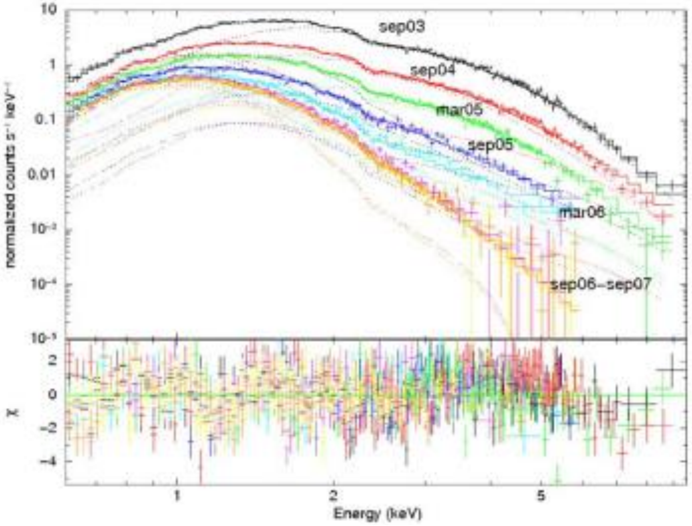
Transient Magnetars

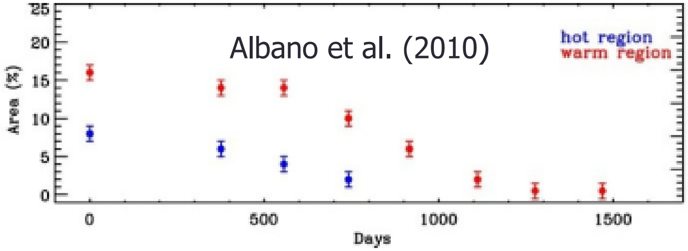
- Sudden increase (≈ hrs) of the persistent flux (≈ 10-1000 over quiescent level)
- Emission of bursts
- Outbust duration months/years
- X-ray spectrum is often thermal (BB+BB, kT ~ 0.3 – 0.9 keV)
- Small emitting area (R_{BB} < 1 km) which shrinks and cools as the outburst declines
- All magnetars discovered in the last 10 yrs are transients (exception is CXOU J171405.7-381031), including the 2 (3?) “low-field” sources

XTE J1810-179



Rea & Esposito (2011)





Albano et al. (2010)

Outbust Models

Heating produced by energy deposition in a limited region of the star surface

Deep crustal heating

(Lyubarsky et al. 2002; Rea & Pons 2012)

- $10^{40} < E < 10^{43}$ erg
- $kT_{max} \sim 0.5$ keV
- nearly constant radius

Surface heating by backflowing currents

(Beloborodov 2009)

- as the twist decays the j-bundle shrinks
- $L \sim R^2 \sin^4\theta$

Deep crustal heating (a la Pons & Rea)

- Ok for the early decay of Swift J1822.3-1606 (< 250 d; Rea et al. 2012)
- Overpredicts the flux at later times (SGR 0418+5729, Rea et al. 2013; SGR 0418+5729, Rodriguez et al. 2014; Swift J1834.9-0846, Esposito et al. 2013)
- No variation of the size of the emitting region, as observed in several sources (e.g. XTE J1810-179)

Current heating (a la Beloborodov)

- Ok for XTE J1810-179
- Luminosity too low to explain sources with $B < 10^{14}$ G if twist extent consistent with observed emitting area (SGR 0501+4516, SGR 0418+5729; Rea et al., 2009, 2013)
- No clear observational indication of $L \sim A^2$ during the decay

The “Low-Field” Magnetars

- Three peculiar magnetar candidates discovered since 2009: SGR 0418+5729 (van der Horst et al. 2010, Esposito et al. 2010, Rea et al. 2010), Swift J1822.3−1606 (Rea et al. 2012, Scholz et al. 2012) and 3XMM J1852+0033 (Rea et al. 2014)
- All the features of a (transient) magnetar
  - Rapid, large flux increase and decay
  - Emission of bursts
  - $P \approx 8\text{-}11$ s, $\dot{P} < 10^{-13}$ s/s,
  - $B < 4\text{x}10^{13}$ G ($B = 6\text{x}10^{12}$ G in SGR 0418+5729)

Neutron Star Evolution

- Rotational evolution

$$I\Omega\dot{\Omega} = -\frac{B_p^2 R^6 \Omega^4 \sin^2 \alpha}{6c^3}$$

- Thermal evolution

$$\frac{dE_{th}}{dt} = c_v \frac{dT}{dt} = -L_\nu - L_\gamma$$

Neutrino luminosity

Photon luminosity

- Magnetic evolution

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \left\{ \eta \nabla \times \vec{B} + \frac{c}{4\pi e n_e} \left(\nabla \times \vec{B}\right) \times \vec{B} \right\}$$

Ohm

Hall

Faraday induction equation
η is the magnetic diffusivity and strongly depends on T
Coupled thermal and magnetic evolution !

Magneto-thermal Evolution

(Pons, Miralles & Geppert 2009; Viganò et al. 2013)

Faraday induction equation

η is the magnetic diffusivity and strongly depends on T

Cou

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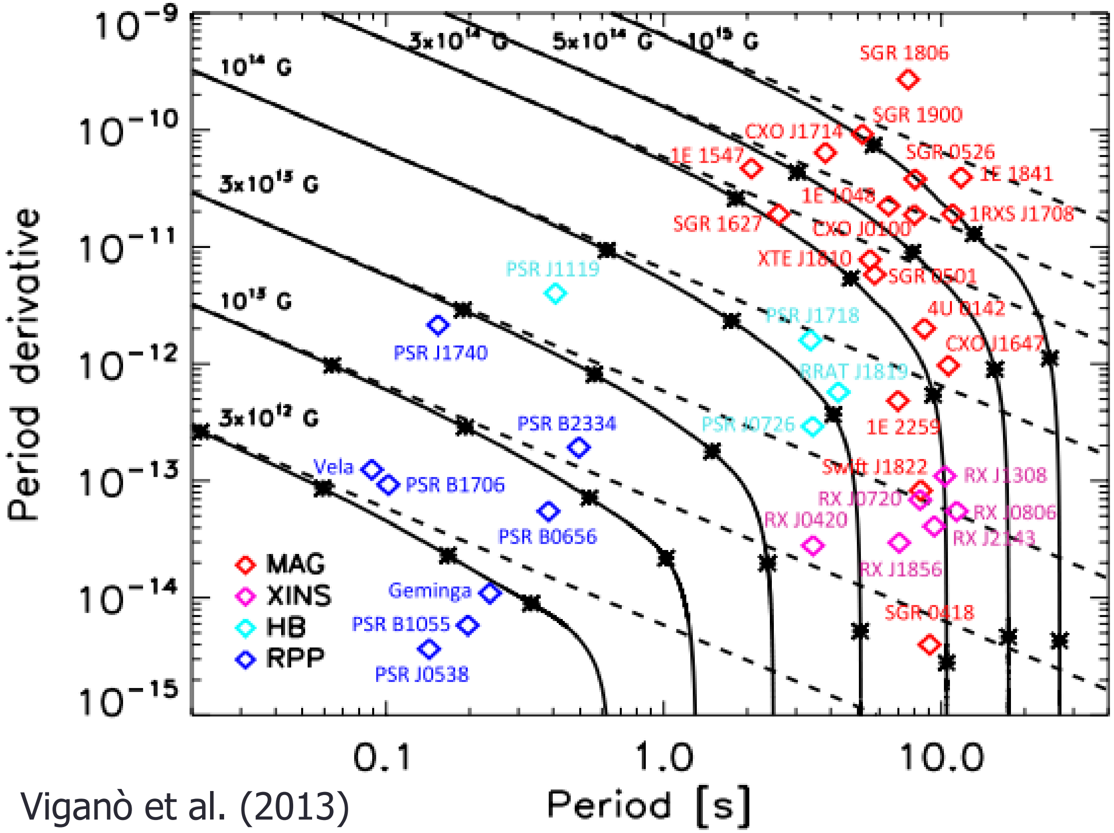
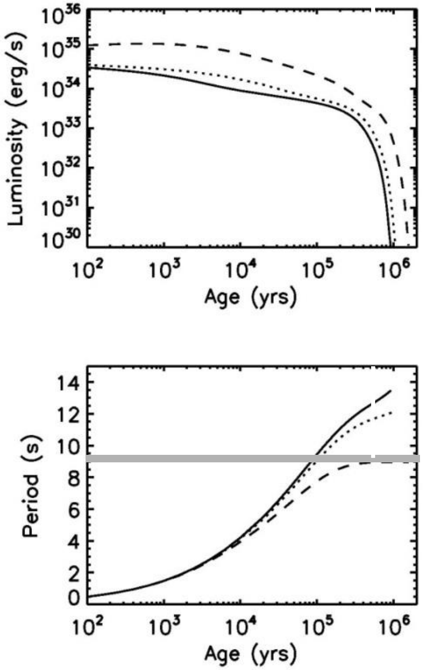


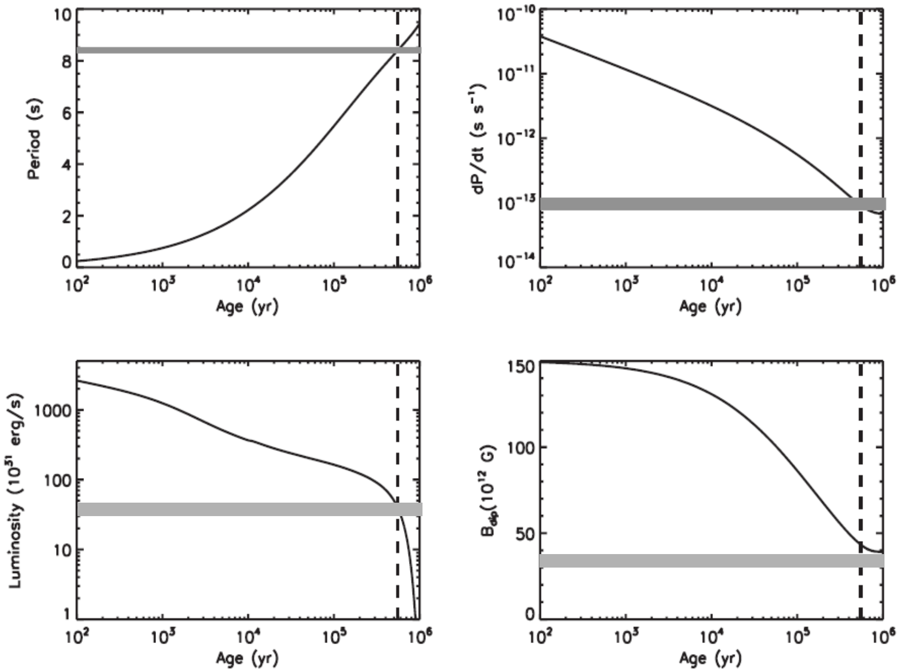
Viganò et al. (2013)

Are low-field sources old ?

SGR 0418 (Turolla et al. 2011)



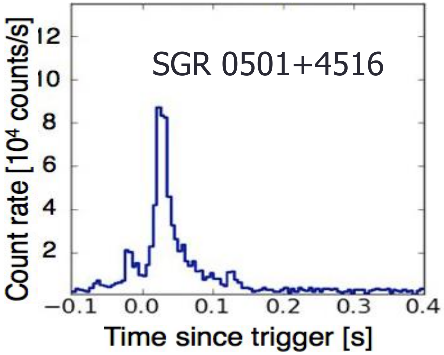
SGR 1822 (Rea et al. 2012)

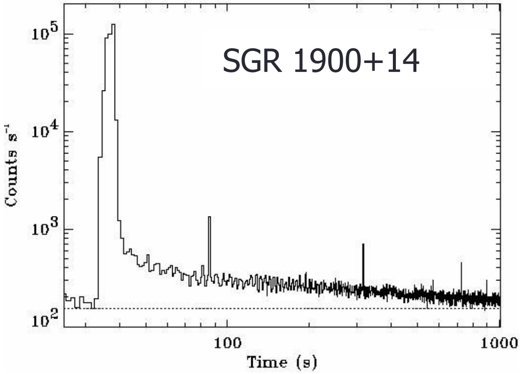


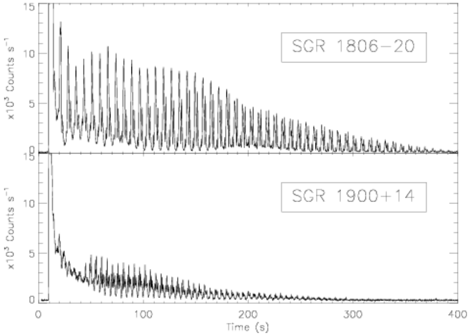
“Low-field” sources look indeed oldish (≈ 10^6 yr) magnetars in which the surface magnetic field substantially decaied

Bursts & Flares

- Short bursts
  - t ~ 0.1 – 1 s, L ~ 10^{39} – 10^{41} erg/s , thermal spectrum (kT ~ 10 keV), seen in both SGRs and AXPs
- Intermediate bursts
  - t ~ 1 – 40 s, L ~ 10^{41} – 10^{43} erg/s , thermal spectrum, seen in both SGRs and AXPs
- Giant flares
  - only three observed, each from a different SRG, L ~ 10^{44} – 10^{47} erg/s, initial spike (~ 0.1s) + pulsating tail (~ 100 s)







Burst Trigger Mechanism(s)

Rapid magnetic field reconfiguration is a key ingredient, but no precise model as yet

Secular magnetic evolution builds stresses that are released catastrophically in the bursts

Alvén speed

$$v_A = 10^8 \mathrm{cm/s} \left(\frac{B}{10^{16} \mathrm{G}} \right) \left(\frac{10^{15} \mathrm{g/cm}^3}{\rho} \right)^{1/2}$$

Shear velocity

$$v_s = 1.1 \times 10^8 \mathrm{cm/s} \left(\frac{\rho}{10^{14} \mathrm{g/cm}^3} \right)^{1/6} \left(\frac{Z}{38} \right) \left(\frac{302}{A} \right)^{2/3} \left(\frac{1 - X_n}{0.25} \right)^{2/3}$$

- Magnetic evolution leads to an unstable configuration in the core ⇒ MHD instabilities with growth time $\approx R/v_A \approx 0.1$ s
- Magnetic stresses rupture the crust ⇒ release of elastic energy over a timescale $\approx \pi R/v_s \approx 0.3$ s
- Core and crust evolve smoothly, stresses are released in the magnetosphere via plasma instabilities/magnetic reconnection ⇒ very short timescale, < 0.01 s ($v_A \sim c$)

All three scenarios provide timescales in rough agreement with burst duration/rise time

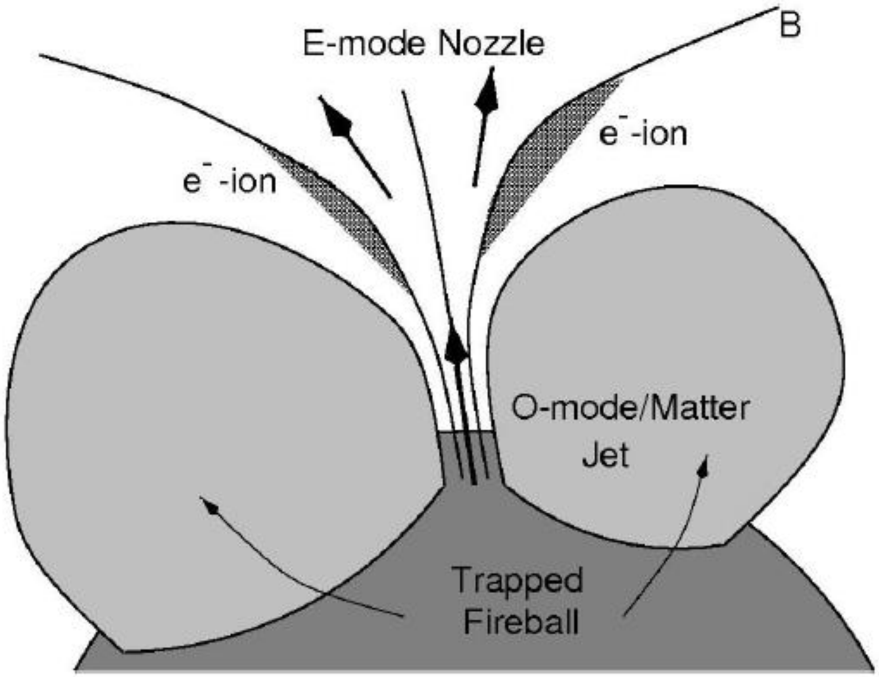
Correct energetics (including giant flares)

Burst Emission

- Magnetic reconfiguration produces particle acceleration
- Electrons moving along the curved field lines emit γ-rays which drive a pair cascade
- The pair plasma is confined by the magnetic field if

$$B_{\rm dipole} > 2 \times 10^{14} \left(\frac{E_{\rm fireball}}{10^{44}\ {\rm erg}} \right)^{1/2} \left(\frac{\Delta R}{10\ {\rm km}} \right)^{-3/2} \left(\frac{1 + \Delta R/R}{2} \right)^{3}\ {\rm G}$$

- Confinement leads to an optically thick "fireball"
- Radiation escapes preferentially in the X-mode, due to the much reduced opacity

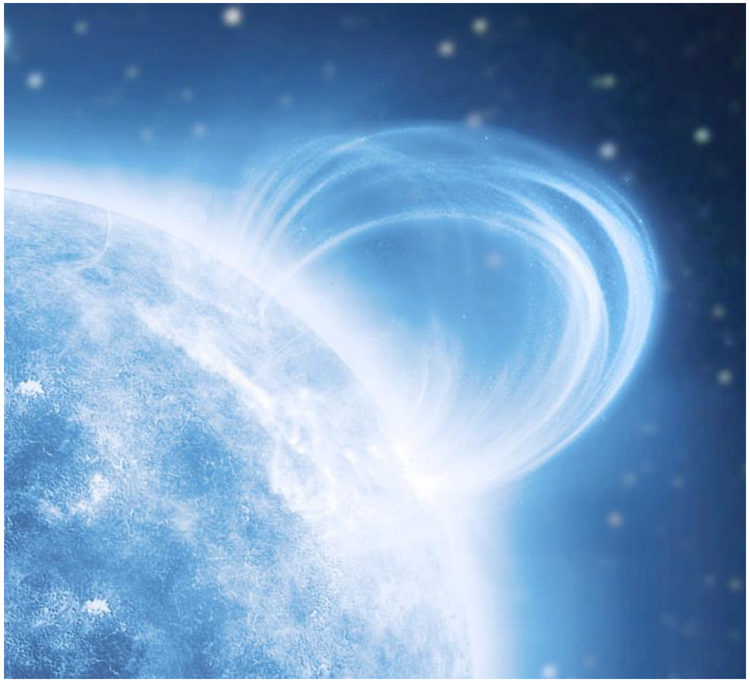


No detailed model for burst emission available as yet

Future Developments

- Further support to the magnetar model: search for cyclotron line in other sources (preliminary results promising)
- Twisted magnetosphere model in general agreement with observations; hard vs soft power-laws
  - Nustar (and ASTRO-H)
  - More detailed modeling of magnetospheric currents
- Magnetar emission polarized: polarization measures key
- Only a general picture for the burst emission: need a quantitative model to compare with observations
- Extragalactic magnetars: relation with (long) GRBs ?
- The neutron star zoo: evolutionary links among different classes

An addendum to Andrea's talk



An artist impression of SGR 0418 with the ejected magnetic loop

Of course, reality is a trifle more complicated…