Power of agile and flexible observations of the large effective area NICER telescope — Examples of magnetars and transients

Teruaki Enoto (RIKEN, Japan)
George Younes, Wynn Ho, Chin-Ping Hu, Wataru Buz Iwakiri, and on behalf of the NICER Magnetar & Magnetosphere team

@teru_enoto

NICER Summer 2022 Science Workshop (18+2 min)
X-ray observatory NICER on the ISS

- The largest effective area 1,900 cm² at 1.5 keV with high-time resolution (<100 ns)!
X-ray observatory NICER on the ISS

- The largest effective area 1,900 cm$^2$ at 1.5 keV with high-time resolution (<100 ns)!

The Crab Pulsar

Review

The Crab Pulsar is one of the most studied objects among RRATs. Its magnetic field strength inferred from the measured period and its derivative is $B_d = 5 \times 10^{13} \text{G}$, which is at a similar level to those of low-B magnetars (section 3.3), high-B pulsars (section 3.4), and XINS (section 3.5) and is close to the upper end of the scale of the magnetic field $B_d$ for Figure 16.

Figure 16. Pulsar distribution in the $P$–$\dot{P}$ diagram of (upper-left panel) nulling and mode-changing pulsars which show a discontinuous change in the radio profile, (upper-right) intermittent pulsars which have a correlation between the discontinuous radio change and spin-down state, (bottom-left) RRATs which exhibit sporadic radio pulses, and (bottom-right) pulsars with a giant radio pulse(s) (GP). The data are taken from [82, 115, 117, 270, 331, 587, 674, 829, 833, 856] for nulling and mode-changing pulsars, [124, 436, 493, 505] for intermittent pulsars, the RRATalog (table A1 in appendix) for RRATs, and [153, 169, 228, 229, 373, 402, 403, 419–421, 451, 452, 726, 739] for pulsars with a GP. As in Figure 1, large open black circles, pentagons, diamonds, and squares are for magnetars, XINSs, HBPs with x-ray emission, and CCOs, respectively.
Short exposure to detect the Crab pulsation
Short exposure to detect the Crab pulsation

Detection significance of X-ray pulses

- Pulse signals are detectable within 1 sec
- Free from pileups, dead time, and data transfer loss (throughput 3.8×10⁴ cps).
Best Use of the NICER Telescope’s Performance?

1. Large effective area (~1900 cm² at 1.5 keV)
2. High-time resolution (<100 ns)
3. Free from pileups, dead time, and data transfer loss (up to ~4×10⁴ cps)
4. Flexible observations (quick response to ToO, even within a day)

• Examples and applications
  • Discovery of an X-ray enhancement at the Crab giant radio pulses
  • Prompt follow-ups of new magnetars to identify pulsar characteristics
  • Comprehensive studies of magnetar short bursts
  • Search for gravitational waves from rotation powered pulsars
  • Automated transient alert system from MAXI (OHMAN project)
Giant radio Pulses (GPs) from rotation-powered pulsars

- Sporadic sub-millisecond radio bursts $10^{2-3}$ times brighter than the normal pulses.
- Only from known ~12 sources, power-law distribution of fluence.
- Fast radio bursts (FRBs) are extragalactic GPs from young and energetic pulsars?

(Sallmen et al., 1999)

(Mikami et al., 2016)
GPs from the Crab Pulsar

- Crab pulsar has been observed in almost all electromagnetic waves, including radio, infrared, optical, X-rays, and gamma rays.

- GPs of the Crab Pulsar randomly occur in the radio band at the main or inter pulses.

- GPs were thought to be a phenomenon observed only at radio. However, optical enhancement coinciding with GPs was discovered (Shearer et al., Science 2003).

- Many teams have been trying to search for an enhancement in X-rays or gamma rays for 20 years, but only the upper limits have been obtained (Chandra, Suzaku...).
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Two Radio Observatories (2 GHz) in Japan

- 34-m radio telescope of the Kashima Space Technology Center (NICT)
- 64-m radio dish of the Usuda Deep Space Center (JAXA)

(Credit) NICT/Kashima
(Credit) JAXA/Usuda
Long-term monitoring simultaneous in radio and X-rays

- Coordinated 15 observations with the two radio telescopes in 2017-2019
- The X-ray main pulse peak $\phi=0.99125\pm0.00004$ relative to the radio peak, corresponding to the source-intrinsic 304 us radio delay.
Discovery of X-ray enhancement coinciding with GPs

- Detected $\sim 2.5 \times 10^4$ GPs at the main pulse phase with the 1.5-day exposure in total accumulated in 2017-2019.

Enoto et al., Science, 2021
Discovery of X-ray enhancement coinciding with GPs

- X-ray enhancement of $3.8\pm0.7\%$ (1σ error) at the pulse phase $\phi=0.985-0.997$.

Enoto et al., Science, 2021
Discovery of X-ray enhancement coinciding with GPs

- X-ray enhancement of 3.8±0.7% (1σ error) at the pulse phase φ=0.985-0.997.

Optical enhancement (Strader et al., ApJ 2013)

3.2±0.5% (φ=0.987-0.999)

Enoto et al., Science, 2021

5.4σ Detection
Verified our X-ray detection

- We confirmed this detection via different verifications.

Enoto et al., Science, 2021
Implication for the mystery of FRBs

• Hypothetical bright GP is a candidate for the origin of FRBs, especially repeating FRB sources (e.g., repeating FRB 121102).

• The energy source of such FRBs is assumed to be the spin-down luminosity.

• The discovery of X-ray enhancement suggests:
  • Since bolometric luminosity of GPs, including X-rays, is revealed to be $10^{2-3}$ times higher than we previously thought, the simple GP model for FRBs became more difficult because pulsars quickly lose its rotational energy.
  • Another example of the connection between the coherent radio emission and incoherent X-ray radiation in the neutron star magnetosphere.

See the supplementary part of Enoto et al., Science 2021
Kashiyama & Murase, 2017; Kisaka, Enoto, Shibata 2017
Magnetars seen with NICER

• >2,500 known pulsars ($10^5$ in our Galaxy?)
  • Challenge to unification of different neutron star classes
• NICER Magnetar and Magnetosphere (M&M) subgroup is focusing on highly magnetized sources.
• Collaborating with radio telescopes
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NICER Follow-ups of Magnetar Outbursts

- Since the launch in 2017, one transient magnetar campaign per year on average.

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Note</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017 July</td>
<td>4U 0142+61</td>
<td>Re-brightening in 2017</td>
<td>Guver et al., 2019</td>
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<tr>
<td></td>
<td></td>
<td>Pulse morphology change</td>
<td>Borgdese et al., 2021</td>
</tr>
<tr>
<td>2019 February</td>
<td>XTE J1810-197</td>
<td>Re-brightening in 2019</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radio-loud magnetar</td>
<td>Guver et al., 2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Borgdese et al., 2021</td>
</tr>
<tr>
<td>2020 March</td>
<td>Swift J1818.0-1607</td>
<td>New magnetar</td>
<td>Hu et al., 2020, Rajwade et al., 2022</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radio-loud magnetar</td>
<td></td>
</tr>
<tr>
<td>2020 April</td>
<td>SGR 1935+2154</td>
<td>Galactic FRB event</td>
<td>Younes et al., 2017, 2021, and many</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Burst storm events</td>
<td></td>
</tr>
<tr>
<td>2020 October</td>
<td>SGR 1830-0645</td>
<td>New magnetar</td>
<td>Younes et al., 2022a,b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pulse peak migration</td>
<td>Coti Zelati et al. 2021</td>
</tr>
<tr>
<td>2021 June</td>
<td>Swift J1555.2-5402</td>
<td>New magnetar</td>
<td>Enoto et al., 2021</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Long lasting outburst</td>
<td></td>
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</tbody>
</table>
SGR 1935+2154 — Magnetar and FRB connection

- Galactic magnetar SGR 1935+2154
  - discovered in 2014 (~9 kpc?)
  - $P = 3.24$ s, $P_{\text{dot}} = 1.43 \times 10^{-11}$ s/s
  - $B \sim 2.2 \times 10^{14}$ G
- A burst was detected with Swift/BAT at 18:26 on April 27, 2020.
- X-ray follow-up observations by several X-ray satellite, including NICER (on source 6 hours later on April 28, 00:40).
- Intense bursting activity for at least 7 hours (burst storm): 217+ bursts in 20 minus
FRB detected from SGR 1935+2154

- Two-peak FRB coincided with a magnetar X-ray burst (Insight-HMXT, INTEGRAL, AGILE, and Konus-Wind)
FRB-associated burst vs. Other magnetar bursts

- Example of a magnetar short burst from SGR 1935+2154 observed with NICER+GBM compared with the FRB-associated event.

Younes et al., arXiv: 200611358
• Cutoff energy vs. X-ray flux in 1-250 keV.

• Brighter magnetar short burst shows higher cutoff energy.

• X-ray flux of the FRB-associated burst is in the distribution of the other (canonical) magnetar bursts.

• However, the cutoff energy of the FRB-associated one is higher than the others.
At which pulse phase the FRB event happened?

- Pulse profile of SGR 1935+2154 at 1 day and 21-39 days after the burst
- Folded burst peak time (light blue) does not show a clear pulse profile.
- The pulse phase of the FRB event happened at the peak of the pulse profile.
Comprehensive Studies of Magnetar Short Bursts

- NICER’s large effective area is ideal to search for weak short bursts
- M&M team is working for comprehensive studies of magnetar short bursts.

### Burst Analyses

Tables B1 and B2 summarize the detected magnetar short bursts by Swift/BAT and NICER, respectively. For the burst search, we recalibrate the event files using nicerl2 with criteria of $\text{elv}=30$ $\text{br} \_\text{earth}=30$ underonly $\text{range}=0-300$ overonly $\text{range}=0-2$ $\text{expr}=''2.0''$ to maximize the time coverage. The corresponding integrated fluence distribution detected with NICER is shown in Figure B1. It shows a power law–like distribution with a low-fluence Figure B1.

### Table B1: A List of Short Bursts from Swift J1555.2−5402 Detected with Swift/BAT

<table>
<thead>
<tr>
<th>No.</th>
<th>Trigger ID</th>
<th>Time (UTC)</th>
<th>Duration (ms)</th>
<th>$S/N$</th>
<th>$kT$ (keV)</th>
<th>Fluence (10$^{-9}$ erg cm$^{-2}$)</th>
<th>$\chi^2$ (57 dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1053220</td>
<td>2021-06-03T09:45:46.589</td>
<td>12 ± 2.8</td>
<td>9.9</td>
<td>6.66 ± 0.98</td>
<td>9.09 ± 2.32</td>
<td>33.98</td>
</tr>
<tr>
<td>2</td>
<td>1053653</td>
<td>2021-06-05T23:52:04.582</td>
<td>14 ± 4.5</td>
<td>7.3</td>
<td>8.53 ± 1.40</td>
<td>7.47 ± 2.62</td>
<td>28.54</td>
</tr>
<tr>
<td>3</td>
<td>1053961</td>
<td>2021-06-07T12:33:40.020</td>
<td>4 ± 2.2</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>1056025</td>
<td>2021-06-16T14:44:30.489</td>
<td>7 ± 2.8</td>
<td>6.9</td>
<td>6.58 ± 2.22</td>
<td>&lt;3.08</td>
<td>31.20</td>
</tr>
<tr>
<td>5</td>
<td>1057131</td>
<td>2021-06-21T17:04:36.839</td>
<td>12 ± 4.5</td>
<td>6.9</td>
<td>6.47 ± 2.03</td>
<td>&lt;3.82</td>
<td>55.54</td>
</tr>
</tbody>
</table>

Notes: Reported errors are 90% confidence for each parameter. Time: burst detection time (UTC) determined as the start time of $T_{90}$. $S/N$: Signal-to-noise ratio of the BAT image in 15–350 keV. $kT$: blackbody temperature (keV) when fitted by the single blackbody model. Fluence: burst fluence in the 15-150 keV band (10$^{-9}$ erg cm$^{-2}$). $\chi^2$: fitting $\chi^2$ values for 57 dof.

* Burst 3 is too weak to constrain the spectral–fit parameters.
SGR 1830-0645 — Pulse Peak Migration

- Near-daily NICER observation during the first 37 days of an outburst suggested pulse peak migration in phase.
- Tectonic motion of the crust? Inferred speed of the crustal motion is <100 m/day.
- Hot spot of particle bombardment from a twisted magnetosphere — untwist and dissipate on 30-40 day timescale?
Swift J1555.2-5402 — New magnetar in 2021

- Burst detected with Swift/BAT on 2021 June 3, followed by NICER 1.6 hours after the burst.
- Long lasting persistent X-ray flux (4e-11 erg/s/cm² in the 2-10 keV)
Searching for Gravitational Waves (GW) from Pulsars

- LIGO/Virgo/KAGRA sensitive at $v_{gw} > 20$ Hz
  - ~500 pulsars with $v_{\text{spin}} > 10$ Hz
  - Most sensitive GW searches use simultaneous EM timing observations (tracking of pulsar spin)
- GW searches of O3 data (2019–20)
  - using NICER timing of
    - young magnetic pulsars (Abbott+2021a,b; 2022b,c)
    - pulsar glitches (Abbott+2022b)
    - accreting millisecond pulsars (Abbott+2022a)
  - 6 of 24 below “spin-down limit” are due to NICER timing
  - constraints on neutron star mountains and oscillations
- Multi-messenger future with GWs and NICER
  - O4 to take place 2023 Mar to 2024 Feb
  - NICER pulsar timing project approved thru 2024 Feb
NICER and MAXI joint teams have been organizing systematic agile follow-up and subsequent monitoring of MAXI-discovered X-ray transients. This is the key why NICER data sets in early outbursts are available for discoveries. 61 transients were observed by Feb 2022, most of which are within 12 hours of their discoveries.
OHMAN (On-orbit Hookup of MAXI and NICER)

- Fully automatic follow-up observation system beyond the national border in ISS
- Primarily targets are unknown MAXI transients, stellar flares, long X-ray bursts, etc.
- Started in 2022 June, and expected trigger rate is about once a month

(Future example) application to magnetars

1. Send MAXI data in real-time
2. Detect transients by a laptop on ISS
3. NICER Follow-up observation within 10 minutes (targets within 2 minutes)

- MAXI has detected 3 short bursts from SGR 1935+2154 since 2020.
- OHMAN will enable NICER to observe persistent emission immediately after a short burst

Slide credit: Wataru Buz Iwakiri
1. Advantages of the NICER performance are large effective area (~1900 cm² at 1.5 keV), high-time resolution (<100 ns), high throughput (free from pileups, dead time, and data transfer loss up to \( \sim 4 \times 10^4 \) cps), and flexible observations (quick response to ToO, even within a day).

2. Here we showed some examples and applications:
   a) Discovery of an X-ray enhancement at the Crab giant radio pulses
   b) Prompt follow-ups of transient magnetars and burst studies
   c) Long-term monitoring of magnetar pulse profile (migration)
   d) Search for gravitational waves from rotation powered pulsars
   e) Automated transient alert system from MAXI (OHMAN project)