Systematic study of magnetar outbursts

Francesco Coti Zelati

Institute for Space Sciences, CSIC-IEEC, Barcelona

In collaboration with

N. Rea (CSIC-IEEC, U. Amsterdam), J. A. Pons (U. Alicante),
S. Campana (INAF-OAB), P. Esposito (U. Amsterdam)

Coti Zelati et al., submitted

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Observational properties

- About 25 X-ray pulsars with $L_x \sim 10^{33} - 10^{36}$ erg s$^{-1}$

- X-ray luminosity generally larger than the rotational energy loss rate

- soft and hard X-ray emission (0.5-200 keV); thermal + PL spectrum

- rotating with $P \sim 2 - 12$ s

- magnetic fields of $\sim 10^{13} - 10^{15}$ Gauss

- flaring activity in soft gamma-rays ($0.01 - 10^2$ s; $L_x \sim 10^{39} - 10^{47}$ erg s$^{-1}$)

- faint infrared/optical emission

- transient pulsed radio emission (in 4 cases)

see Rea & Esposito (2011); Turolla et al. (2015); Kaspi & Beloborodov (2017) for reviews.
Magnetar flaring activity (timescale: seconds/minutes)

**Short bursts**
- duration $\sim 0.01-1s$
- $L_x \sim 10^{39} - 10^{41}$ erg s$^{-1}$
- soft $\gamma$-rays thermal spectra ($kT \sim 30-40$ keV)

**Intermediate bursts**
- duration 1-40 s
- peak $\sim 10^{41} - 10^{43}$ erg s$^{-1}$
- abrupt on-set
- usually soft $\gamma$-rays thermal spectra

**Giant Flares**
- very rare events (only 3 observed)
- $L_x > 3 \times 10^{44}$ erg s$^{-1}$
- initial peak lasting <1 s with a hard spectrum
- ringing tail that can last > 500s, with softer spectrum and showing the NS spin pulsations
Magnetar outburst activity (timescale: months/years)

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Outburst mechanisms

1. **Internal source of heat**: Local magnetic stresses deform part of the stellar crust. Plastic flows convert the magnetic energy into heat. Partly is conducted up to the surface and radiated (thermal afterglow).

2. **External source of heat**: Crustal displacements twist up the external B-field. Returning currents hit and heat the NS surface. The bundle dissipates as the energy supply from the star interior decreases.

Both processes are likely at work. Emission can be sustained up to a few years.

Motivation for the study

A systematic and homogeneous analysis of the spectral properties of magnetars in outbursts is needed to:

(i) model all outbursts cooling curves in a consistent way;
(ii) unveil possible correlations among different parameters

Deeper insight into the emission processes via modelling with internal crustal cooling codes.

Varying the injected energy

Varying the quiescent luminosity
- 23 outbursts
- 14 magnetars + 2 high-B RPPs + CCO in RCW 103
- about 1100 X-ray observations (12 Ms) between 1998 and mid May 2017
- reduction of raw data sets, extraction of spectra for all observations
- spectral fitting with BB, 2BB, BB+PL and more physically-motivated models
- extraction of fluxes and luminosities in each observation
- extraction of the light curves
- empirical modelling of the bolometric cooling curves
- estimate of the outburst energetics and decay-timescale
High quality X-ray spectra

1E 1547-5408 (2008)
Chandra

SGR 0418+5729
XMM-Newton

Swift 1822.3-1606
XMM-Newton

1E 1547-5408 (2009)
Chandra

SGR 1833-0832
XMM-Newton

Swift 1834.9-0846
Chandra
Cooling curves: XTE J1810-197

Absorbed X-ray flux

BB$_1$ X-ray luminosity

BB$_2$ X-ray luminosity

X-ray luminosity

Bolometric

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The outburst sample, fitted models, energetics and timescales

\[ L(t) = L_q + \sum_{i=1}^{j} A_i \times \exp\left(-t/\tau_i\right) \]

\[ E = \int_0^{t_{\text{QUI}}} L(t) \, dt \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Component</th>
<th>Best-fitting decay model</th>
<th>( \tau ) (d)</th>
<th>( \tau_1 / \tau_2 / \tau_3 )</th>
<th>( E ) (erg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGR 1627–41 (1998)</td>
<td>BB/bol</td>
<td>2EXP</td>
<td>–</td>
<td>( 234^{+37}<em>{-35} / 1307^{+373}</em>{-265} )</td>
<td>( 2 \times 10^{42} )</td>
</tr>
<tr>
<td>1E 2259+586 (2002)</td>
<td>BB1 EXP</td>
<td></td>
<td>( 1.41 \pm 0.05 )</td>
<td>( 47^{+40}_{-16} / 21 \pm 13 )</td>
<td>( 10^{41} )</td>
</tr>
<tr>
<td></td>
<td>BB2 EXP</td>
<td></td>
<td>( 376^{+72}_{-65} )</td>
<td>( 372^{+29}<em>{-27} / 328^{+38}</em>{-36} )</td>
<td>( 4 \times 10^{42} )</td>
</tr>
<tr>
<td>XTEJ1810–197</td>
<td>BB1 EXP</td>
<td></td>
<td>( 2.9 \pm 0.7 )</td>
<td>( 9 \pm 1 / 458 \pm 64 )</td>
<td>( 10^{42} )</td>
</tr>
<tr>
<td></td>
<td>BB2 EXP</td>
<td></td>
<td>( 2.4^{+0.8}<em>{-0.6} / 53 \pm 3 / 238^{+17}</em>{-13} )</td>
<td>( 2 \times 10^{43} )</td>
<td>( 10^{42} )</td>
</tr>
<tr>
<td>SGR 1627–41 (2008)</td>
<td>BB/bol</td>
<td>3EXP</td>
<td>( 2.9 \pm 0.7 )</td>
<td>( 5.7^{+0.7}<em>{-0.4} / 508^{+23}</em>{-43} )</td>
<td>( 2 \times 10^{43} )</td>
</tr>
<tr>
<td>SGR 0501+4516</td>
<td>BB EXP</td>
<td></td>
<td>( 33 \pm 2 )</td>
<td>–</td>
<td>( 8 \times 10^{40} )</td>
</tr>
<tr>
<td></td>
<td>PL EXP</td>
<td></td>
<td>( 364 \pm 15 )</td>
<td>( 3 \pm 1 / 109 \pm 8 / 2870^{+228}_{-116} )</td>
<td>( 2 \times 10^{43} )</td>
</tr>
<tr>
<td>SGR 1806–20</td>
<td>bol EXP</td>
<td></td>
<td>( 128^{+20}_{-16} )</td>
<td>( 128^{+20}_{-16} )</td>
<td>( 10^{42} )</td>
</tr>
<tr>
<td>CXOUJ11647–4552 (2006)</td>
<td>BB EXP</td>
<td></td>
<td>( 0.78^{+0.1}<em>{-0.1} / 16.7^{+1.0}</em>{-0.9} / 207^{+12}_{-11} )</td>
<td>( 14.6 \pm 0.8 / 817^{+54}_{-52} )</td>
<td>( 3 \times 10^{41} )</td>
</tr>
<tr>
<td></td>
<td>PL EXP</td>
<td></td>
<td>( 7 \pm 2 / 28^{+3}<em>{-3} / 60^{+15}</em>{-14} )</td>
<td>( 7 \pm 2 / 28^{+3}<em>{-3} / 60^{+15}</em>{-14} )</td>
<td>( 3 \times 10^{41} )</td>
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<tr>
<td>SGR 1833+5729</td>
<td>BB/bol</td>
<td>2EXP</td>
<td>( 0.08 \pm 0.01 )</td>
<td>( 17.7 \pm 0.4 )</td>
<td>( 2 \times 10^{41} )</td>
</tr>
<tr>
<td>Swift J1822.3–1606</td>
<td>BB EXP</td>
<td></td>
<td>( 47 \pm 16 )</td>
<td>–</td>
<td>( 6 \times 10^{40} )</td>
</tr>
<tr>
<td></td>
<td>PL EXP</td>
<td></td>
<td>( 39^{+20}<em>{-16} / 382^{+53}</em>{-31} )</td>
<td>( 39^{+20}<em>{-16} / 382^{+53}</em>{-31} )</td>
<td>( 8 \times 10^{42} )</td>
</tr>
<tr>
<td></td>
<td>bol EXP</td>
<td></td>
<td>( 79^{+50}_{-35} )</td>
<td>( 33.7^{+10}_{-9} )</td>
<td>( 3 \times 10^{41} )</td>
</tr>
<tr>
<td></td>
<td>bol EXP</td>
<td></td>
<td>( 205^{+73}_{-70} )</td>
<td>( 42^{+14}<em>{-9} / 264^{+49}</em>{-29} )</td>
<td>( 4 \times 10^{42} )</td>
</tr>
<tr>
<td>SGR 1745–2900</td>
<td>BB/bol</td>
<td>2EXP</td>
<td>( 81^{+6}<em>{-20} / 324^{+27}</em>{-17} )</td>
<td>( 81^{+6}<em>{-20} / 324^{+27}</em>{-17} )</td>
<td>( 10^{43} )</td>
</tr>
<tr>
<td>1E 1048.1–5937 (2011)</td>
<td>BB/bol</td>
<td>2EXP</td>
<td>( 56 \pm 6 )</td>
<td>–</td>
<td>( 4.5 \times 10^{41} )</td>
</tr>
<tr>
<td>PSR J1119–6127</td>
<td>bol EXP</td>
<td>3EXP</td>
<td>( 110^{+13}<em>{-10} / 856^{+27}</em>{-27} )</td>
<td>( 110^{+13}<em>{-10} / 856^{+27}</em>{-27} )</td>
<td>( 10^{43} )</td>
</tr>
<tr>
<td>PSR J1846–0258</td>
<td>bol EXP</td>
<td>2EXP</td>
<td>( 0.25 \pm 0.06 )</td>
<td>( 507^{+59}_{-49} )</td>
<td>( 2 \times 10^{42} )</td>
</tr>
</tbody>
</table>
## Correlations & Anticorrelations

<table>
<thead>
<tr>
<th>First parameter</th>
<th>Second parameter</th>
<th>Corr/Anticorr, Significance (σ)</th>
<th>PL index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiescent X-ray flux</td>
<td>Maximum flux increase</td>
<td>(a) 5.4 / 4.6</td>
<td>-0.7</td>
</tr>
<tr>
<td>Quiescent X-ray luminosity</td>
<td>Maximum luminosity increase</td>
<td>(a) 5.7 / 4.9</td>
<td>-0.7</td>
</tr>
<tr>
<td>Spin-down luminosity</td>
<td>Quiescent bolometric thermal luminosity</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Dipolar magnetic field</td>
<td>Quiescent bolometric thermal luminosity</td>
<td>(c) 3.2 / 2.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Dipolar magnetic field</td>
<td>Peak luminosity</td>
<td>(c) 2.5 / 2.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Dipolar magnetic field</td>
<td>Decay timescale</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Dipolar magnetic field</td>
<td>Outburst energy</td>
<td>(c) 3.7 / 3.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Characteristic age</td>
<td>Outburst energy</td>
<td>(a) 3.3 / 3.0</td>
<td>-0.4</td>
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<tr>
<td>Peak luminosity</td>
<td>Outburst energy</td>
<td>(c) 4.0 / 3.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Quiescent bolometric thermal luminosity</td>
<td>Outburst energy</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>Decay timescale</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Outburst energy</td>
<td>Decay timescale</td>
<td>(c) 3.9 / 3.6</td>
<td>0.5</td>
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<tr>
<td>Outburst energy</td>
<td>Maximum luminosity increase</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Decay timescale</td>
<td>Maximum luminosity increase</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Correlations & Anticorrelations

The definition of “transient” magnetars as opposed to the “persistent” magnetars is deceptive: it only reflects their different quiescent luminosities.

Large flux enhancements can only be observed in faint quiescent magnetars.
Correlations & Anticorrelations

CCOs depart significantly from the trend.

Expected in the ‘hidden magnetic field’ scenario: fallback accretion onto the NS (10^{-3} - 10^{-2} M_{\text{Sun}} in hrs-days) can bury a B field of a few 10^{12} G into the inner crust (Viganò & Pons 2012; Torres-Fornè et al. 2016).

The external B field is lower than the internal ‘hidden’ B field, hence does not trace the bolometric luminosity.

RPPs depart a bit from the trend.

The larger luminosity wrt the prediction is likely due to slamming particles heating the NS surface, providing an additional source of heat.
Correlations & Anticorrelations

Young magnetars undergo more energetic outbursts

Broad agreement with the idea that magnetar outbursts are ultimately powered by the dissipation of the B-field

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Correlations & Anticorrelations

Similar decay pattern for all magnetar outbursts

Expected in the interior crustal cooling model
(the deeper the location of the energy release, the more energetic
the outburst, the longer the time for heat diffusion)

Expected in the untwisting bundle model \( (T \propto E^{0.5}) \)

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The magnetar outburst online catalog

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