INTEGRAL discovery of a magnetar burst with associated radio emission.

The first fast burst observed both in radio and hard X-ray comes from the magnetar SGR 1935+2154.
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INTEGRAL discovery of a magnetar burst with associated radio emission.

Preamble

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Introduction

Magnetars

- Isolated neutron stars powered by magnetic energy (24+5 sources).
- Slowly rotating ($P \sim 1 - 10$ s) and fast spin-down ($\dot{P} \sim 10^{-10} - 10^{-11}$ s/s)
- $L_X \approx 10^{34} - 10^{36}$ erg/s $>\dot{E}_{\text{rot}}$
- Many transients with $L_{\text{Quiesc}} \approx 10^{32}$ erg/s
- show rarely (5 cases) some transient pulsed radio emission, associated to X-ray outbursts but very bright, with large pulse-to-pulse variability, with pulse morphologies that change enormously in minutes
- Reviews from Kaspi & Beloborodov (2017) and Mereghetti et al. (2015).
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Introduction: Magnetars

Magnetar locations

From the McGill online catalog (Olausen & Kaspi, 2014),

- located in the Galactic plane or Magellanic Clouds
- associated with young stellar clusters and supernova remnants (8+2)
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Introduction: Magnetars

Magnetar persistent spectra

Comparison of spectra from X-per, Geminga, and the magnetically-powered AXP 4U 0142+61 (from Mereghetti et al. 2015)

The combined Swift/Nustar spectrum of 1E 2259 (from Kaspi & Beloborodov 2017)

Thermal spectrum $kT \sim 0.5$ keV with hard tails up to 200 keV
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Introduction: Magnetars

SGR and AXMPs are magnetars

- Soft Gamma Repeaters (SGR) were discovered in 1979. Initially confused with GRB, it was realised they originate from Galactic objects with softer spectra.

- Neutron-star origin of SGR 0526−66 was clear from pulsation at 8 s.

- The model of spontaneous magnetic field decay was proposed in the 90s to explain both bursts (crustal quakes or reconnections) and persistent emission.

- Magnetic field exceeding $10^{14}$ G was required and it was confirmed by high spin-down in several sources.

- Anomalous X-ray pulsars (AXP) were discovered in 80s and 90s characterized by soft spectra, higher-than-usual luminosity, and several seconds long periods.

- In 2002, SGR-like bursting activity was discovered from an AXP, confirming the link.

The distinguishing feature is the bursting activity with burst duration less than seconds.
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Introduction: Magnetars

Magnetar flaring - Short bursts ($\Delta t \lesssim 1\,\text{s}$)

Examples of single bursts (from Kaspi & Beloborodov 2017)

- $L_X \sim 10^{39} - 10^{41}\,\text{erg/s}$
- Hard X-ray/Soft $\gamma$-ray thermal spectra with $kT \sim 30 - 40\,\text{keV}$
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Introduction: Magnetars

Magnetar flaring- Intermediate bursts ($\Delta t = 1 - 40\,\text{s}$)

- Emission of a forest of bursts
- At peak $L_X \sim 10^{41} - 10^{43}\,\text{erg/s}$
- Abrupt onset
- Hard X-ray/Soft $\gamma$-ray thermal spectra
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Introduction: Magnetars

Magnetar flaring - Giant bursts \( (L_x \gtrsim 3 \times 10^{44} \text{ erg/s}) \)

The giant burst of SGR 1806–20 seen with SPI-ACS (the peak at \( 2 \times 10^6 \) counts is not shown) (from Mereghetti et al. 2005)

- Initial spike with hard spectrum, thermal tail with energy \( 10^{44} \) erg and pulsation from the magnetar
- Stringent upper limit on radio emission (Tendulkar et al., 2016).
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Introduction: Magnetars

Outburst activity models

Internal source of heat

• Local magnetic stresses deform part of the stellar crust.
• Plastic flows convert the magnetic energy into heat.
• Energy is partly is conducted up to the surface and radiated (thermal afterglow)

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.

Probably both mechanisms are at work to sustain emission for years.
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Introduction: Fast radio bursts

- **Fast radio bursts (FRBs)** are millisecond-duration pulses that originate from as-yet-unidentified extragalactic sources.
- First one discovered in 2007
- Similar to pulses from Galactic radio pulsars, but the flux density is $10^{10}$ times larger
- More than 100 sources
- Multiple bursts have been detected from $\sim 20$ FRB sources and only a few have secure localizations (first by Areceibo FRB 121102, then by CHIME)
- Two semi-periodic (several days) FRB sources
- FRB 121102, the first to be localized, is in a star-forming region in a dwarf galaxy with a luminosity distance of about 1 Gpc.
- Astoundingly large all-sky rate
  \[ \Gamma_{\text{FRB}}(>1, \text{Jyms}) \sim 10^3 - 10^4 \text{sky}^{-1}\text{day}^{-1} \]
  above a 1 Jy ms fluence threshold
  \[ \rightarrow 10^3 \text{Gpc}^{-3}\text{yr}^{-1} \]
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**SGR 1935+2154**

- Discovered in 2014 owing to a 0.5-s burst observed by Swift (Israel et al., 2016)
- $P = 3.24$ s, $\dot{P} = 1.4 \times 10^{-11}$
- $B = 2.2 \times 10^{14}$ Gauss
- Spin-down age: $\tau = 3600$ years
- $L_{\text{spin-down}} = 2 \times 10^{34}$ erg/s
- The source spectrum is well modelled by a blackbody with $kT = 0.5$ keV plus a power-law component with $\Gamma = 2$
- Likely associated to SNR G57.2+0.8 (Kothes et al., 2018)
- Estimated distances of the SNR $\sim 12.5$ kpc (Kothes et al., 2018), 4.5–9 kpc (Ranasinghe et al., 2018), and $6.6\pm0.7$ (Zhou et al., 2020).
INTEGRAL discovery of a magnetar burst with associated radio emission. SGR 1935+2154: ID of a “normal” magnetar

**Bursting story of SGR 1935+2154**

- Four outbursts observed before 2020
- Hundreds of bursts and one intermediate flare in 2016 (Kozlova et al., 2016; Lin et al., 2020a)
- The burst most prolific magnetar.

*From (Younes et al., 2017).*

*Duration of bursts and fluence for burst forest in 2020 (Lin et al., 2020a).*

**Swift-INTEGRAL-eRosita persistent emission**

Evolution of the SGR 1935+2154 mean flux measured in soft X-rays with Swift/XRT (red points) and SRG/eROSITA (blue point) and upper limits from INTEGRAL in hard X-rays (black points). The horizontal dashed line shows the persistent flux level in the 0.5-4 keV energy band, calculated with parameters from Younes et al. (2017).
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SGR 1935+2154: The 2020 outburst.

The first FRB–magnetar burst coincidence

On 28 April 2020, a soft/X-ray burst is observed in timing coincidence with a FRB, both coming from the direction of SGR 1935+2154.

<table>
<thead>
<tr>
<th>Apr. 28</th>
<th>14:34:24</th>
<th>$T_0$</th>
<th>Burst from SGR 1935+2154</th>
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<tbody>
<tr>
<td></td>
<td>14:34:29</td>
<td>$T_0+5\text{s}$</td>
<td>IBAS Alert sent, 0.5 s-long burst of $\sim100$ Crab, associated to SGR 1935+2154</td>
</tr>
<tr>
<td></td>
<td>20:45</td>
<td>$T_0+6\text{hr}$</td>
<td>CHIME radio 400-800 MHz</td>
</tr>
<tr>
<td>Apr. 29</td>
<td>03:04</td>
<td>$T_0+12.5\text{hr}$</td>
<td>STARE 2 radio 1.4 GHz</td>
</tr>
<tr>
<td></td>
<td>09:30:38</td>
<td>$T_0+19\text{hr}$</td>
<td>INTEGRAL (first to report association)</td>
</tr>
<tr>
<td></td>
<td>10:53</td>
<td></td>
<td>INTEGRAL</td>
</tr>
<tr>
<td></td>
<td>11:05</td>
<td></td>
<td>AGILE (no imaging, $3\sigma$ association)</td>
</tr>
<tr>
<td></td>
<td>15:34:34</td>
<td>$T_0+1\text{d}$</td>
<td>Konus-WIND (no imaging)</td>
</tr>
<tr>
<td></td>
<td>19:05</td>
<td></td>
<td>Insight-XHMT</td>
</tr>
<tr>
<td></td>
<td>19:42</td>
<td></td>
<td>Konus-WIND (no imaging)</td>
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</table>
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SGR 1935+2154: The STARE2 radio detection

STARE2 Detection plots

The de-dispersed FRB seen by FLARE2 (Bochenek et al., 2020).

The FRB FLARE2 localisation (Bochenek et al., 2020).
INTEGRAL discovery of a magnetar burst with associated radio emission. SGR 1935+2154: The STARE2 radio detection

**STARE2 burst facts**

- STARE2 is an array of 3 radio telescopes operating at 1.4 GHz in USA.
- termed ST 200428A (=FRB 200428), detected in the 1281–1468 MHz band.
- fluence of $1.5 \pm 0.3$ Mega-Jansky milliseconds.
- Energy release $4 \times 10^3$ greater than in any Galactic fast radio burst
- just 40 times less energetic than the weakest extragalactic FRB
- STARE2 had been observing for 448 days prior to ST 200428A, with an effective field of view of 1.84 steradian and a detection threshold of 300 kJy for millisecond duration bursts.

*Duration and luminosity of radio emission (Bochenek et al., 2020).*

- volumetric rate for bursts with energy releases equivalent to or greater than ST 200428A of $7.2^{+8.8}_{-6.1} \times 10^7 \text{Gpc}^{-3}\text{yr}^{-1}$, consistent with an extrapolation of the luminosity function of bright FRBs.
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CHIME Detection plots

- Two sub-bursts with temporal widths of 0.585±0.014 ms and 0.335±0.007 ms separated by 28.91±0.02 ms.
- RA=293.9, Dec=+22.1, with systematic uncertainties of order 1°, compatible with SGR 1935+2154
- DM 332.7206±0.0009 pc cm$^{-3}$, < than Galactic (500–700)
- 400–800-MHz isotropic peak spectral luminosity $190_{-90}^{+190} d_{10 \text{ kpc}} \text{ MJy kpc}^2$
- Emitted energy $3_{-1.6}^{+3} d_{10 \text{ kpc}} \times 10^{34} \text{ erg.}$
- Peak 400–800-MHz luminosity $7_{-4}^{+7} d_{10 \text{ kpc}} \times 10^{36} \text{ erg/s}$
- roughly factor 2 uncertainty on flux due to large off-beam.
- The STARE2 peak corresponds to the CHIME second peak.

The de-dispersed FRB seen by Chime (The CHIME/FRB Collaboration et al., 2020).

- The Canadian Hydrogen Intensity Mapping Experiment (CHIME) radio telescope consists of four fixed reflecting cylinders sensitive to 400–800 MHz.

- CHIME is a transit instrument with a $\approx 3 \times 120^\circ$ instantaneous field of view.
INTEGRAL discovery of a magnetar burst with associated radio emission. SGR 1935+2154: The CHIME radio detection

FRB fluence and the magnetar burst

Comparison of short radio burst energetics. The observed burst fluence at radio frequencies from 300 MHz to 1.5 GHz for Galactic neutron stars and extragalactic FRBs are plotted with their estimated distances. Gray diagonal lines indicate loci of equal isotropic burst energy with an assumed fiducial bandwidth of 500 MHz. FRB distances are estimated from their extragalactic dispersion measure contribution including the simulated variance. Pulsar distances are estimated based on the NE2001 Galactic electron distribution model. Objects with accurately measured distances (parallax or host galaxy redshift) are indicated with vertical lines. (The CHIME/FRB Collaboration et al., 2020).
INTEGRAL discovery of a magnetar burst with associated radio emission. SGR 1935+2154: The INTEGRAL detection

Light curve in the 20-200 keV range obtained with the IBIS/ISGRI instrument. We used an adaptive binning to ensure at least 40 counts per time bin. All the times are in the geocentric frame and referred to $t_0=14:34:24$ UTC of April 28, 2020. The blue lines (at 0.19, 0.395, 0.536, and 0.79 s) indicate the time intervals used for the spectral and imaging analysis. The orange line (adapted from Fig. 1 of The CHIME/FRB Collaboration et al. (2020)) marks the position of the radio pulses. The inset shows the brightest part of the burst, binned at 1 ms. The radio pulses are represented here with two Gaussian curves centered at 0.42848 s and 0.45745 s (Table 1 of The CHIME/FRB Collaboration et al. (2020)). The red line in the inset is the fit to the ISGRI data with a combination of Gaussian curves (see text for details), that yields the following times for the three narrow peaks: $t_1=0.434^{+0.004}_{-0.002}$ s, $t_2=0.462^{+0.001}_{-0.001}$ s, and $t_3=0.493^{+0.002}_{-0.003}$ s.
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The spectrum

- We obtained a best-fit photon index $\Gamma = 0.7^{+0.4}_{-0.2}$, peak energy $E_p = 65 \pm 5$ keV, and 20–200 keV flux of $(8.5 \pm 0.4) \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ ($\chi^2_\nu = 1.8$ for 13 dof).

- We fitted the spectra of the time intervals preceding and following the main pulse imposing a common value for the photon index: $\Gamma = 0.62^{+0.22}_{-0.18}$ and find $E_p$ of $34 \pm 8$ keV (before main pulse), $60 \pm 5$ keV (main pulse), and $125^{+50}_{-29}$ keV (after main pulse).

- Evidence for a spectral hardening as a function of time

Unfolded energy spectra of burst-G fitted with a cut-off power law model (top panel). The three spectra refer to the main pulse (black squares), to the interval before (red circles), and after the main pulse (blue stars). The lower panel shows the residuals in units of $\sigma$. 
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SGR 1935+2154: The INTEGRAL detection

A hard spectrum

- the spectrum was harder than that of typical SGR bursts.
- Its peak energy $E_p=65\pm5$ keV, is larger than a large sample of bursts from SGR 1935+2154 observed with the Fermi/GBM instrument (Lin et al., 2020a)
- the most similar burst was detected on April 22, 2020 (Cherry et al., 2020; Hurley et al., 2020) by other satellites with $E_p=52\pm2$ keV and a 20-200 keV fluence of $\sim 10^{-5}$ erg cm$^{-2}$, but a simple time profile consisting of a single pulse lasting 0.6 s with fast rise and no evidence for sub-structures (Ridnaia et al., 2020a).
- the burst was harder than that of the intermediate flare emitted by SGR 1935+2154 on April 12, 2015. This was at least a factor 10 more energetic, but had $E_p=36$ keV and a smooth time profile (Kozlova et al., 2016).
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SGR 1935+2154: The INTEGRAL detection

Other bursts

Light curves of the bursts detected by IBIS/ISGRI during the April-May observations.

Time profiles of five short X-ray bursts from SGR 1935+2154 detected by Konus-Wind in April-May 2020, in the 18–320 keV energy band. (Ridnaia et al., 2020b).

In contrast with typical magnetar bursts, which have smooth time profiles and start with a prominent, sharp rise of the intensity, the April 28 burst demonstrates slowly rising, spiky light curve.
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**SGR 1935+2154: Distance Estimate**

- Swift/XRT detected an X-ray ring with radius of \( \sim 85'' \) on April 27, about one hour after a “burst forest”.
- The angular radius \( \theta \) of a ring produced by a burst emitted at \( t_B \) at distance \( d_s \) and scattered by dust at distance \( d_d \), increases as:

\[
\theta(t) = \left[ \frac{827 \ (1 - x)}{d_s} \frac{x}{x} (t - t_B) \right]^{1/2}
\]

where the distances are in parsecs, \( \theta \) in arcseconds, \( t \) in seconds, and \( x = \frac{d_d}{d_s} \).

**X-ray images (0.2-10 keV) of SGR 1935+2154 obtained with Swift/XRT on 2020 April 27. The first observation clearly shows a ring of scattered emission that extends for more than 1' from the source, and that completely faded away the following day.**
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\[ d = 512 \pm 16 \text{ pc from 3D distrib. optical extinction (Green et al., 2019)} \]

\[ t_B = \text{April 27 18:33:10 (Ursi et al., 2020; Palmer, 2020).} \]

\[ d_s = 4.4^{+2.8}_{-1.3} \text{ kpc} \]
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A rare phenomenon

• A highly polarized faint radio flare from SGR 1935+2154 was detected by the Five-hundred-meter Aperture Spherical radio Telescope (FAST) in China on April, 30 at 21:43:00.5 UTC (Zhang et al., 2020). At this time the source was 12.9° off-axis and we could derive a 5σ upper limit on the fluence of any burst shorter than 1 s at the level of 2.3×10⁻⁸ erg cm⁻² in the 20–200 keV band.

• FAST and STARE2 derived fluence upper limits for many other hard X-ray bursts eight orders of magnitude deeper than the fluence of FRB 200428.

• → FRB–SGR burst associations are rather rare.

Timeline of FAST and other observations (Lin et al., 2020b).
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Magnetar bursts and FRBs

Comparison of the spectral energy distribution of the FRB/X-ray burst from SGR 1935+2154 (red) with the upper limits for other magnetars and FRB obtained from simultaneous radio and X-ray observations (Hurley et al., 2005; Tendulkar et al., 2016; Kozlova et al., 2016; Scholz et al., 2017; Lin et al., 2020b; The CHIME/FRB Collaboration et al., 2020; Bochenek et al., 2020; Scholz et al., 2020; Pilia et al., 2020)
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The radio X-ray plane

Radio versus X-ray (starting from 0.5 keV) isotropic luminosity for FRBs and magnetar bursts. The range of FRB luminosity corresponds to a variety of events reported in the past years. The contours correspond to the containment of number of sources (75%, 50%,...). This is encouraging for further follow-up campaigns.
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Final considerations

• The first evidence of connection of magnetar flares and fast radio bursts
• The luminosity gap between FRB and this magnetar FRB is compatible with FRB 200428 being on the tail of the FRB population
• Not all magnetar bursts are associated to radio emission
• Not all magnetar FRB are associated to X-ray emission
• The repeating FRB and in particular the periodic ones are 100 times brighter and the long period of 16 days is not typical of any magnetar phenomenon, as well as their long duration (Tavani et al., 2020; Margalit et al., 2020)
• The tight timing coincidence (X-ray burst peaks are within ms of radio peaks) favors an origin within the light cylinder $r_l \approx 10^{10} \text{ cm}$, unless relativistic beaming is invoked
• Coherent synchrotron maser radio emission could be produced at $10^{11} \text{ cm}$ with shock of baryonic ejecta (Margalit et al., 2020), but extragalactic FRB must be produced by a population of more extreme and exotic magnetars
• Some models of curvature emission in the magnetosphere explain the double radio peak (Wang et al., 2020).
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References I


Hurley, K., Mitrofanov, I. G., Golovin, D., et al. 2020, GRB Coordinates Network, 27625, 1


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References II

Palmer, D. M. 2020, The Astronomer's Telegram, 13675, 1
Zhang, C. F., Jiang, J. C., Men, Y. P., et al. 2020, The Astronomer’s Telegram, 13699, 1
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Data of HXMT (Li et al., 2020)

Localisation of the burst

The light curves in different energy bands and hardness ratio

The average spectrum is best fitted by a power law with exponential cutoff