Emission Model(s) of Magnetars

Silvia Zane, MSSL, UCL
on behalf of a large team of co-authors

"Current Understanding and Future Studies of Magnetars: Research Strategy in the Astro-H era."

A celebration in honour of
Prof Noriaki Shibazaki

Tokyo, Japan, 1th Sept 2012

- SGRs/AXPs as “magnetars”, the most extreme compact objects
- Multiband emission mechanisms - from Radio-IR to X-rays
Congratulations to Prof Noriaki Shibazaki

- X-ray bursts, X-ray transients, Soft X-ray sources
- Pulsars, low mass binaries, Galactic buldge sources
- QPOs
- SNRs
- Theoretical studies
- Envelope oscillations
- Gamma ray lines
- NS evolution, interior and instabilities
- Accretion
- GRBs, jets
- Magnetars
- Suzaku
- ... and lots and lots more!!
MAGNETARs: the most extreme NSs

(Isolated) neutron stars where the main source of energy is the (super-strong) magnetic field

Most observed NS have $B = 10^9 - 10^{12} \text{ G}$ and are powered by accretion, rotational energy, residual internal heat

$$B \geq B_{\text{QED}} \approx 4.41 \times 10^{13} \text{ G} : \text{quantum effects important}$$

In Magnetars:
- External field: $B = 10^{14} - 10^{15} \text{ G}$
- Internal field: $B > 10^{15} \text{ G}$

Low field magnetars: SGR0418+5279 and SGR1822: still a quite large internal component, >50-100 times larger than Bdip

## AXPs/SGRs: magnetar candidates

<table>
<thead>
<tr>
<th>Source</th>
<th>P (s)</th>
<th>Pdot (s/s)</th>
<th>Hard-X</th>
<th>Short bursts</th>
<th>Outbursts</th>
<th>Association</th>
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<td>6.978948446 (39)</td>
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</table>
Soft X-ray spectra

- 0.5 - 10 keV emission well represented by a blackbody plus a power law: WHY??
- Long term spectral evolution, with correlation among some parameters (as spectral hardening, luminosity, spin down rate...)
- Evolution of "transient" AXPs

AXP 1E1048-5937; from Rea, SZ et al, 2008
- Black, blue, green are taken in 2007, 2005, 2003 (XMM-Newton)
- Red lines: total model, dashed lines: single BB and PL components
Multiband Emission: hard X-rays

- INTEGRAL revealed substantial emission in the 20-100 keV band from SGRs and AXPs
- Hard power law tails, $\Gamma \approx 1-3$
- Hard Emission pulsed
Multiband Emission: hard X-rays

Sasamz Mus and Gogus 2011

Integral/Comptel/Fermi SED of 4U0142+61

Also, no detections so far from the Fermi-LAT team (ApJ, 2010)
Multiband Emission: Optical/IR

- Also, Optical/IR!
- Faint K~19-21 and sometimes variable IR counterparts
- Fossil disk or inner magnetosphere?

Durant and van Kerkwijk 2005
Twisted magnetospheres

Twisted magnetospheres support large current flows (>>>of the Goldreich-Julian current).

Thermal seed photons (i.e. from the star surface) travelling through the magnetosphere experience efficient resonant cyclotron scattering onto charged magnetospheric particles (e- and ions)

⇒ the thermal surface spectrum get distorted
⇒ typical PL tail.

This can explain the BB+PL spectral shape observed <10keV.

See also Daniela’s talk
A Monte Carlo Approach

(Nobili, Turolla, SZ 2008a,b)

- Follow individually a large sample of photons, treating probabilistically their interactions with charged particles
- Can handle very general (3D) geometries
- Quite easy to code, fast
- Ideal for purely scattering media
- Monte Carlo techniques work well when $N_{\text{scat}} \approx 1$

Basic ingredients:
- Space and energy distribution of the scattering particles
- Same for the seed (primary) photons
- Scattering cross sections
A Monte Carlo Approach

Surface Emission

Magnetosphere setting (twisted dipole)

Radiative transfer, Monte Carlo code

GOAL: probe the magnetospheric properties of the neutron star via spectral analysis of X-ray data

(Nobili, Turolla, SZ 2008a,b; SZ, Rea, Turolla & Nobili, 2009)

Predicted spectra, lightcurves, polarization to be compared with X-ray data
Photon propagation in a magnetized medium

- Magnetized plasma is anisotropic and birefringent, radiative processes sensitive to polarization state
- Two normal modes of photon propagation: ordinary (O) and extraordinary (X) mode

Thomson Scattering Magnetic Cross Sections

Completely differential cross sections at resonance (ERF)

\[ \left. \frac{d\sigma}{d\Omega'} \right|_{o-o} = \frac{3\pi r_0 c}{8} \delta(\omega - \omega_c) \cos^2 \theta \cos^2 \theta' \]
\[ \left. \frac{d\sigma}{d\Omega'} \right|_{x-x} = \frac{3\pi r_0 c}{8} \delta(\omega - \omega_c) \]
\[ \left. \frac{d\sigma}{d\Omega'} \right|_{x-o} = \frac{3\pi r_0 c}{8} \delta(\omega - \omega_c) \cos^2 \theta' \]

\[ r_0 = \frac{e^2}{mc^2}, \omega_c = \frac{eB}{mc}, \theta, \theta' \text{ angles between photon and particle} \]

velocity before and after scattering
Relativistic QED second order cross section (transition from the ground to an arbitrary state $f$):

\[
\left( \frac{\partial^2 \sigma}{\partial \phi' \partial \mu'} \right)_{s,f} = \frac{3\sigma_T}{16\pi} \frac{\omega' (2 + \omega - \omega') e^{-(\omega^2 \sin^2 \theta + \omega'^2 \sin \theta')/2B}}{(1 + \omega - \omega' - \Delta \cos \theta')} \sum_{n=0}^{\infty} \sum_{i=1}^{2} (F^{(1)}_{n,i,s,f} + F^{(2)}_{n,i,s,f})^2
\]

(resonant terms)

F’s are complicated complex functions that depend on
- $n$ - intermediate (virtual) Landau level
- $i$ - electron spin of the intermediate excited state
- $f$ - electron spin of the final state
- $s$, $s'$ - initial and final photon polarization states
**XSPEC implementation:**

- Build up a huge archive of models
- \( B = 10^{14} \, G \)
- \( \gamma_{\text{bulk}} - 1 = 2^{[1/(1+T_e)]/T_e} \); then \( T_e = T_e/2 \)
  
  (bulk kinetic energy = av. \( E_{th} \) for a 1D Maxwellian; \( T_e = kT_e/m_e c^2 \))

- The resulting archive is a 22MB table with 4 model parameters:
  \( T, \beta_{\text{bulk}}, \Delta \phi \) + a normalization constant \( \Rightarrow \) same number of degree of freedom as in the BB+PL model

Note: we also built up a second archive (300 MB table) with viewing angles effects included

For the viewing angle geometry we need to include two further dof, i.e. two angles which describe the disalignement between magnetic, spin axis and LOS \( (0 \leq \chi \leq 180 \text{ and } 0 \leq \xi \leq 90) \)

(Nobili, Turolla, SZ 2008a,b)
XSPEC Implementation and fit of all magnetars spectra (<10 keV)
SZ, Rea, Turolla and Nobili MNRAS 2009

fit with NTZ model only

1RXS J1708-4009
\( \chi^2 = 0.97 \) (197)

CXOU J0100-7211
\( \chi^2 = 1.21 \) (101)

SGR 1627-41
\( \chi^2 = 1.16 \) (81)

SGR 1900+14
\( \chi^2 = 0.99 \) (135)

1E 1841-045
\( \chi^2 = 1.04 \) (152)
reproducing the source long-term evolution: fit with NTZ only

\[ \chi^2 = 1.11 \ (164) \]
\[ \chi^2 = 1.22 \ (515) \]
\[ \chi^2 = 0.98 \ (288) \]
reproducing the Transient AXPS evolution

XTE J1810-197: 8 XMM observations between Sept 2003 and Sept 2007: coverage of the source during 4 years. Unique opportunity to understand the phenomenology of TAXPs.

FIRST TIME A JOINT SPECTRAL/TIMING MODELLING WITH A MODEL BASED ON 3D SIMULATIONS!

+ similar for CXOU J164710.2-455261

Albano, SZ et al, 2010
From TAXP XTE J1810-197, 3T thermal map:

- Soon after the outburst \( \Rightarrow \) surface thermal map with 3 components: hot cap, surrounding warm corona, rest of the NS surface cooler

- Hot cap decreases in A and T indistinguishable from the corona \(~\text{March '06}.\)

- Warm corona shrinks at \( T_w \sim 0.3 \text{ keV} \sim \text{const.} \)
  Still visible in our last observation (Sept. '07), with a size down to 0.5% of the NS surface.

- Rest of the NS: \( T \sim \text{ROSAT (quiescent)}, \) during the entire evolution

- \( \Delta \Phi \) decreases (\(~0.8 \text{ rad to } ~0.5 \text{ rad}\)) during the first two years, then \(~\text{constant}.\)

\( \chi \sim 148^\circ \quad \xi \sim 23^\circ \)

Albano, SZ et al, 2010
(Good) Results:

- A self-consistent spectral and timing analysis, based on realistic modelling of resonant scattering, explain TAXPS outburst (a large number of datasets over a baseline of years). Similar strategy applied to TAXPs XTE J1810-197, CXOU J164710.2-455261 (Albano, SZ et al, 2010) and 1e1547 (Bernardini, SZ et al 2011)

- 3D model of resonant scattering of thermal, surface photons reproduces almost all AXPs and SGRs spectra below 10keV with no need of extra components and their long term evolution

- Twisted magnetosphere model, within magnetar scenario, in general agreement with observations

Caveats:

- Results support to a picture in which only a limited portion of the magnetosphere was affected by the twist (see also Beloborodov 2009)

- Future developments will require detailed spectral calculations in a magnetosphere with a localized twist which decays in time.

- Major source of uncertainty is the nature and energy distribution of scattering particles

- Charge velocity is a model parameter. Fits require mildly relativistic particles, $\gamma_e \sim 1$
Hard X-ray: effects of velocity and B-field topology

Nobili, Turolla and SZ, 2008. QED calculations

Hard X-ray: effects of B-field topology

Vigano, SZ et al, 2012 Astro-ph 1111.4158
Hard X-ray emission is expected:

- RCS onto the magnetospheric charges or curvature emission produce LOT of hard X-ray emission (probably, in certain cases, too many to be compatible with Comptel and Fermi UL!)
- But the spectral details depend dramatically on $v$ and $B$ fields
- No quantitative prediction possible!

Need to break the degeneracy...

- Coupled spectral and timing simulations
- More sensitive hard X-rays observations: PPS, detailed of the spectral turn-over soft/hard X-rays: Astro-H?
IR Emission: the inner magnetospheric origin?

A thermal photon scatters where:

\[ \gamma (1 - \beta \cos \vartheta) \epsilon = \epsilon_B = m_e c^2 \frac{B}{B_Q} \]

- Photon energy in the particle frame
- Local cyclotron energy

\[ \gamma = \gamma_{res} \sim \frac{m_e c^2}{\epsilon} \frac{B}{B_Q} \]

1) \( \lambda_{acc,res} \ll L \) e\( \pm \) can accelerate up to \( \gamma_{res} \) before the end of the flux tube

2) \( \lambda \ll \lambda_{acc,res} \) the mean free path for RCS is shorter than the acceleration length

If the moving charges are e\( \pm \) \( \frac{B}{B_Q} \geq 0.05 \) \( \frac{R}{R_{NS}} \leq 6 \)
A region of intense pairs creation near the footpoints:

\[
\gamma + B \rightarrow e^+ + e^- + B
\]

\[
\varepsilon' \sim \gamma_{\text{res}}^2 \varepsilon / (1 + \gamma_{\text{res}} \varepsilon / m_e c^2) > 2m_e c^2 / \sin \theta'
\]

\[
\alpha_{\pm} \geq 1 / R_{NS}
\]

The second condition is verified in all this region for pairs created near threshold

\[
e\Phi / m_e c^2 \approx \gamma_{\text{res}} \approx 500 \text{ B}/B_Q
\]

Charges undergo only few scatterings with thermal photons, but they loose most of their kinetic energy in each collision. A steady situation is maintained against severe Compton losses because electrons/positrons are re-accelerated by the E-field before they can scatter again.
Spectrum of the curvature radiation emitted by the fast-moving charges

- IR/optical emission is coherent (bunching mechanism, two stream instability, electron positron/electron ion)
- $N$ particles in a bunch of spatial scale $l$ radiate as a single particle of charge $Q = Ne$
- amplification of radiated power by a factor $N$ (Lesch 1998, Saggion 1975)
- $l \sim c/\nu_{pl}$

Zane, Nobili & Turolla, Aströ-phy 1008.1725 2011
A POSSIBLE SCENARIO

A: e± pairs generated from high energy RCS photons. 
γ≈1000
CR in IR/Optical

B: Mildly relativistic pairs slowed down to 
γ~ a few (Compton drag).
Soft X-ray spectra through RCS of surface thermal photons

B+C: γ~ 10^5 or more.
CR or RCS up to the high energy band (100-1000 KeV) INTEGRAL?

Nobili, Turolla, SZ, 2011
Overall Picture & Future Developments:

- Presence of an “intermediate” region populated by mildly relativistic pairs \( \Rightarrow \) RCS onto these charges may account for the soft X-ray spectra.
- Curvature radiation from pairs with \( \gamma \sim 1000 \) in the inner magnetosphere provides enough energy reservoir to account for the optical/IR emission (if bunching is active).
- The physical structure of the magnetosphere is still an open problem.
- Better model of the charge acceleration in the flux tubes / twist localized.
- More physical modeling of the high E emission.
- Curvature and RCS radiation from external regions may account for the INTEGRAL emission - a breaking mechanism is necessary not to violate Comptel UL (compton losses, etc..)
- Possible correlation between IR/hard Xrays, although independent fluctuations are expected.
“Magnetar activity” (bursts, outbursts, …) detected so far only in high-B sources ($B_p > 5 \times 10^{13} G$): AXPs+SGRs (♀) and PSR J1846-0258, PSR J1622-4950 (♀)

The ATNF Catalogue lists 20 PSRs with $B_p > 5 \times 10^{13} G$ (HBPSRs)

A high dipole field does not always make a magnetar, but a magnetar has necessary a high dipole field
SGR 0418+5729

- 2 bursts detected on 2009 June 05 with Fermi/GBM, spin period of 9.1 s with RXTE within days (van der Horst et al. 2010)
- All the features of a (transient) magnetar
  - Period derivative?

Monitoring now extends to ~ 900 d (as to mid 2012)

Positive detection of

\[ \dot{p} \sim 5.14 \times 10^{-15} \text{ s/s} \]
\[ B_p = 7 \times 10^{12} \text{ G} \]

(Rea et al. in preparation)

Previously reported upper limit

\[ B_p \sim 7.5 \times 10^{12} \text{ G} \] (Rea et al. 2010)

See also Daniela’s talk
More Coming: SGR 1822-1606

- Latest discovered magnetar, outburst in July 2011
- Monitored with Swift, RXTE, Suzaku, XMM-Newton and Chandra
- Quiescent source found in archival ROSAT pointings ($L_X \sim 4 \times 10^{32}$ erg/s)

\[ P = 8.44 \text{ s} \]
\[ \dot{P} = 8.3 \times 10^{-14} \text{ s/s} \]

\[ B_p = 2.7 \times 10^{13} \text{ G (second weakest after SGR 0418)} \]

\[ \tau_c = 1.6 \text{ Myr} \]  
(Rea et al 2012)

\[ \tau_c = 29.5 \text{ Myr for SGR 0418} \]
A Magnetar at Work

• What really matters is the internal toroidal field $B_\phi$

• A large $B_\phi$ induces a rotation of the surface layers

• Deformation of the crust $\Rightarrow$ fractures $\Rightarrow$ bursts/twist of the external field
Calculation of magnetic stresses acting on the NS crust at different times (Perna & Pons 2011; Pons & Perna 2011)

Max stress sustained by the crust as in Chugunov B Horowitz 2010

Activity strongly enhanced when $B_{\text{tor,0}} > B_{\text{p,0}}$

$B_{\text{tor,0}} = 2.5 \times 10^{16} \text{ G}$
$B_{\text{p,0}} = 2.5 \times 10^{14} \text{ G}$

$B_{\text{tor,0}} = 8 \times 10^{14} \text{ G}$
$B_{\text{p,0}} = 1.6 \times 10^{14} \text{ G}$
Is a large $B_{\text{tor}}$ necessary associated with a large $B_p$?

Clear that a dipolar $B$ is not enough to explain the variety in phenomenology: why some “high $B$” pulsars do not display bursts, while some “low field” SGRs do?
Are “low-field” SGRs Old Magnetars?

- **Main issues** (Turolla, SZ et al. 2011)
  - Spectrum of the persistent emission (OK)
  - $P$, $\dot{P}$ and $B_p$ from magneto-rotational evolution
  - Capacity of producing bursts

- **Clues** (Rea et al. 2010)
  - Large characteristic age (> 24 Myr)
  - Weak bursting activity (only 2 faint bursts)
  - Low dipole field ($B < 7.5 \times 10^{12} G$)
Magneto-rotational Evolution

- Long term 2D simulations of magneto-thermal evolution of a NS
- Coupled magnetic and thermal evolution (Pons, Miralles & Geppert 2009)
- Hall drift ambipolar diffusion, OHM dissipation (mainly crustal processes)
- Standard cooling scenario (Page et al. 2004), toroidal+poloidal crustal field, external dipole

\[ M = 1.4 \, M_\odot, P_0 = 10 \, \text{ms}, \]
\[ B_{p,0} = 2.5 \times 10^{14} \, \text{G} \]
\[ B_{\text{tor},0} = 0 \, (-), \, 4 \times 10^{15} \, (\cdots), \]
\[ 4 \times 10^{16} \, \text{G} \, (\cdots) \]

\[ P \sim 9 \, \text{s}, \, \dot{P} \sim 5 \times 10^{-15} \, \text{s/s}, \]
\[ B_p \sim 7 \times 10^{12} \, \text{G}, \, L_X \sim 10^{31} \, \text{erg/s} \]

for an age \( \sim 1 \, \text{Myr} \)

SGR 0418 (Turolla, SZ et al. 2011)
$B_{p,0} = 1.5 \times 10^{14} \, G$

$B_{\text{tor,0}} = 7 \times 10^{14} \, G$

$P \sim 8.5 \, s$, $\dot{P} \sim 8 \times 10^{-15} \, s/s$, 

$B_p \sim 3 \times 10^{13} \, G$, 

$L\chi \sim 3 \times 10^{32} \, \text{erg/s}$

for an age $\sim 0.5 \, \text{Myr}$

SGR 1822 (Rea, SZ et al. 2012)
Wear and Tear

Crustal fractures possible also at late evolutionary phases ($\approx 10^5 - 10^6$ yr; Perna & Pons 2011)

Burst energetics decreases and recurrence time increases as the NS ages

For $B_{p,0} = 2 \times 10^{14}$ G and $B_{\text{tor},0} = 10^{15}$ G, $\Delta t \approx 10 - 100$ yr

Very close to what required for SGR 1822

Fiducial model for SGR 0418 has similar $B_{p,0}$ and larger $B_{\text{tor},0}$ ⇒ comparable (at least) bursting properties

Young: 400-1600 yr (SGRs)
Mid age: 7-10 kyr (AXPs)
Old: 60-100 kyr (old AXPs)

(Perna and Pons 2011)
Inferences

SGR 0418+5729 (and SGR 1822-1606) is a low-B source: more than 20% of known radio PSRs have a stronger $B_p$.

Their properties compatible with aged magnetars $\approx 1$ Myr old.

A continuum of magnetar-like activity across the $P-\dot{P}$ diagram.

No need for a super-critical field.

See also Daniela’s talk.
Tuning in to Magnetars

- “Canonical” SGRs/AXPs are radio silent and have $L_X/L_{\text{rot}} > 1$

- Radio PSRs with detected X-ray emission have $L_X/L_{\text{rot}} < 1$

- Ephemeral (pulsed) radio emission discovered from XTE J1810−197, 1E 1547−5408 and PSR 1622−4950 after outburst onset

- Magnetar radio emission quite different from PSRs (flat spectrum, variable pulse profiles, unsteady)
All radio-loud magnetars have $L_X/L_{\text{rot}} < 1$ in quiescence.

The basic mechanism for radio emission possibly the same as in PSRs.

Active only in sources with $L_X/L_{\text{rot}} < 1$ (could be persistent radio emitters too).

What is producing the different behaviors?
Potential drop, $\Delta V = 4.2 \times 10^{20} (\dot{\mathcal{P}}/P^3)^{1/2}$ statvolt $\sim L_{\text{rot}}^{1/2}$

Radio: curvature from accelerated charge particles, extracted by the surface by the electrical voltage gap due to $B_{\text{dip}} \Rightarrow e+/e-$ pair cascade

Magneto-thermal evolution

- **HBPSR**, $B_{p,0} = 2 \times 10^{13} \ G$, $B_{\text{tor},0} = 0 \ G$
- **moderate magnetar**, $B_{p,0} = 2 \times 10^{14} \ G$, $B_{\text{tor},0} = 2 \times 10^{14} \ G$
- **extreme magnetar**, $B_{p,0} = 10^{15} \ G$, $B_{\text{tor},0} = 10^{16} \ G$

HBPSRs always stay in the “radio-loud” zone (cooling before slowing down)
moderate magnetars exit in $\approx 10$ kyr (slow down before cooling)
extreme magnetars exit in $< 1$ kyr (slow down even faster before cooling)
THANKS !