Magnetar observations in the Swift-Fermi Era

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The Fermi Observatory

Gamma-ray Burst Monitor (GBM)
- NaI and BGO Detectors
  - 8 keV - 40 MeV

Large Area Telescope (LAT)
- 20 MeV -> 300 GeV

Spacecraft Partner:
General Dynamics

Launched 2008 June 11

**KEY FEATURES**

- **Large field of view**
  - LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours.
  - GBM: whole un-occulted sky at any time.

- **Over 7 decades energy range**
  - 8 keV - 300 GeV
GBM

- 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
Spectroscopy
Bridges gap between NaI and LAT.

GBM NaI detector.
8 keV -- 1000 keV
126 cm², 1.27 cm
Triggering, localization, spectroscopy.
• **GBM Triggered sources**
  - Gamma-ray bursts (GRBs)
  - Soft gamma repeaters (SGRs) aka magnetars
  - Terrestrial gamma flashes (TGFs)
  - Short transients detected by on-board trigger algorithm
  - Solar Flares

• **Non-triggered sources**
  - Pulsed sources detected by power spectral analysis and/or epoch folding
  - Longer-term transients and persistent sources detected by Earth occultation
Magnetars are magnetically powered neutron stars

- ~17 are discovered to date - three in 2008-2010 - Only 2 extragalactic sources

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

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

- $T_{\text{spindown}}(P/2 \dot{P}) = 2-220 \text{ kyrs}$

- $B \sim [1-10] \times 10^{14} \text{ G}$ (mean surface dipole field: $3.2 \times 10^{19} \sqrt{P \dot{P}}$)

- Bright sources, $L \sim 10^{33-36} \text{ erg/s}$, >> rotational E-loss

- No evidence for binarity so far (fallback disks?)

- SNe associations?
Neutron star populations which may comprise Magnetars:

**Soft Gamma Repeaters (SGRs)**

**Anomalous X-ray Pulsars (AXPs)**

**Dim Isolated Neutron Stars (DINs)**

**Compact Central X-ray Objects (CCOs)**

**Rotation Powered PSRs?!** PSR J1846−0258
Magnetar-like X-ray bursts were detected from the young pulsar PSR J1846-0258.

Rotation-powered PSR with an inferred surface dipolar magnetic field of $4.9 \times 10^{13}$ G, $P_s = 0.3$ s, Age ~ 900 yrs

Bursts accompanied by a sudden flux increase ($200L_X$) and unprecedented change in timing behavior (spin up->spin down).

Is there a continuum of magnetic activity that increases with inferred magnetic field strength?

Gavriil et al 2008
### GBM Magnetar Key Project

**PI: Chryssa Kouveliotou**

<table>
<thead>
<tr>
<th>SGR Source</th>
<th>Active Period</th>
<th>Triggers</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0501+4516</td>
<td>08/22/08-09/03/08</td>
<td>26</td>
<td>New source at Perseus arm</td>
</tr>
<tr>
<td>1806-20</td>
<td>11/29/08</td>
<td>1</td>
<td>Old source - reactivation</td>
</tr>
<tr>
<td>J1550-5418</td>
<td>10/03/08-10/20/08</td>
<td>7</td>
<td>Known source - first time exhibiting burst active episodes</td>
</tr>
<tr>
<td></td>
<td>01/22/09-02/24/09</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td></td>
<td>03/22/09-04/17/09</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>J0418+5729</td>
<td>06/05/09</td>
<td>2</td>
<td>New source at Perseus arm</td>
</tr>
</tbody>
</table>

**SGR 1833-0832** discovered 10/03/19 with Swift and RXTE - no GBM detection

[http://gammaray.nsstc.nasa.gov/gbm/science/magnetars](http://gammaray.nsstc.nasa.gov/gbm/science/magnetars)
SGR 0501+4516

- Swift triggered on 4 bursts on 22 August 2008
- RXTE ToO program triggered ~4 hours after the first Swift trigger for 600 s
- \( P = 5.7620 \text{ s (} \nu=0.173547943(1) \text{ Hz)} \) was reported ~ 9 hours after the first Swift trigger!
- \( P = 7.4980 \times 10^{-12} \text{ (} \dot{\nu}=-1.752(8) \times 10^{-13} \text{ Hz/s)} \) and \( B = 2.1 \times 10^{14} \text{ G} \)
- CXO HRC location: RA = 05h 01m 06.756s DEC = +45d 16m 33.92s (0.1” error)
- IR Counterpart with UKIRT, \( K \sim 18.6 \) (Tanvir & Varricatt 2008)
- GBM triggered on 26 events from the source - total of 56 events in ~ 3.5 days
Swift observations between 412 and 546 days after the source activation in 2008, show that the flux remained constant at ~ $7 \times 10^{-12}$ erg/cm$^2$ s for over a year after the first 100 days of decline.

This corresponds (assuming a distance of 2 kpc) to $L = 3.3 \times 10^{33}$ erg/s

Gogus et al 2010
2008, RXTE/PCA

2008-2009, Swift/XRT

Gogus et al 2010
Gogus et al. 2010
Persistent source spectra

Phase-resolved spectra (BB+PL) during the fourth day after activation. The BB component remains constant corresponding to an emitting region size of $R=0.3$ km.
GBM recorded a total of 29 Bursts

Lin et al 2010

<table>
<thead>
<tr>
<th>E_{peak} (keV)</th>
<th>Fluence (ergs/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max : 8.61</td>
<td>Max : 10.61</td>
</tr>
<tr>
<td>Center : 92.77</td>
<td>Center : 22.34</td>
</tr>
<tr>
<td>FWHM : 197.13</td>
<td>FWHM : 20.62</td>
</tr>
</tbody>
</table>

Average burst energy (at 2 kpc) = $1.5 \times 10^{38}$ erg
($2 \times 10^{37} - 9 \times 10^{39}$ erg)

Lin et al 2010
PRE in thermonuclear bursts

- Luminosity reaches Eddington limit, triggering Photospheric Radius Expansion (PRE).
- Expanding layers cool, leading to a multi-peaked light curve.
- Standard candle to measure a neutron star distance or mass/radius and hence equation of state.

\[ L_{\text{Edd}}, \infty = \left[ \frac{4\pi cGM}{\kappa(1 + z_{\text{ph}})} \right] \]

Watts et al 2010
PRE in thermonuclear bursts

Counts/s

Time

>10 keV

5-10 keV

2-5 keV
PRE in magnetar bursts

- Identifying PRE during a magnetar burst would give us the magnetic Eddington limit. If the magnetic field is known (e.g. from timing) this would again constrain distance/equation of state.

$$F_{\text{crit}} \approx 10^{-2} \text{ ergs/cm}^2/\text{s} \left( \frac{B}{10^{14} \text{ G}} \right) \left( \frac{1 \text{ keV}}{E_{\gamma}} \right) \times \left( \frac{1 \text{ kpc}}{d} \right)^2 \left( \frac{L_{\text{Edd}}}{2 \times 10^{38} \text{ ergs/s}} \right)$$

- PRE can only occur under certain burst emission scenarios. A PRE burst will therefore also constrain the burst trigger mechanism, a major unknown.

Miller 1995
The first magnetar candidate PRE burst

- Distance and field strength known.
- Predicted critical flux matches that recorded by GBM!
- Emission becomes softer during the dip in the light curve.

Watts et al 2010
Watts et al. 2010
SGR 1550-5418
formerly known as AXP 1E1547.0-5408
formerly known as an ASCA CCO in G327.0-0.13

- $P = 2.069\text{s}$
- $\dot{P} = 2.318 \times 10^{-11} \text{s/s and } B = 2.2 \times 10^{14} \text{ G}$
- Near IR detection, $K_s = 18.5 \pm 0.3$
- GBM triggered on 131 events from the source; many more in the data
SGR 1550-5418 Bursting Activity

Von Kienlin et al. 2010
Van der Horst et al. 2010
Magnetar in a Frenzy: SGR J1550-5418

450 bursts on one day...

...even when the Earth is in the way!

Van der Horst et al. 2010
Van der Horst et al. 2010
Adopting a distance to the SGR of 5 kpc, we estimate a total isotropic-equivalent energy release of $10^{42}$ ergs during this activation.

Van der Horst et al. 2010
Magnetar twist and shake...

Kaneko et al. 2010
Spectral Analysis

Time Integrated Spectrum \([T_0 + 72 - 248 \text{ s}]\)

- **8 – 909 keV** Burst Free

- **Total Energy**
  \[4.3 \times 10^{40} \text{ ergs}\]

- **Additional Blackbody** \((kT = 18 \text{ keV})\):
  \[\text{DCstat} = 13.5 \text{ (for 2 DOF)}\]

Kaneko et al. 2010
Time Resolved Spectra ($n F_n$)

$[T_0 + 72 - 117, 122 - 169, 173 - 223 \text{ s}]$

74 - 117 s  Power Law only  (Blackbody is not needed)

$122 - 169 \text{ s}$

$173 - 223 \text{ s}$

$F_{BB}/F_{TOTAL} = 26\%$  $25\%$

Kaneko et al. 2010
Evidence for the Blackbody Component

**Temporal Properties**
- Pulsations most significant in $120 - 210$ s
- Pulse fraction peaks in $50 - 74$ keV
- Pulsations not seen above $110$ keV

**Spectral Properties**
- Blackbody required in $122 - 223$ s
- Blackbody $kT \sim 17$ keV (Wien peak $\sim 50$ keV)
- $F_{BB} \rightarrow 25\%$
- $F_{PWRL} \rightarrow 75\%$

Kaneko et al. 2010
Blackbody: Radius of the Emitting Region

Assuming a hot spot of radius $R_{HS}$ on the neutron star surface

For $D = 5$ kpc, $kT = 17$ keV:

$$A_{HS} \approx 0.044 \left(\frac{D}{5 \text{ kpc}}\right)^2 \text{ km}^2$$

$$\Rightarrow R_{HS} \approx 120 \text{ m}$$

which is the size of the magnetically-confined hot plasma and is $<< 1\%$ of the NS surface area

Kaneko et al. 2010
SGR 0418+5729

- GBM triggered on 5 June 2009 - new source confirmed with IPN
- RXTE ToO program triggered ~ 4 days after the GBM triggers
- \( P = 9.0783(1) \) sec
- \( \dot{\nu} \sim 2 \times 10^{-14} \) Hz/s at 3\( \sigma \) and \( B < 10^{14} \) G
- CXO location: \( RA = 04h 18m 33.867s, \ Dec = +57d 32' 22.91" \)
- No IR (\( Ks > 21.3 \), Wachter et al 2009) or optical (\( R > 24 \), Ratti, Steeghs & Jonker 2009) counterpart detected
- GBM triggered on 2 events from the source
SGR 1833-032

- Swift/BAT triggered on 19 March 2010 (also seen with INTEGRAL, Kuiper & Hermsen 2010)– new source confirmed with XRT
- RXTE ToO program triggered <3.25 hours after the BAT trigger
- \( P = 7.5654091 \) sec
- \( \dot{P} \approx 4.39 \times 10^{-12} \) s/s at 3\( \sigma \) and \( B = 1.8 \times 10^{14} \) G
- CXO location: RA = 18h 33m 44.37s, Dec = -08d 31’ 07.5”
- No IR (Ks > 22.4) counterpart detected
- RXTE detected 4 more events from the source
Gogus et al. 2010

- 0.2-4 keV
- 4 - 6 keV
- 6 - 10 keV

Counts vs. Phase (cycle)

Normalized Counts vs. Phase (cycle)
Flux (10^{-12} erg cm^{-2} s^{-1}) vs Time (d) for various sources, including SGR 1900+14, SGR 0501+4516, SGR 1833–0832, SGR 1627–41, 1E 1547–5408, CXOU J164710–455216, and RX J0420.0-5022.
Magnetar Candidates
SGR burst time history with Fermi/GBM

![Graph showing SGR burst times](image)

- SGR 0526-66
- SGR 1627-41
- SGR 1806-20
- SGR 1900+14

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- SGR 1550-5418 (7/131)
- SGR 0501+4516 (26)
- SGR 0418+5729 (2)
CONCLUSIONS II

We still do not understand the differences - if any - between AXPs, SGRs and rotationally powered pulsars, in:

- persistent emission spectra
- glitching properties
- magnetic field strengths
- burst fluences and spectra

The associations of magnetars with SNRs, and their environments and track possible proper motions, now with two best candidates

The progenitor properties of magnetars, such as mass and cluster memberships

Could we identify PRE in magnetar flares and probe the neutron star EOS?