Recent *Suzaku* Studies of the X-ray Emission from Magnetars

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On behalf of *Suzaku* Magnetar Key Project


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Magnetar Class

- Soft Gamma Repeater
- Anomalous X-ray Pulsar

- Strong Field (B > 1E+14 G)
- Young (τ < 100 kyr)
- Lx ~ 1e+35 erg/s

Magnetic Field B ∝ sqrt(P Pdot)
Characteristic Age τ ∝ P / 2Pdot

[Manchester+2005]
**Activity & Energetics of Magnetars**

**“Giant Flares”** (from three Soft Gamma Repeater)

- **SGR 1900+14**
  - Aug. 27, 1998
  - Ulysses, 25-150 keV
  - Flash
  - Tail
  - 5.18-second period

- Pulsating Tail
  - 1.2e+44 erg
  - kT ~ 20 keV

**“Short Bursts”**

- 1E1048.1-5937
  - (Gavriil+2002)

**“Persistent X-ray Emission”**

- 1E 1841-045 (Kes 73)
- Lx ~ 1e+34--1e+35 erg/s

- Morii+2010, PASJ
- CXO

- Suzaku (Enoto+2009, ApJL)

**How the postulated strong magnetic field are dissipated and converted into the radiation?**

- Initial Spike E>8.3e+44 erg/s
- kT ~ 20 keV
- R = 8.0\(^{+2.9}_{-2.1}\) d\(_{10}\) km
- kT\(_L\) = 3.3\(^{+0.5}_{-0.4}\) keV
- R = 0.46\(^{+0.16}_{-0.14}\) d\(_{10}\) km
- kT\(_H\) = 15.1\(^{+2.5}_{-1.9}\) keV
### Suzaku Observations of Magnetars

#### Magnetar on the Galactic Plane

<table>
<thead>
<tr>
<th>Number</th>
<th>Magnetar Name</th>
<th>Classification</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SGR 1806-20</td>
<td>SGR</td>
<td>Esposito et al., A&amp;A (2007)</td>
</tr>
<tr>
<td>2</td>
<td>SGR 1900+14</td>
<td>SGR</td>
<td>Nakagawa et al., PASJ (2009)</td>
</tr>
<tr>
<td>3</td>
<td>1E 1841-045</td>
<td>AXP</td>
<td>Morii et al., PASJ (2011)</td>
</tr>
<tr>
<td>5</td>
<td>1E 2259+586</td>
<td>AXP</td>
<td>Nakano et al., in prep</td>
</tr>
<tr>
<td>6</td>
<td>4U 0142+61</td>
<td>AXP</td>
<td>Enoto et al., PASJ (2011)</td>
</tr>
<tr>
<td>7</td>
<td>1RXS J1708-40</td>
<td>AXP</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1E 1547.0-5408</td>
<td>AXP (ToO in 2009)</td>
<td>Enoto et al., PASJ (2010) Yasuda et al. in prep</td>
</tr>
<tr>
<td>10</td>
<td>SGR 1833-0832</td>
<td>SGR (ToO in 2010)</td>
<td>Nishioaka et al., in prep</td>
</tr>
</tbody>
</table>

Main Suzaku Topics on Magnetars

- Soft & Hard Persistent Emission
- Transient Magnetars
- Short Bursts

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Persistent Emission: Typical AXP 4U 0142+61

Challenge to provide a more unified characterization of magnetars.

**Soft Component (0.2-10 keV)**
- ~Blackbody (~0.3 keV)
- $L_x(2-10\text{ keV}) = 10^{35}\text{ erg/s} > L_{sd} = 10^{32}\text{ erg/s}$
- NS Surface Emission

**Hard Component (>~10 keV)**
- PL ($\Gamma$~1) & Cutoff < 1 MeV (see also den Hartog+2008)
- $L_x(10-70\text{ keV}) = 7 \times 10^{35}\text{ erg/s}$
- Origin is unknown

**Enoto et al., 2011**

Discovered by INTEGRAL (Kuiper +2006)
Examples of Suzaku Magnetar Spectra

- τ ~ 0.2 kyr, B ~ 2e+15 G
- τ ~ 18 kyr, B ~ 1.7e+14 G
- τ ~ 1.4 kyr, B ~ 2e+14 G
- τ ~ 70 kyr, B ~ 1.3e+14 G

HR ξ = Fh/Fs = 9.1 @1-60 keV
HR ξ = 0.6
HR ξ = 2.8
HR ξ = 0.2

SGR 1806-20
Outburst
1E 1547.0-5408
Outburst
4U 0142+61
Quiescent
SGR 0501+4516
Quiescent

Wide-band spectra and P-Pdot diagram

HR $\xi = \frac{F_h}{F_s}$ @ 1-60 keV

Magnetic field strength $B_s$ (G)

Energy (keV)

Pulse period $P$ (s)

Hardness Ratio $\xi = \frac{F_h}{F_s}$ vs. $\tau_c$

- Hardness ratio $F_h/F_s$ is negatively correlated with the characteristic age $\tau_c$.
- SGR & AXP are intrinsically the same kinds of object.
- Burst-active and quiescent states follow the same correlation ⇒ common mechanism.
- Interpreted as the relation to an induced electric field of the rotating magnetic field.

Hardening of the Hard Component

Toward the older magnetars, the hard component becomes:
- harder
- weaker relative to the soft component

Emission Mechanism

a. Extremely flat $\Gamma_h$ becomes harder toward sources with old $\tau_c$.

b. $\xi = F_h/F_s$ is negatively/positively correlated with $\tau_c/B$.

**Thermal Bremsstrahlung?**
(Thompson & Beloborodov 2005)

**Resonant Compton up-scattering?**
(Baring & Harding 2007)

- hard X-rays
- Transition layer
- star surface
- resonant magnetic Compton up-scattering
- soft X-rays
- relativistic e+/e-
- hard X-rays
- star surface

And also other models;
Heyl & Hernquist 2007
Trumper+2010
Down Cascade via “Photon Splittings”

Photon Splitting Effect?
(Harding+1997; Enoto+2010)

\[ \frac{\hbar eB}{m_e c} = m_e c^2 \quad \Rightarrow B = 4.4 \times 10^{13} \text{ G} \]

\[ \nu F_\nu \]

Output spectrum

Source Sub MeV photons at the surface

Strong field
Weak field

Theoretical Simulation of photon splittings

\[ \text{Hardness ratio} \]
\[ \text{Photon index} \Gamma_h \]


\[ (E_{\text{max}}, h)(2m_e c^2, 0.95) \]
\[ (2m_e c^2, 0.80) \]
\[ (2m_e c^2, 0.99) \]
Main Suzaku Topics on Magnetars

- Soft & Hard Persistent Emission
- Transient Magnetars
- Short Bursts
Recent Transient Magnetars

- Discovered through short bursts by Swift/BAT
- Outburst of persistent emission (brighter by 1-2 orders of magnitude)

X-ray Decay (slope, initial phase): “stellar interior” or “reconnection”
X-ray Decay SGR 0501+4516 & 1E 1547.0-5408

Absorbed X-ray Flux ($10^{-12}$ erg s$^{-1}$ cm$^{-2}$)

- Swift/XRT (1-10 keV no error)
- Suzaku XIS (1-10 keV)
- Suzaku/HXD & INTEGRAL (20-100 keV)

Time since the first burst from SGR 0501+4516 (MJD=54700.0 12:41:59.0 UT)
X-ray Decay SGR 0501+4516 & 1E 1547.0-5408

SGR 0501+4516

\[ \Gamma = 1.33^{+0.23}_{-0.16} \]

\[ kT = 0.59 \text{ keV} \& 0.24 \text{ keV} \]

\( (0.53 \text{ km} \& 2.2 \text{ km}) \)

Preliminary
X-ray Decay SGR 0501+4516 & 1E 1547.0-5408

SGR 0501+4516

kT=0.59 keV & 0.24 keV (0.53 km & 2.2 km)

Γ=1.33 (+0.23, -0.16)

Preliminary

0.57 keV & 0.25 keV (0.24 km & 1.7 km)
X-ray Decay SGR 0501+4516 & 1E 1547.0-5408

SGR 0501+4516

kT=0.59 keV & 0.24 keV (0.53 km & 2.2 km)

Γ=1.33(+0.23,-0.16)

0.57 keV & 0.25 keV (0.24 km & 1.7 km)

0.60 keV & 0.20 keV (0.15 km & 1.3 km)

Preliminary
X-ray Decay SGR 0501+4516 & 1E 1547.0-5408

**SGR 0501+4516**

- X-ray flux vs. time since the first burst from SGR 0501+4516 (MJD=54700.0 12:41:59.0 UT).
- Fits for the X-ray flux with different models.
- kT=0.59 keV & 0.24 keV (0.53 km & 2.2 km), \( \Gamma=1.33^{+0.23, -0.10} \)
- Preliminary

**1E 1547.0-5408**

- Absorbed X-ray Flux (erg s\(^{-1}\) cm\(^{-2}\)) vs. elapsed day since the onset of the outburst.
- Fits for the absorbed flux with different models.
- 0.57 keV & 0.25 keV (0.24 km & 1.7 km)
- 0.60 keV & 0.20 keV (0.15 km & 1.3 km)
X-ray Decay SGR 0501+4516 & 1E 1547.0-5408

**SGR 0501+4516**

- $kT = 0.59$ keV & 0.24 keV (0.53 km & 2.2 km)
- $\Gamma = 1.33 (+0.23, -0.16)$
- $0.57$ keV & 0.25 keV (0.24 km & 1.7 km)
- $0.60$ keV & 0.20 keV (0.15 km & 1.3 km)

**1E 1547.0-5408**

- $kT = 0.65$ keV (5.2 km)
- $\Gamma = 1.54 (+0.06, -0.05)$

*Preliminary*
X-ray Decay SGR 0501+4516 & 1E 1547.0-5408

**SGR 0501+4516**

- $kT = 0.59 \text{ keV} \& 0.24 \text{ keV} (0.53 \text{ km} \& 2.2 \text{ km})$
- $\Gamma = 1.33^{(+0.23, -0.16)}$
- $0.57 \text{ keV} \& 0.25 \text{ keV} (0.24 \text{ km} \& 1.7 \text{ km})$
- $0.60 \text{ keV} \& 0.20 \text{ keV} (0.15 \text{ km} \& 1.3 \text{ km})$

**1E 1547.0-5408**

- $kT = 0.65 \text{ keV} (5.2 \text{ km})$
- $\Gamma = 1.54^{(+0.06, -0.05)}$
- $kT = 0.63 \text{ keV (3.2 km)}$
- $\Gamma = 1.10^{(+0.68, -0.42)}$
- Hard X-rays were detected (>3σ) even if including the 1% NXB uncertainty

Spectral change in the soft/hard X-rays is a hot topic.

*Preliminary*
Compare to Quiescent X-ray Emission

**4U 0142+61** (1st & 2nd Observations)

- 2007 Observation
- GSO(2009)
- XIS3(2009)
- PIN(2009)

**1RXS J1708-40** (1st & 2nd Observations)

Two Types?

Persistently emitting magnetars (in quiescent) = stable?

Transient Sources = decay at a month time-scale

[Makishima., in prep]
New Magnetar: SGR 1833-0832

New magnetar discovered by Swift/BAT & RXTE on 2010 March 19
Suzaku ToO on 2010 March 27 (40 ks)

A sign of the hard X-rays (~2.4σ) in 15-50 keV

Unfortunately, Suzaku could not observed recent transients SGR J0418+5729 (Rea+2010, Science), but....

Period = 7.565 sec

\[ kT \approx 1.22 \text{ keV} \]

\[ \Gamma = 0.87 \pm 0.67 \]

\[ F_x = 5.0 \times (2.8, +3.6) \times 10^{-11} \text{ erg/s/cm}^2 \]

\[ 2-10 \text{ keV} \]
Possible New SGR?? Swift J1822.3-1606

Discovery from a short burst by Swift/BAT (2011-07-14 at 12:47:47.1 UTC) [Atel #3488]

• Along the Galactic plane (l, b) = (15, -1.0)
• P ~ 8.43 sec [Atel #3491, #3489]
• Transient Behavior in X-rays

New Magnetar??

Swift/XRT 2011-07-15
1.6 ks

Suzaku Window (55-101 days after the onset)

Blackbody Model Preliminary

kT=0.81±0.01 keV, \( N_H = (1.4±0.3)e+21 \) cm\(^{-2}\)

\( F_X = (1.16±0.03)e-10 \) erg/s/cm\(^{-2}\) @2-10 keV

If this is a magnetar, One of the brightest transient hard X-rays may come from this source
Main Suzaku Topics on Magnetars

- Soft & Hard Persistent Emission
- Transient Magnetars
- Short Bursts
Early Burst forests from 1E 1547.0-5408

**Decay of Persistent X-ray Flux**
1E 1547.0-5408 (2009)

**Wide-band All-sky Monitor (WAM)**
Large Effective Area ~400 cm² @1 MeV

Suzaku WAM detected 250 bursts (>5.5 σ) during January 21 23:49--22 23:47 (UT)
Gamma-ray Detection with 3.2 sigma level at least up to ~1 MeV!

- BB+PL: $kT=9.7^{(+21.6, -6.8)}$ keV & $\Gamma=2.1^{(+0.1, -0.2)}$ [Yasuda et al., in prep]
- No break of power-law in 200 keV to 1.2 MeV range
18 weak short bursts were identified with chance probabilities of <10^{-5}.

- X-ray fluences = 2x10^{-9} --10^{-7} erg cm^{-2} (one of the weakest samples)
**Spectral Comparison: Burst vs. Persistent**

**One Short Bursts**

![Histograms of X10 2.0-10.0 keV, PIN 10.0-70.0 keV, GSO 50-150 keV]

- **Burst (Band Function)**
  - $\Gamma = -0.21$

- **Persistent**
  - $\Gamma = 2.8$

Fluence = $7.46(-0.82,+0.48) \times 10^{-8}$ erg cm$^{-2}$

Enoto et al., in prep
Spectral Comparison: Burst vs. Persistent

Weaker Bursts

Stacking 13 bursts

 Persistent

\( \Gamma = 1.5 \)

\( \Gamma = 1.6 \)

Enoto et al., in prep
Spectral Comparison: Burst vs. Persistent

Weaker Bursts

Stacking 13 bursts

$\Gamma = 1.6$

Ratio ~ 180

Spectral Similarity between the stacking weaker bursts and the persistent Emission

Enoto et al., in prep
Short Bursts from SGR 0501+4516

31 weak bursts were detected with an average fluence \( \sim 1 \times 10^{-9} \text{ erg/cm}^2 \) 
(Nakagawa+2011)

2BB+PL model: \( kT = 0.49 \text{ keV}, kT = 1.7 \text{ keV}, \text{ and } \Gamma = 1.0 \)
Persistent X-ray emission may be an assembly of “micro-burst”?  
Nakagawa et al., PASJ, 2007 (see also Lyutikov+2003)

Unresolved “micro-bursts” can reach the persistent luminosity in a certain slope of the Gutenberg-Richter Law (1E 1547.0-5408).  
Enoto et al., in prep
Environments of magnetars
- SNR/magnetar system is different from others?
- “Magnetar characteristic age” vs “SNR age”?

Example

**1E 2259+586**

$\tau_c \sim 230$ kyr

**CTB 109**

$\tau_{SNR} < \tau_c$

Presentation by Nakano-san (tomorrow)
Beyond Suzaku: ASTRO-H & GEMS

E^2 F (keV^2 cm^{-2} s^{-1} keV^{-1})

Frequency (Hz)

10^{-10} to 10^{8}
10^{14} to 10^{20}

Radio
Optical

E (keV)

10^{-11} to 10^{11}
10^{-6} to 10^{6}

X-ray
Gamma-ray

Suzaku/XIS (this work)
Suzaku/HXD (this work)
Soft Component Model
Hard Component Model
XMM-Newton/PN (Rea et al., 2007)
INTEGRAL/ISGRI (den Hartog et al., 2008)
CGRO/COMPTEL (Kuiper et al., 2006)
Fermi/LAT (Abdo et al., 2010)

Gemini (Durant et al., 2006)
Keck2 (Durant et al., 2006)
VLA (Gaensler et al., 2001)
WSRT (den Hartog et al., 2007)

& Optical (Wang et al., 2006)
1. **Soft & Hard X-rays from Magnetars**
   - The broadband hardness ratio $\xi$ is correlated to the characteristic age $\tau_c$ and magnetic field $B$ ($\xi \propto \tau_c^{-0.7}$, $\xi \propto B^{1.2}$).
   - The photon index of the hard X-rays becomes harder for sources with old characteristic ages ($\Gamma_h \sim 1.8$ to 0.4).
   - A study of the spectral trend is a nice target in ASTRO-H (NuStar) with discussions of the origin and cutoff of the Hard X-rays.

2. **Transient Magnetars**
   - The gradual X-ray decay (~1 year) of transient magnetars are appropriate targets of Suzaku, and have been monitored.
   - Simultaneous monitoring of the soft & hard X-rays will become important for understanding the dissipation of magnetic energy.

3. **Short Bursts**
   - High sensitivity of the HXD-PIN allowed us to detect weaker short burst events. The spectral similarity between the burst and persistent emission indicates a possible connection of their emission mechanism.

4. **Magnetar Environment, SNR (& PWN)**
   - The magnetar environments might be a clue to their stellar evolution.