On Magnetar Bursts

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Magnetars are magnetically powered NS

26 sources to date - six in 2008-2013 - All but two (LMC, SMC) are MW sources

Discovered in X/γ-rays/radio; radio, optical and IR observations - Short, soft repeated bursts

\[ P = [2-11] \text{ s}, \ P \sim [10^{-11} - 10^{-13}] \text{s/s} \]

\[ \tau_{\text{spindown}}(P/2 \dot{P}) = 2-220 \text{ kyrs} \]

\[ B \sim [1-10] \times 10^{14} \text{ G} \text{ (mean surface dipole field: } 3.2 \times 10^{19} \sqrt{P\dot{P}} \text{) ; SGR J0418+5729 with } B<7.5 \times 10^{12} \text{ G, SGR 1822.3-1606->B~2.7 \times 10^{13} \text{ G} } \]

Luminosities range from \( L \sim 10^{32-36} \text{ erg/s} \)

No evidence for binarity

SNe associations
NS populations comprising Magnetars

Soft Gamma Repeaters (SGRs)

Anomalous X-ray Pulsars (AXPs)

Dim Isolated Neutron Stars (DINs)

Compact Central X-ray Objects (CCOs)

Rotation Powered Pulsars (PSRs J1846-0258 & J1622-4950)
2008-2013: Good years for Magnetars!

Swift

Fermi

RXTE

IPN
The Gamma-ray Burst Monitor

- 4 x 3 NaI Detectors with different orientations.
- 2 x 1 BGO Detector either side of spacecraft.
- View entire sky while maximizing sensitivity to events seen in common with the LAT.

The Large Area Telescope (LAT)

GBM BGO detector.
200 keV -- 40 MeV
126 cm², 12.7 cm
Triggering, Spectroscopy
Bridges gap between NaI and LAT.

GBM NaI detector.
8 keV -- 1000 keV
126 cm², 1.27 cm
Triggering, Localization, Spectroscopy.
<table>
<thead>
<tr>
<th>Magnetar</th>
<th>Active Period</th>
<th>Triggers</th>
<th>Comments</th>
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<tr>
<td>SGR J0501+4516</td>
<td>Aug/Sep 2008</td>
<td>26</td>
<td><strong>New source</strong> at Perseus arm</td>
</tr>
<tr>
<td>SGR J1550-5418</td>
<td>Oct 2008, Jan/Feb 2009, Mar/Apr 2009, June 2013</td>
<td>7, 331 +, 14, 1</td>
<td>Known source - first burst active episodes</td>
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<tr>
<td>SGR J0418+5729</td>
<td>June 2009</td>
<td>2</td>
<td><strong>New source</strong> at Perseus arm</td>
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<tr>
<td>SGR 1806-20</td>
<td>Mar 2010</td>
<td>1</td>
<td>Old source - reactivation</td>
</tr>
<tr>
<td>AXP 1841-045</td>
<td>Feb 2011, June/July 2011</td>
<td>3, 4</td>
<td>Known source - first burst active episodes</td>
</tr>
<tr>
<td>SGR 1822-1606</td>
<td>July 2011</td>
<td>1</td>
<td><strong>New source</strong> in galactic center region</td>
</tr>
<tr>
<td>AXP 4U0142+61</td>
<td>July 2011</td>
<td>1</td>
<td>Old source - reactivation</td>
</tr>
<tr>
<td>1E 2259+586</td>
<td>April 2012</td>
<td>1</td>
<td>Old source - reactivation</td>
</tr>
<tr>
<td>Unconfirmed Origin</td>
<td>2008-2013</td>
<td>21</td>
<td>Error boxes contain several source candidates</td>
</tr>
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</table>
◆ $P = 2.069s$

◆ $P = 2.318 \times 10^{-11} \text{ s/s and } B = 2.2 \times 10^{14} \text{ G}$

◆ Near IR detection, $K_s = 18.5 \pm 0.3$


◆ Only three other sources have exhibited in the past such “burst storms”: SGR 1806-20, SGR 1900+14, SGR 1627-41

◆ $T_{90}$ burst duration = 155 (10) ms for 353 (unsaturated) bursts
SGR J1550 - 5418: Temporal
SGR J1550 - 5418: Spectral

- 4.55(5) keV
- 39.6(6) keV
- 15.0(2) keV
- -0.93(2)
SGR J1550 - 5418: Spectral

Index = -0.9(1)
SGR J1550 - 5418: Correlations

- GBM data → $E_{\text{peak}}$ as hardness indicator. More accurate than hardness ratios

- Large flux/fluence range: not a simple (anti-) correlation?

- Similar to SGRs J0501+4516, 1806-20, 1900+14

$-0.3(3)$, $0.16(3)$
SGR J1550 - 5418: Correlations

The diagram shows the correlation between fluence and 4ms peak flux. The points represent different categories of bursts:
- October Bursts
- January 22 & 23 Bursts
- Tail' Bursts
- March/April Bursts

A dashed line indicates a power law relationship with a slope of 1.2(4).
SGR J1550 - 5418: phase correlations
SGR J1550 - 5418: phase correlations

[Graph showing phase correlations with different energy bands]

- Counts (×10^7) vs. spin-phase
- Photon Rate (cts/s, 0.5 – 10 keV)

Energy bands:
- 8 – 20 keV
- 20 – 50 keV
- 50 – 200 keV
- 8 – 200 keV
All triggers: temporal properties

Unknown event avg $T_{90} = 61$ ms (known avg $\sim 100$ ms)
All triggers: comparative properties
Unknown source locations

The diagram shows the distribution of unknown source locations in the galaxy, with the x-axis representing Galactic Longitude (deg) and the y-axis representing Galactic Latitude (deg). The upper graph displays the number of bursts, while the lower graph illustrates the spatial distribution of these sources.

The red arrow indicates a specific location of interest, and the black diamonds represent additional significant points.

The patterns and concentrations suggest areas with higher activity or significance in the distribution of these unknown sources.
NEW: GBM
Bursts detected since Fermi launch
SYNERGY: Swift-Fermi-RXTE-IPN

Old source reactivation

SGRs

AXPs

Kouveliotou et al. 2011
SGR J1550-5418 — Example of a burst

- GBM Burst example for SGR J1550-5418.
- Saturation periods clearly seen. Excluded from all analyses.
SGR J1550-5418

- $P = 2.1 \, \text{s}, \dot{P} = 2.32 \times 10^{-11} \, \text{s}^{-1}$
- $B \sim 2.1 \times 10^{14} \, \text{G}$

- Entered high level of activity in 2008-2009
  - Hundreds of bursts on 22 January 2009 seen with many high-energy instruments, e.g., FERMI/GBM (van der Horst et al. 2012)

Kaneko et al. 2010
SGR J1550-5418 — Spectral modeling

GBM-only fit, 8-200 keV

Power-law with high energy exponential cutoff

Classical Comptonization problems

$$\gamma = 1/2 - (9/4 + 4/y_B)^{1/2}$$

$$y_B = (4kT_e/m_e c^2)\max\{\tau_B, \tau_R^2\}$$

Ribicki & Lightman (1979)
SGR J1550-5418 — Spectral modeling

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Ribicki & Lightman (1979)

$$\tau_R >>$$

to accomplish such a spectral curvature will lead to thermalization
SGR J1550-5418 — Spectral modeling

Power-law with high energy exponential cutoff

Classical Comptonization problems

\[ \langle E_{\text{peak}} \rangle \approx 40 \text{ keV}, \langle \gamma \rangle \approx -1 \]

\[ \gamma = 1/2 - (9/4 + 4/y_B)^{1/2} \]

\[ y_B = (4kT_e/m_o c^2) \max\{\tau_B, \tau_H^2\} \]

Two thermally emitting regions, 2BB

\[ kT_{\text{high}} \approx 13 \text{ keV}, kT_{\text{low}} \approx 6 \text{ keV}, \]

\[ R_{\text{high-kT}} \approx 0.3, R_{\text{low-kT}} \approx 17 \text{ km} \]

\[ R^2 = FD^2 / \sigma T^4 \]

Could be thought of as footpoints and surface layer of fireball

\[ P = 2 - 12 \text{ s}, P = 10^{-11} - 10^{-13} \text{ s} \text{ s}^{-1} \]
SGR J1550-5418 — Spectral modeling

GBM+Swift fit, 1-200 keV


Low-energy residuals with the Comptonized model
Perfect fit with the 2BBs

2BBs spectral parameters consistent with GBM only fits
SGR J1550-5418 — Spectral modeling

Time resolved spectroscopy of 50 brightest bursts

- Fit each bin with Comp. model.
- Follow evolution of fit parameters

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SGR J1550-5418 — Spectral modeling

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SGR J1550-5418 — Spectral modeling

Time resolved spectroscopy of 50 brightest bursts

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Similar spectral evolution for all 50 bursts.

Look for correlations of all 50 bursts simultaneously
SGR J1550-5418 — Spectral modeling
Time resolved spectroscopy of 50 brightest bursts
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Index $\gamma > -1$!!!
SGR J1550-5418 — Spectral modeling

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\[< \text{High } kT > \sim 13 \text{ keV}\]
\[< \text{Low } kT > \sim 6 \text{ keV}\]

SGR J1550-5418 — Spectral modeling

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SGR J1550-5418 — Spectral modeling

Time resolved spectroscopy of 50 brightest bursts

- Two thermally emitting regions during bursts
  - Highly coupled with energy equipartition between the two
  - $kT_{\text{high}}$: adiabatically expanding/contracting region — Could be thought of as the footprints of the plasma fireball.
  - $kT_{\text{low}}$: more complicated to interpret! — Representing the outer surface layer of the plasma?
  - $R^2 \propto kT^4$ relation places the plasma close to the surface of the NS.

SGR J1550-5418 — Spectral modeling

Time resolved spectroscopy of 50 brightest bursts

- Fit each bin with 2BB model.
- Follow evolution of fit parameters

\[ R_{\text{sat}} \sim 31 \text{ km} \]

\[ R_s \sim c/\nu \]

\[ R_s \sim 10 D_{15}^{-2} \left( \frac{\theta_{\text{max}}}{10^{-3}} \right) \left( \frac{V_\mu}{1.4 \times 10^8} \right) l_5 \text{ km}, \]

\[ R_\nu < R_{\text{sat}}, \text{ or insufficient excitation} \]

SGR J1550-5418 — Spectral modeling

Time resolved spectroscopy of 50 brightest bursts

- Fit each bin with 2BB model.
- Follow evolution of fit parameters

\[ R_{\nu} \sim 10 \, B_{15}^{-2} \left( \frac{\theta_{\text{max}}}{0.1} \right) \left( \frac{V_{\mu}}{0.8 \times 10^8 \, \text{cm s}^{-1}} \right)^{-1} l_5 \, \text{km} \]

\[ R_{\nu} < R_{\text{sat}} \]

\[ B \gtrsim 4.5 \times 10^{15} \left( \frac{R_{\text{max}}}{30 \, \text{km}} \right)^{-1/2} \left( \frac{\theta_{\text{max}}}{0.1} \right)^{1/2} \left( \frac{V_{\mu}}{0.8 \times 10^8 \, \text{cm s}^{-1}} \right)^{-1/2} l_5^{1/2} \, \text{G} \]

\[ E_{\text{max}} \sim 4 \times 10^{40} \, l_5^2 \, B_{15}^{-2} (\theta_{\text{max}}/0.1)^2 \, \text{erg} \implies B \lesssim 5.8 \times 10^{17} (\theta_{\text{max}}/0.1) l_5 \, \text{G} \]

Conclusion

• Strength of high-time resolution in studying magnetar bursts
  • Track the evolution of the emitting regions
  • Put to test the emission from a photon-pair plasma fireball
  • Prediction of intrinsic parameters of the system

• Motivation for a more in depth theoretical calculation of emergent spectrum of magnetar bursts, with the many physical and geometrical effects.
ENERGETICS

Fluence: $7 \times 10^{-9} - 1 \times 10^{-5}$ erg/cm$^2$

$E = (2 \times 10^{37} - 3 \times 10^{40}) d_5^2$ erg

Flux: $8 \times 10^{-7} - 2 \times 10^{-4}$ erg/cm$^2$s

$L: 5 \times 10^{38} - 1 \times 10^{41}$ erg/s

1806-20: $3.0 \times 10^{36} - 4.9 \times 10^{39}$ erg
1900+14: $7 \times 10^{35} - 2 \times 10^{39}$ erg
1627-41: $10^{38} - 10^{41}$ erg
0501+4516: $2 \times 10^{37} - 1 \times 10^{40}$ erg
1E2259+586: $5 \times 10^{34} - 7 \times 10^{36}$ erg

Total Energy Release:
$6.6 \times 10^{41} d_5^2$ erg (8-200 keV)
Magnetar Giant Flares

E up to $3 \times 10^{46}$ erg
1 erg cm$^{-2}$ at Earth

Hurley 2008
What is the evolutionary link between different types of sources?

Rotation powered PSRs -> SGRs -> AXPs -> DINS

(Kouveliotou 1999, Perna & Pons 2011, Turolla et al. 2011, Espinoza et al. 2011)
1. Since the Fermi launch, GBM has detected bursts from 8 sources: one third of the total population in five years!
2. The GBM magnetar burst spectra provide the first evidence for an unusual hardness $E_{\text{peak}}$ - flux relationship.
3. Evidence for higher energetic content in SGR bursts than in AXP bursts.
4. Upper limits on the LAT emission detection only.
The next five years of Magnetar observations:

• Population studies of magnetars
• Understand the links between PSRs – Magnetars – DINS
• Systematic searches for seismic vibrations in magnetar bursts-
  independent B-field measurement: STAND BY ON THESE RESULTS
• Giant flare detection becomes a strong possibility (for a rate of 1/
  source/10yrs, we expect one in the next three years - last was in 2004)
• Confirm pulsed emission breaks >100 keV will constrain $E_{\text{max}}$ of particles
  and localization of emission

Overarching theoretical issues:

• Localize the burst energy injection possibly on or near the NS surface to
  determine the injection mechanism
• Detection of gravitational waves from magnetar Giant Flares
• Determination of the magnetic Eddington limit

Synergy with new observatories:
NuSTAR, LIGO, LOFAR, AstroSAT, SVOM

Serendipitous Discoveries:
Always welcome!