XMM-Newton reveals magnetars’ magnetospheric densities

Nanda Rea

University of Amsterdam
Astronomical Institute “Anton Pannekoek”
NWO Veni Fellow

In collaboration with:
Silvia Zane
Roberto Turolla
Maxim Lyutikov
Diego Gotz
Luciano Nobili
Introduction: Magnetars

- bright X-ray pulsars $L_x \sim 10^{33}-10^{36}$ erg/s
- rotating with periods of 2-12s
- large period derivatives
- glitches
- bursts on many timescales (ms to 100s)
- transient outbursts
- radio pulsars only during outbursts

Introduction: Magnetars

- Radio
- IR and optical
- Soft X-rays
- Hard X-rays
- Gamma-rays
Introduction: Magnetars

Main point: closed field lines in NS magnetospheres are not dead. Populated by hot, highly over-dense plasma, $n >> n_{GJ}$ (e.g. Thompson, Lyutikov & Kulkarni 2002; Liutykov & Gavriil 2006)

Twisted magnetospheres are filled with plasma which may modify radiation properties.

\[
\sigma_{RCS} \sim \left( \frac{R_L}{r_e} \right) \sigma_T \sim 10^5 \sigma_T
\]

with

\[
R_L \sim 8R_{NS} \left( \frac{B_{NS}}{B_{crit}} \right)^{1/3} \left( \frac{1\,\text{keV}}{\hbar\omega_B} \right)^{1/3}
\]
ω₀ = ωₜₙ

Δr ~ r βₜ / 3 << r

How does a warm plasma in the magnetosphere modify the emergent spectra?
Resonant Cyclotron Scattering in Magnetars

3 free parameters, same as for the empirical blackbody+powerlaw model:

same statistical significance

Optical depth
\[ \tau_{RCS} = \int \sigma_{RCS} n_e \, dz \] (1-10)

Electron thermal velocity \( \beta_T \) (0.1-0.5)

Surface Temperature (keV) \( kT \) (0.1-1.3)
## The Magnetar Sample

<table>
<thead>
<tr>
<th>Hosts</th>
<th>P (s)</th>
<th>B (10^{14} G)</th>
<th>kT (keV) / Γ</th>
<th>L (10^{33} erg/s) (0.2-10 keV)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 0142+61</td>
<td>8.7</td>
<td>1.3</td>
<td>0.46 / 3.4</td>
<td>72</td>
<td>hard X</td>
</tr>
<tr>
<td>RXS J1708-4009</td>
<td>11</td>
<td>4.7</td>
<td>0.44 / 2.4</td>
<td>80-190</td>
<td>hard X</td>
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<tr>
<td>1E 1841-045</td>
<td>Kes 73</td>
<td>11.8</td>
<td>0.44 / 2.0</td>
<td>110</td>
<td>hard X</td>
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<tr>
<td>1E 2259+586</td>
<td>CTB 109</td>
<td>7.0</td>
<td>0.41 / 3.8</td>
<td>17 - 159</td>
<td>~ transient/hard X</td>
</tr>
<tr>
<td>CXO J0100-72</td>
<td>in SMC</td>
<td>8.0</td>
<td>0.38 / 2.0</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>1E 1048-5937</td>
<td>6.4</td>
<td>3.9</td>
<td>0.63 / 2.9</td>
<td>5.3 - 250</td>
<td>~ transient</td>
</tr>
<tr>
<td>1E 1547-5408</td>
<td>2.0</td>
<td>2.2</td>
<td>0.52 / 2.9</td>
<td>2.6 - 170</td>
<td>transient/radio</td>
</tr>
<tr>
<td>XTE 1810-197</td>
<td>5.5</td>
<td>2.9</td>
<td>0.67 / 3.7</td>
<td>5 - 260</td>
<td>transient/radio</td>
</tr>
<tr>
<td>CXO 1647-4552</td>
<td>in Wes1</td>
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<td>0.68/2.0</td>
<td>1-130</td>
<td>transient</td>
</tr>
<tr>
<td>AX J1845-0258</td>
<td>G29.6+0.1</td>
<td>7.0</td>
<td>/ 4.6</td>
<td>5 - 120</td>
<td></td>
</tr>
<tr>
<td>SGR 1900+14</td>
<td>OB</td>
<td>5.2</td>
<td>5.7</td>
<td>0.43 / 2.0</td>
<td>200 - 350</td>
</tr>
<tr>
<td>SGR 1806-20</td>
<td>OB</td>
<td>7.5</td>
<td>7.8</td>
<td>0.6 / 1.4</td>
<td>320 - 540</td>
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<tr>
<td>SGR 0526-66</td>
<td>in LMC</td>
<td>8.0</td>
<td>7.4</td>
<td>0.53 / 3.1</td>
<td>260</td>
</tr>
<tr>
<td>SGR 1627-41</td>
<td>G337.0-0.1?</td>
<td>6.4</td>
<td>/ 2.9</td>
<td>4 - 100</td>
<td>outburst</td>
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</tbody>
</table>
Resonant Cyclotron Scattering in Magnetars

AXPs with hard X-ray emission

Resonant Cyclotron Scattering in Magnetars

Transient AXPs


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Resonant Cyclotron Scattering in Magnetars

SGRs with hard X-ray emission

SGR 1900+14

Flux

1 - Energy (keV) - 200

BB+PL

SGR 1806-20

Flux

1 - Energy (keV) - 10

BB+PL

RCS+PL

RCS+PL

Flux

1 - Energy (keV) - 10

SGR 1806-20

Resonant Cyclotron Scattering in Magnetars

Magnetospheric e- density of $n \sim 1.5 \times 10^{13} \text{ cm}^{-3} = 10^3 n_{GJ}$

kT \sim 0.2-0.6 \text{ keV} \\
\beta_{\text{bulk}} \sim 0.2-0.4 \\
\Delta\varphi \sim 1 - 1.8 \\

\text{Magnetospheric } e^- \text{ density consistent with the simplified 1D model, hence being } \sim 10^3 n_{\text{GJ}} \\

Conclusions

...done

• We built an analytical model to threat resonant cyclotron scattering
  – Implementing it in XSPEC for real data fitting

• Resonant cyclotron scattering reproduces all magnetar spectra
  – This model has a clear physical motivation, unlike BB+PL models

• We could derive for the first time the magnetospheric density of magnetars
  – Much larger than for normal pulsars, as indeed predicted by the theory

• Absorption values now matches what has been derived from single edge fitting
  – The BB+PL model overestimates the $N_H$

http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/models/rcs.html

in progress...

• More advanced 3D Monte-Carlo models for magnetar magnetospheres
  – Full 3-D magnetosphere (Fernandez & Thompson 2007; Nobili, Turolla & Zane 2008)
  – Application to the data (Rea et al. in prep; Albano et al. in prep)