Enhanced X-ray Emission Coinciding with Giant Radio Pulses from the Crab Pulsar

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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?

![Crab pulsar 1.4 GHz](image)

![Fluence histogram](image)

(Sallmen et al., 1999)

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

Figure 16. Pulsar distribution in the $P – P'\dot{P}$ 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.

(Enoto, Kisaka, and Shibata, ROPP 2019)
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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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)!
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Short exposure to detect the Crab pulsation

10600 cycles, 3984527 events, 357.713 s exposure
Short exposure to detect the Crab pulsation

Detection significance of X-ray pulses

- Pulse signals are detectable within 1 sec, ×50 larger photon statistics than Hitomi.
- Free from pileups, dead time, and data transfer loss (throughput $3.8 \times 10^4$ cps).

NICER X-ray spectrum of the Crab pulsar and nebula

- Pulsar + Nebula: $1.1 \times 10^4$ cps (0.3-10 keV)
- Background: <1% of Crab
  ~370 photons/cycle
NICER Magnetar and Magnetosphere (M&M) Group

- has collaborating with radio telescopes for magnetars and highly magnetized pulsars including the Crab pulsar for simultaneous radio-Xray observations.

- Example (1) Detection of single X-ray pulses from a transient and radio loud magnetar XTE J1810-197

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- Example (2) A new magnetar Swift J1818.0-1607 with young characteristic age of ~470 yr, as a missing link between magnetars and high-B pulsars.
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- has collaborating with radio telescopes for magnetars and highly magnetized pulsars including the Crab pulsar for simultaneous radio-Xray observations.

- Example (3) Galactic magnetar SGR 1935+2154 as a FRB source!
GPs from the Crab Pulsar

It is yet unclear whether the observed $P - \dot{P}$ distribution of RRATs is genuinely related to their pulsar-intrinsic properties or is rather an observational selection effect whereby longer-periods RPPs are detected with higher signal-to-noise ratios in single-pulse searches.

Among RRATs, PSR J1819−1458 is one of the most studied objects. 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.

The data are taken from [82, 115, 117, 270, 331, 587, 674, 839, 878, 905] 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.
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)
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 $\phi = 0.9915 \pm 0.00004$ 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.
Discovery of X-ray enhancement coinciding with GPs

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

![Graph showing X-ray pulse profile and GRP occurrence per phase bin. The X-ray evaluation area is highlighted and marked with an arrow.]
Discovery of X-ray enhancement coinciding with GPs

- X-ray enhancement of 3.8±0.7% (1σ error) at the pulse phase \( \phi=0.985-0.997 \).
**Verified our X-ray detection**

- Look elsewhere Effect
  - statistically valid!
  - Our detection 3.8%

- Lag analysis
  - only at GPs

- Including significance as the data increases

- We confirmed this detection via different verifications (see the paper).
• Our X-ray detection is consistent with the previous upper limits in the X-rays (~10% or higher limits)
• X-ray enhancement (3.8%) is at the same as that in the optical detection (3.2%).
• Only the upper limit (<10%, 3σ) for the interpulse GPs at $\phi = 1.378-1.402$. 
• High-energy pulsar component (optical and X-rays) is distinct from the radio coherent component.

• No difference of the GP-associated X-ray spectrum from the normal pulses.

• X-ray flux of the pulsar component $4.4 \times 10^{-9}$ ergs/s/cm$^2$ (0.3-10 keV) is $10^3$ and $10^7$ times higher than those at the optical (5,500Å) and radio (2 GHz) bands, respectively.

• Despite ~4% enhancement, the total emitted energy at GPs is $10-10^2$ larger than we previously know.
Emission mechanism of GPs?

- The emission mechanism of normal radio pulses and GPs is still a mystery.
- Amplification factor at GP is $\sim 10^2$-$10^3$ times at the radio band, while those for the optical and X-rays are an imbalance at only 4%!
- Since radio waves are coherent radiation, they require aligned motions, states and a dense plasma.

**Coherent radiation**  
(radio)

Since the phase is nearly aligned, the intensity is proportional to the **square** of the number of particles.

**Incoherent radiation**  
(Optical and X-rays)

Since the phase is not aligned, the intensity is proportional to the number of particles.
Emission mechanism of GPs? (One Hypothesis)

- A sheet of dense plasma is formed in the outer part of the pulsar magnetosphere.
- The plasma sheet is structurally unstable and tear apart to form plasma blobs.
- The blobs repeatedly collide and merge, and sometimes grow to ~100 times (thickness).
- As the blobs coalesce, radio pulses are generated in the dense region, while X-rays are emitted from the entire sheet.

Based on Philippov et al. ApJL 2019
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Implication for the mystery of FRBs

• Hypothetical bright GRP 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 GRP 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. This is also shown the FRB-associated bursts from SGR 1935+2154. Burst activities of magnetars (magnetic energy release) is more favored for FRBs?

See the supplementary part of Enoto et al., Science 2021
Kashiyama & Murase, 2017; Kisaka, Enoto, Shibata 2017
End of the Kashima Radio Observatory Operation

- The Kashima 34-m radio telescope, operated by the National Institute of Information and Communications Technology (NICT), has been an important instrument for radio astronomy.

- It was severely damaged by Typhoon No. 15 in 2019 and its operation was terminated.

- This achievement is one of the last precious legacies left by the Kashima 34 m radio telescope.

- We are looking forward to have another chance to collaborate with other radio telescopes as well.
Summary

1. The electromagnetic radiation mechanism from pulsars still has many unsolved problems. Giant pulses (GPs) are sporadic radio bursts 100-1000 times brighter than the normal radio pulses, and thus a powerful probe to investigate a pulsar magnetosphere within a single rotation.

2. NICER Magnetar and Magnetosphere (M&M) working group coordinated a simultaneous X-ray and radio observation campaign for the Crab pulsar in 2017-2019. We detected the X-ray enhancement by $3.8\pm0.7\%$ ($5.4\sigma$ detection) coinciding with radio GPs at the main pulse phase.

3. This implies that the total emitted energy from GPs is tens to hundreds of times higher than previously known. Repeating fast radio bursts are difficult to be explained by a model based on hypothesized bright GPs powered by the rotational energy loss. Young magnetars are favored?
A layer of plasma compressed by the magnetic field

The magnetic field and plasma get fragmented into small pieces to form lumps

From high-energy particles in the lumps

International Space Station

NICER

X-ray

From the whole lumps

Radio waves

64-m radio antenna at Usuda

34-m radio antenna at Kashima

the Crab Pulsar

Lumps of plasma collide

(Credig) Higgstan.com