Recent Progress in Observations of Magnetars

Wim Hermsen (SRON Netherlands Institute for Space Research & Astronomical Institute “Anton Pannekoek”, University of Amsterdam)

collaborators

Lucien Kuiper (SRON)
Peter den Hartog (Stanford Univ. HEPL/KIPAC)
Felix ter Beek (University of Amsterdam)
Outline of presentation

- Introduction

- New constraints from RXTE-HEXTE, INTEGRAL-IBIS and Fermi-GBM

- The January 2009 outburst of the "transient" AXP 1E1547.0-5408 / SGR J1550-5418: Evolution of timing and spectral characteristics over 27 months

- Summary
<table>
<thead>
<tr>
<th><strong>AXP / SGR</strong></th>
<th><strong>Hosts</strong></th>
<th><strong>P (s)</strong></th>
<th><strong>B (10^{14} \text{G})</strong></th>
<th><strong>comments (O=opt, I=IR)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 0142+61</td>
<td></td>
<td>8.69</td>
<td>1.3</td>
<td>hard X-rays, O, I</td>
</tr>
<tr>
<td>RXS J1708-4009</td>
<td></td>
<td>10.99</td>
<td>4.7</td>
<td>hard X-rays</td>
</tr>
<tr>
<td>1E 1841-045</td>
<td>Kes 73</td>
<td>11.77</td>
<td>7.1</td>
<td>hard X-rays</td>
</tr>
<tr>
<td>1E 2259+586</td>
<td>CTB 109</td>
<td>6.98</td>
<td>0.5</td>
<td>transient/ hard X-rays, O, I</td>
</tr>
<tr>
<td>CXO J0100-72</td>
<td>in SMC</td>
<td>8.02</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>1E 1048-5937</td>
<td></td>
<td>6.4</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>1E 1547-5408/SGR1550-5418</td>
<td></td>
<td>2.0</td>
<td>2.2</td>
<td>outbursts/radio/ hard X-rays, I</td>
</tr>
<tr>
<td>XTE 1810-197</td>
<td></td>
<td>5.5</td>
<td>2.9</td>
<td>transient/radio, O</td>
</tr>
<tr>
<td>CXO 1647-4552</td>
<td>in Wes 1</td>
<td>10.61</td>
<td>1.3</td>
<td>outburst, radio</td>
</tr>
<tr>
<td>CXO 1714-3810</td>
<td>CTB 37B</td>
<td>3.82</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>SGR 1900+14</td>
<td>OB</td>
<td>5.17</td>
<td>6.5</td>
<td>GF/ hard X-rays /outbursts</td>
</tr>
<tr>
<td>SGR 1806-20</td>
<td>OB</td>
<td>7.55</td>
<td>18</td>
<td>GF/ hard X-rays /outburst, I, QPO</td>
</tr>
<tr>
<td>SGR 0526-66</td>
<td>in LMC</td>
<td>8.05</td>
<td>7.3</td>
<td>GF</td>
</tr>
<tr>
<td>SGR 1627-41</td>
<td></td>
<td>2.59</td>
<td>2.2</td>
<td>outburst</td>
</tr>
<tr>
<td>SGR 0501+4516</td>
<td></td>
<td>5.76</td>
<td>2.0</td>
<td>outburst/ transient hard-X, O</td>
</tr>
<tr>
<td>SGR 1833-0832</td>
<td></td>
<td>7.56</td>
<td>1.8</td>
<td>outburst</td>
</tr>
<tr>
<td>AX J1844-0258</td>
<td>G29.6+0.1</td>
<td>6.97</td>
<td>-</td>
<td>transient , candidate</td>
</tr>
<tr>
<td>SGR 0418+5729</td>
<td></td>
<td>9.08</td>
<td>&lt;0.075</td>
<td>outburst</td>
</tr>
<tr>
<td>PSR 1622-4950</td>
<td></td>
<td>4.32</td>
<td>2.8</td>
<td>radio, extremely variable; X-ray quiet</td>
</tr>
<tr>
<td>(PSR J1846-0258)</td>
<td>Kes 75</td>
<td>0.32</td>
<td>0.5</td>
<td>high B-field pulsar, radio quiet)</td>
</tr>
</tbody>
</table>
Challenges in magnetar studies over last decade

1\textsuperscript{st} SGRs = AXPs = magnetars?
- Fall-back-disk scenario, e.g. Alpar 2001, Trümper et al. 2011
- Massive rotating WDs, Malheiro et al. 2011
- Quark stars, Xu 2007, Orsaria et al. 2010

2\textsuperscript{nd} timing characteristics like those of rotation-powered pulsars /radio pulsars?

3\textsuperscript{rd} Production mechanisms, scenario's of radio, IR, optical, soft X-ray, hard X-ray emissions in bursts, radiative outbursts, persistent emission?

4\textsuperscript{th} Connection with radio pulsar population?
- SGR 0418+5729
- PSR 1622-4950
- PSR J1846-0258
Focus of this presentation: persistent soft and hard X-ray emission

Sources with persistent soft and hard X-ray emission:

- AXP 1E1841-045
- AXP 1RXS J1708-4009
- AXP 4U0142+614
- AXP 1E1547.0-5408 (transient hard X-ray emission)
- AXP 1E 2259+586

- SGR 1900+14  (Götz et al. 2006)

- SGR 1806-20  (Mereghetti et al. 2005; Molkov et al. 2005)
- SGR 0501+4516 (transient hard X-ray emission)
**Persistent X-ray emission**: two characteristic peaks in luminosity, each exceeding spin-down luminosity 1-3 orders of magnitude

Non-thermal persistent emission above 10 keV discovered with INTEGRAL
**Persistent X-ray emission**: two characteristic peaks in luminosity, pulsed component up to the highest energies

AXP 4U 0142+61

20-160 keV pulse profile

Den Hartog, Kuiper, Hermsen et al. 2008
**Persistent non-thermal emission**

AXP 1RXS J170849-400910

**INTEGRAL**

20-270 keV pulse profile

den Hartog, Kuiper, Hermsen 2008
Persistent soft pulse and hard pulse separated in pulse phase:

- Different components produced in different sites of the magnetosphere with energy source being the high B field.
Persistent emission below $\sim 10$ keV)

- BB ($kT \sim 0.3$-$0.6$ keV + power law index $\sim 2$-4) or
- two BBs ($kT_1 \sim 0.3$ keV, $kT_2 \sim 0.6$ keV)
e.g. Rea et al. 2007; Güver et al. 2007, 2008

- Resonant cyclotron scattering
e.g. Thompson, Lyutikov & Kulkarni, 2002
  Lyutikov & Gavrill, 2006
  Fernandez & Thompson, 2007
  Rea et al. 2008
  Nobili et al. 2008
  Zane et al. 2009, 2010
Persistent non-thermal emission above ~20 keV:

From RXTE, INTEGRAL, Swift, Suxaku observations spanning more than 10 years

- Stable (pulsed) flux over > 10 year within ~20%
- Stable (in shape and phase) pulse profile over > 10 year
For persistent non-thermal emission above ~20 keV:

**NO AGREED physical model (scenario) yet!**

Recent attempts:
- Bähring & Harding (2007); resonant magnetic Compton upscattering
- Beloborodov & Thompson 2007, Beloborodov, 2009; acceleration in a twisted corona
- Pavan et al. 2009; multipolar force-free magnetospheres
- Trümper et al. 2010; accretion from a fall-back disk
New developments (1)

- Increased statistics on the time-averaged pulse profiles and spectra for RXTE-HEXTE and INTEGRAL-IBIS

(Kuiper, Ter Beek, Hermsen, 2011, in prep.)
Example: RXTE HEXTE and INTEGRAL ISGRI update for 4U0142+614

4U 0142+614

HEXTE exposure increase since Kuiper et al. (2006)
103.6 ks $\rightarrow$ 515.9 ks
20-50 keV: 3.4$\sigma$
50-100 keV: 2.1$\sigma$

Now,
20-40 keV: 7.9$\sigma$

ISGRI exposure increase only moderately since den Hartog et al. (2008)
2.1 Ms $\rightarrow$ 3.2 Ms
RXTE HEXTE and INTEGRAL ISGRI updates for 1E1841-045 and 4U0142+614

Multi-years profiles (~10 yrs average)

Pulses in stable phase intervals

Be careful in interpreting variations in shape (low statistics!)
New developments (2)

- First results from 2.3 years of FERMI-GBM monitoring

(Kuiper, Ter Beek, Hermsen, 2011, in prep.)
Fermi GBM data selection and analysis

- Timing Analysis for those AXPs with established HE-emission and with valid contemporaneous phase-coherent timing solutions (RXTE monitoring): 1E1841-045, 4U 0141+614, 1RXS J1708-4009 and 1E1547.0-5408

- Only CTIME data (256 ms; 8 energy channels, 8 - 2000 keV) from 12 NaI detectors are used → source angle selections

- Remove short-duration events like bursts/flare

- Optimise event selections

- Phase folding of selected bary-centered count-rate data on proper timing model (Aug. 2008 – Dec. 2010; 2.3 y)

<table>
<thead>
<tr>
<th>Source</th>
<th>Start [MJD]</th>
<th>End [MJD]</th>
<th>Screened exposure [Ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 0142+614</td>
<td>54690</td>
<td>55496</td>
<td>41.686</td>
</tr>
<tr>
<td>1RXS J1708-4009</td>
<td>54690</td>
<td>55516</td>
<td>40.505</td>
</tr>
<tr>
<td>1E 1841-045</td>
<td>54690</td>
<td>55524</td>
<td>51.106</td>
</tr>
<tr>
<td>1E 1547.0-5408</td>
<td>54855</td>
<td>54890</td>
<td>1.5673</td>
</tr>
</tbody>
</table>
Fermi GBM results on AXPs: data accumulated over 2.3 years

Curves are fits to the INTEGRAL profiles in the corresponding energy window $\sim 27$-300 keV

Consistent stable (!) profiles

GBM pulse-profiles: Sum of channels 2-4
$\sim 27$-300 keV
Fermi GBM results on AXPs: data accumulated over 2.3 years

GBM pulse-profiles: Sum of channels 2-4
\(~27\text{-}300\text{ keV}\)
From ① the extracted pulsed count rates per energy channel and ② the angular averaged response information, the photon spectrum can be reconstructed adopting certain model shape.

Power-law:

$$F(E) = F_0 \cdot (E/E_0)^\alpha$$

Power-law with super-exponential cutoff

$$F(E) = F_0 \cdot (E/E_0)^\alpha \cdot \exp\left(-\left(E/E_c\right)^2\right)$$

Simulated instrument response for NaI detectors 0 and 8 (Kippen et al. 2007)
Power-law with super-exponential cutoff

\[ F(E) = F_0 \cdot (E/E_0)^\alpha \cdot \exp(- (E/E_c)^2) \]

is approximation to model spectrum B

A. Beloborodov (2010)
Total and pulsed high-energy spectra of persistent AXPs

Power-law fit to pulsed spectra above 10 keV acceptable?

No break required (yet)

Total and pulsed spectra above 10 keV look now similar; pulsed fraction about constant up to 100 keV

Break required
Total and Pulsed high-energy spectra of persistent AXPs

No break required (yet)
Lower limit: 429 keV

Break required at $125^{+26}_{-20}$ keV

$F(E) = F_0 \cdot (E/E_0)^\alpha \cdot \exp\left(-\frac{(E/E_c)^2}{2}\right)$

Break required at $231^{+64}_{-52}$ keV
Resistive untwisting magnetosphere after a star quake / glitch:
A growing cavity and a shrinking current-carrying bundle of field lines at the pole ("j-bundle"), becoming quasi stable;

Beloborodov, 2009

Prediction: (1) j-bundle produces a shrinking hot spot on the star
(2) A high-multiplicity e+- outflow forms in the j-bundle, producing nonthermal emission from radio to hard X-rays
Resistive untwisting magnetosphere after a star quake / glitch: A growing cavity and a shrinking current-carrying bundle of field lines at the pole ("j-bundle"), becoming quasi stable;

Beloborodov, 2009

We need to study a post-outburst decay over the broad energy range including low-energy and high-energy X-rays
AXPs, SGRs decaying from an outburst

Decays from radiative outbursts (after a timing glitch) could so far only be studied for energies below ~10 keV, e.g.:

- AXP 1E2259+586: Woods et al. 2004
- XTE J1810-197: Gotthelf & Halpern 2007
- SGR 0501+4516: Rea et al. 2009, Göğüş et al. 2010
- SGR J1833-0832: Göğüş et al. 2010, Esposito et al. 2011
- SGR 1900+14: Göğüş et al. 2011

**AXP 1E 1547.0-5408 / SGR J1550-5418 is the first of which the post-outburst decay can be studied over the broad energy range up to ~300 keV**

Kuiper, Hermsen, den Hartog and Urama et al. 2011 (in prep.)
AXP 1E1547.0-5408

- Discovered in an *Einstein* HRI observation in 1980

- Gelfand & Gaensler (2007) proposed association of a candidate magnetar (X-ray spectrum; variability) and candidate SNR (4’ diameter shell)

- Detection of radio-emitting magnetar, $P \sim 2$ s by Camilo et al. (2007) using Parkes data collected on June 8, 2007:

  $$B_s \sim 2.2 \times 10^{14} \text{ G}; \tau \sim 1.4 \text{ kyr}$$

  Noisy timing behaviour.

- SWIFT monitoring and XMM-Newton ToO in June-Oct 2007 \(\Rightarrow\) decay from outburst?; Pulsed X-rays; 7% Pf (Halpern et al. 2008)

On Oct. 3, 2008 several short bursts detected by SWIFT BAT (GCN Circ. 8311)
Factor ~100 increase in flux (2-10 keV) showing decay; activity till mid Oct. (FERMI GBM)

SGR-like activity commenced on 22 January 2009 initiated strong short burst detected by SWIFT-BAT (GCN Circ. 8833): Many strong bursts detected by several instruments aboard different spacecrafts, SWIFT BAT, INTEGRAL SPI-ACS, FERMI GBM, Konus WIND, Suzaku WAM etc.

Example of strong burst with pulsating tail

Radio/X-ray alignment: X-rays ~ 0.2 ahead
Flux evolution AXP 1E1547.0-5408 at soft X-rays since Oct. 2008 (RXTE PCA)

TOTAL EMISSION, ~2-10 keV

Note: reference level subtracted
2.7 ks Scan obs. May 15, 1997

See also:
Ng et al. (2010)
Israel et al. (2010)
Bernardini et al. (2011)
Jan. 22, 2009 radiative outburst accompanied by timing glitch!

$\Delta n [Hz]$  

$\frac{Dn}{n} \sim 3 \times 10^{-6}$; 

$\frac{D(dn/dt)}{dn/dt} = -0.67!!!$

$\Delta (dv/dt) = +12.7(4) \times 10^{-12} \text{ Hz/s}$

$\sim 2-10 \text{ keV}$

Spin evolution RXTE/Swift

No change in flux at 2$^{nd}$ similarly strong glitch in $v$ and $dv/dt$
Total flux 2-10 keV


Total soft X-ray flux and pulsed soft X-ray flux evolve very differently

Also no evident change in pulsed flux at 2nd glitch

See also:
Ng et al. (2010)
Israel et al. (2010)
Bernardini et al. (2011)
Pulse profile evolution of 1E1547.0-5408

Oct. 3, 2008 Outburst
MJD 54743-54768

Jan. 22, 2009 Outburst
MJD 54771-54845

New pulsed component (~4-30 keV) delayed w.r.t. Jan. 22, 2009 glitch by > 11 days and fades to zero within ~350 days!

Very different morphology as function of energy!
**1E 1547-5408:** **Total** emission detected with **INTEGRAL** ISGRI up to ~300 keV Few days after glitch on 22 January 2009

*INTEGRAL*
Pulsed emission detected
up to ~150 keV


Confirmed by Suzaku, Enoto et al. 2010)

+ Swift observations for total emission within 13 days after glitch

---

W. Hermsen, Physics of NSs 2011, Saint-Petersburg, July 2011

33
Spectral evolution of total and pulsed emission 1 – 300 keV during time window of maximum luminosity above 10 keV (up to ~100 days after glitch)

**Total** emission is high immediately after glitch (Swift < 10 keV and INTEGRAL > 10 keV)

**Pulsed** emission after glitch:
- PCA < 7 keV high immediately
- PCA > 7 keV increase delayed by up to ~40 days

Spectral shape mimics that of persistent emission of AXPs
- 1E 1841.0-045
- 4U0142+614
- 1RXS J1708-40

Also, Suzaku (Enoto et al. 2010), Total HE emission $\Gamma_{\text{total}} \sim 1.5$
Transient magnetar 1E1547.0-5408 seen by Fermi/GBM after glitch.

Power-law fit not acceptable: break required.
Pulse profile evolution of 1E1547.0-5408 over >510 days after glitch

~2-4 keV  ~4-11keV  ~11-33 keV

- Oct. 3, 2008 Outburst
  MJD 54743-54768
  MJD 54771-54845
- Jan. 22, 2009 Outburst
  MJD 54853-54864
  MJD 54868-54954
  MJD 54962-55004
  MJD 55026-55112
  MJD 55120-55191
  MJD 55213-55264

Evolution pulsed spectra

RXTE PCA  HEXTE
INTEGRAL
Spectral evolution of 1E1547.0-5408 over >510 days after glitch

Evolution total spectra

Evolution pulsed spectra

Spectral shapes similar to that of persistent of AXPs!
Summary (1)

- A strong glitch detected for AXP 1E1547.0-5408 in January 2009, triggered a radiative outburst and the creation of a new non-thermal hard X-ray pulse in the profile, which decayed to undetectable levels in ~350 days.

- The new pulsed emission above 10 keV reached its maximum ~40 days after the glitch.

- The total soft and hard X-rays and the pulsed soft X-rays reached their maximum flux directly after the glitch.

- The total and pulsed X-ray spectra after the glitch resemble the total and pulsed spectra of the persistent emission of AXPs.

- A similar second glitch on 17 October 2009 did NOT trigger an outburst.
Summary (2)

- Improved statistics of RXTE-HEXTE and INTEGRAL-IBIS data, plus first results from FERMI-GBM show that the shape of the total and pulsed spectra of the persistent hard X-ray emission from AXPs becomes similar up to ~100 keV.

- The pulsed fraction for energies 10–100 keV is in the range 25-40%.

- The total and pulsed hard X-ray spectra require a spectral break, bend above 100 keV.