Magnetar Bursts At All Scales

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General Properties of Magnetars

- Characterized by bright hard X-ray / soft gamma ray bursts
- Slowly rotating systems ($P_{\text{spin}} \sim 2 - 12$ s)
- Rapidly spinning down ($dP/dt \sim 10^{-13} - 10^{-11}$ s/s)
- Bright X-ray sources ($L \sim 10^{34} - 10^{35}$ erg/s)
- Transient magnetars ($L \sim 10^{32}$ erg/s in quiescence)
- Young systems as deduces from their galactic locations
- Unique X-ray spectral properties
Magnetar Family Picture

- SGR 1806−20
- SGR 1627−41
- SGR 1900+14
- SGR J1550−5418
- SGR J0501+4516
- SGR J0418+5729
- SGR J1833−0832
- Swift J1822.3-1606
- Swift J1834.9-0846
- SGR J1745-29
- N49
- LMC
Typical SGR Bursts

- Brief (~0.1–few s)
- Irregular times between bursts (seconds - years)
- Diverse time profiles
- Intense (~$10^{36} - 10^{41}$ erg/s)
- Distinct from giant flares in duration, luminosity and energy spectrum
Intermediate Events (Woods & Thompson 2006)
More Intermediate Events

(Mereghetti et al. 2010)

(Göğüş et al. 2010)
Giant Flares

SGR 0526–66

(Mazets et al. 1979)

SGR 1806–20

(Hurley et al. 2005)

SGR 1900+14

(Hurley et al. 1999)
The Magnetar Perspective

A magnetar—*neutron star powered by its super-strong magnetic field* ($10^{14} - 10^{15} \text{ G}$) can account for the extraordinary March 5\(^{th}\) event: burst energetics, short-hard spike; 8 s modulation (Duncan & Thompson 1992) super-Eddington luminosities (Paczynski 1992)

ROSAT observations of the point X-ray source in N49 \rightarrow dissipation of magnetic energy (DT 1992)

DT (1992); Thompson & Duncan (1993): Formation of magnetars via efficient dynamo if $P_0 \sim 1–3 \text{ ms}$
Bursts via Crust Cracking

B fields are so strong that drifting field lines can stress and eventually crack the crust (Thompson & Duncan 1995)

\[
\text{Stress} = \text{Shear modulus} \times \text{Strain} \\
\left(\frac{B^2}{8\pi}\right) = \mu \times \theta
\]

For NS crust, \(\mu \sim 10^{31} \text{ erg/cm}^3\) (Baym & Pines 1971)

Most materials will crack at \(\theta \sim 10^{-3}\)

\[
B = 2.5 \times 10^{15} \, G \frac{\sqrt{\mu}}{10^{31}} \sqrt{\frac{\theta}{10^{-3}}}
\]
Upper Limit on Magnetar B-fields

Magnetic energy has to be less than the gravitational binding energy of the neutron star:

\[
\left( \frac{B^2}{8\pi} \right) \left( \frac{4}{3} \pi R^3 \right) \leq \frac{GM^2}{R}
\]

\[
B \leq 10^{18} G \left( \frac{M}{1.4M_s} \right) \left( \frac{R}{10 \text{ km}} \right)^{-2}
\]
Consequences of Crust Cracking:

Thompson & Duncan 1995:

- Sudden crustal disturbance would inject magnetic (Alfven) waves into the magnetosphere.
- Alfven waves would provide momentum and energy to produce trapped photon, $e^-$ and $e^+$ fireball.
- When photons escape, $e^-$ and $e^+$ annihilate and the fireball radiates and cools, that is observed as bursts.

(Image by R. Duncan)
Bursts via Reconnection

When brought together, oppositely oriented magnetic field lines will split and reconnect in a lower energy configuration, and release magnetic energy (TD 1995, Lyutikov 2003).

Solar flares are bright, energetic and observed in X-rays / soft gamma rays.

(Wikipedia)
Magnetic Field Reconfiguration

(Woods et al. 2001)
Crack Scale and Burst Size

Large scale fracturing ➔ Giant events and possible field reconfiguration

Relatively large size cracking ➔ Intermediate events and oscillating tail

Local cracking ➔ short bursts
Fallback Disk: An Alternative Model

Spin period clustering (Alpar 2000)

X-ray enhancements (Ertan et al. 2003, Çalışkan et al. 2013)

IR/Optical emission (Ertan & Çalışkan 2006): IR disk around 4U 0142+61: passive (Wang, Kaplan & Chakrabarti 2006), active (Ertan et al. 2007)

Hard X-ray emission (Trümper et al. 2010)

Energetic bursts cannot be explained with accretion
Reclassification of Magnetars Based on Their Bursting Behavior

<table>
<thead>
<tr>
<th>Prolific Bursters</th>
<th>Prolific Transients</th>
<th>AXPs with SGR-like Bursts</th>
<th>Transients with Low Burst Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGR 1900 + 14</td>
<td>SGR 1627 - 41</td>
<td>1E 1048-5937</td>
<td>SGR 0418 + 5729</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1E 2259+586</td>
<td></td>
</tr>
<tr>
<td>SGR 1806 – 20</td>
<td>SGR 1550 - 5418</td>
<td>4U 0142+61</td>
<td>SGR 1833 - 0832</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1E 1841-045</td>
<td></td>
</tr>
<tr>
<td>SGR 0526 – 66</td>
<td>SGR 0501 + 4516</td>
<td>CXO J164710.2-455216</td>
<td>Swift 1822.3 – 1606</td>
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<td></td>
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<td>XTE J1810-197</td>
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<td>Swift 1834.9 – 0846</td>
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<td>AX J1818.8 - 1559?</td>
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<td></td>
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<td>SGR 1745 – 29</td>
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</table>
## SGR Burst Spectra (Time Integrated)

<table>
<thead>
<tr>
<th></th>
<th>Swift/XRT CXO, XMM</th>
<th>RXTE/PCA RXTE/HEXTE</th>
<th>Swift/BAT INTEGRAL</th>
<th>Fermi/GBM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 – 10 keV</td>
<td>2 – 30keV</td>
<td></td>
<td>15 – 150 keV</td>
<td>8 – 200 keV</td>
</tr>
<tr>
<td>15 – 150 keV</td>
<td>BB + BB Compt</td>
<td>BB + BB OTTB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>BB + BB Compt</td>
<td>BB + BB OTTB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scholtz &amp; Kaspi 12</td>
<td>Kaneko et al. in prep.</td>
<td>Israel et al. 08 Mereghetti et al. 09</td>
<td>von Kienlin et al. 12 van der Horst et al. 12 Lin et al. 12</td>
<td></td>
</tr>
</tbody>
</table>

Comptonized model (Compt): a single power law with a high E exponential cutoff
Broadband Spectral Studies

SGR 1900+14: The storm, XRT+BAT, 0.5-150 keV (Israel et al. 2008)
SGR J1550-5418 normal bursts, XRT+GBM, 0.5-200 keV (Lin et al. 2012)
SGR 1550–5418 in 2008 – 2009

(von Kienlin et al. 2012)
SGR 1550–5418: Oct 08 & Mar 09

22 relatively weak events in Oct 2008 are best described with a single blackbody function.

15 events seen March 2009 are better fit with OTTB

(von Kienlin et al. 2012)
SGR 1550–5418 in January 2009
GBM only

286 integrated spectra are well described with BB + BB, and equally well with the Compt model.

(von der Horst et al. 2012)
XRT-GBM Simultaneous Event

42 simultaneous bursts were identified in the January 2009 active episode

(Lin et al. 2012)
SGR 1550–5418: Broadband Spectral Analysis

Joint spectral fits: BB + BB model fits are significantly better than the Compt model.

(Lin et al. 2012)
SGR 1550–5418: Broadband Spectral Analysis

\[ R^2 \propto (kT)^{-3.5} \]

(Lin et al. 2012)
2\textsuperscript{nd} Outburst of SGR 0501+4516
1st Outburst of SGR 0501+4516 in July 1993

On 1993 July 25, BATSE triggered on two short and soft events originating from similar locations

(Göğüş et al. 2010)
XMM–Newton View of SGR 0501+4516

49 ks observation collected 100s of short bursts

Crucial to study the link between low fluence bursts and persistent emission

Talk by L. Lin

(Lin et al. 2012)
Search for QPOs

High frequency QPOs were detected in the data of two giant flares (Israel et al. 2005; Strohmayer & Watts 2006, …)

There are thousands of short bursts. Are there hidden oscillations in short bursts as well?

Huppenkothen et al. (2013): the most rigorous search for QPOs in the GBM data of 27 SGR 0501+4516 bursts using Bayesian statistics
→ no evidence for QPOs in the unbinned spectra
→ there is a candidate (7 Hz) in the binned spectra of a burst

The candidate can be due to a quasi periodic process or an unmodelled effect of noise

Search in other bursts is ongoing

(Huppenkothen et al. 2013)
SGRs with Low Burst Rates

**SGR 0418+5729**  
(van der Horst et al. 2010)  
\[ B_d = 6 \times 10^{12} \text{ G} \]  
(Rea et al. 2010; 2013)

**SGR 1833 − 0832**  
(Göğüş et al. 2010)  
\[ B_d = 2 \times 10^{14} \text{ G} \]
SGR 1822.3–1606
$B_d = 2.7 \times 10^{13} \text{ G}$
(Rea et al. 2012)

SGR 1834.9–0846
$B_d = 1.4 \times 10^{14} \text{ G}$
(Esposito et al. 2012)

(SGRs with Low Burst Rates)
SGRs with Low Burst Rates

**SGR 1745–29**
(Kannea et al. 2013)

\[ B_d = 3 \times 10^{14} \text{ G} \]
(Gotthelf et al. 2013)
SGRs with Low Burst Rates

How can sources with low dipole magnetic fields (e.g., SGR 0418+5729 or SGR 1822.3–1606) generate bursts?

XMM – Newton observations of SGR 0418+5729 on 2009 August 12 for 65 (36) ks might have observational clues.
Surface Thermal Emission and Magnetospheric Scattering Model:
(Özel 2003; Lyutikov & Gavril' 2006; Güver, Özel & Lyutikov 2006)

1 - Magnetic field dissipation and / or Cooling
2 - Radiative equilibrium models for ionized, strongly magnetized Hydrogen Atmosphere

\[ \tau = \sigma \int N_e \, dz \]

4 - General Relativistic Effects

Resonant Cyclotron Scattering Region
Surface B-field of SGR 0418+5729

The NS atmosphere models with $B=10^{12}$ G or $10^{13}$ G do not fit.

STEMS provides a good fit, yielding $B_s = 1.0 \times 10^{14}$ G.

This is the phase averaged value, it can be stronger in local settings; it is strong enough to generate bursts.

Implies significantly non-dipolar magnetic field.

(Güver, Göğüş & Özel 2011)
X-ray flux of SGR 1745–29 is constant for ~10 days following the onset.

Similar flux trend was seen in SGR 1833 – 0832.

Continuous heating of the crust by trapped fireball?

(Kannea et al. 2013)
$T_{90}$ of Burst Active Episode

Time since the onset of an outburst during which 90% of all observed bursts are recorded.

<table>
<thead>
<tr>
<th>Source</th>
<th>$T_{90}$–BurstActivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGR 1550–5418 (2009)</td>
<td>4.6 days</td>
</tr>
<tr>
<td>SGR 1627–41 (1998)</td>
<td>4.1 days</td>
</tr>
<tr>
<td>SGR 0501+4516 (2008)</td>
<td>3.7 days</td>
</tr>
<tr>
<td>SGR 1900+14 (1998)</td>
<td>93 days</td>
</tr>
<tr>
<td>SGR 1806–20 (2003/04)</td>
<td>very long</td>
</tr>
</tbody>
</table>

Burst active episode of a prolific transient lasts for ~4 days.
Summary

Transient SGRs: prolific vs. low burst rate

SGR burst spectral studies: crucial, especially in broadband

SGR burst temporal studies: difficult but can be rewarding

Better understanding of persistent emission and its link (?) to bursts are critical — XMM-Newton has been very instrumental
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WEBSITE: http://fermi.gsfc.nasa.gov/science/mlgs/explosive_transients/
E1.12 Highly Magnetized Neutron Stars

Themes:

What is required to produce SGR-like bursts?

Are all high-B NSs different manifestations of the same underlying objects, or do they represent distinct evolutionary sequences?