Novel Paradigms of Magnetars Opened by Advanced Timing Studies

~Exploring the Archive Treasure~

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Advanced Timing Studies = search for a periodicity in the data considering systematic variations of the pulse phase, depending on a long periodicity, or on the energy.

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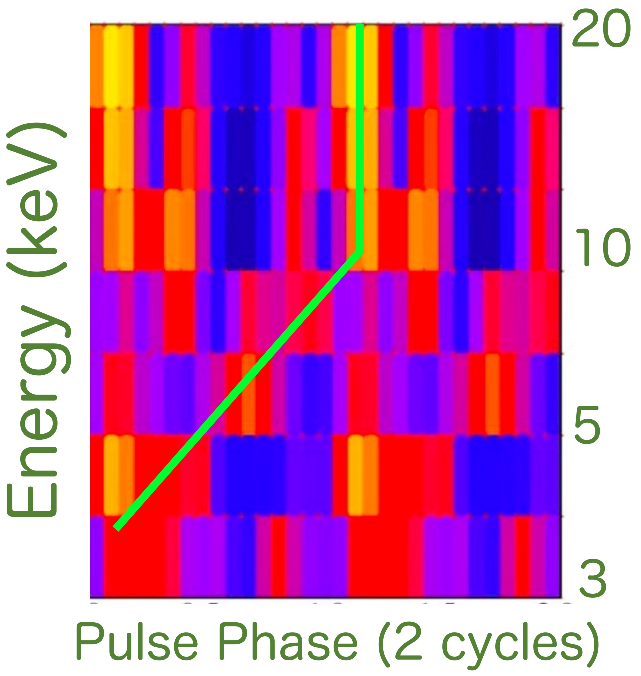
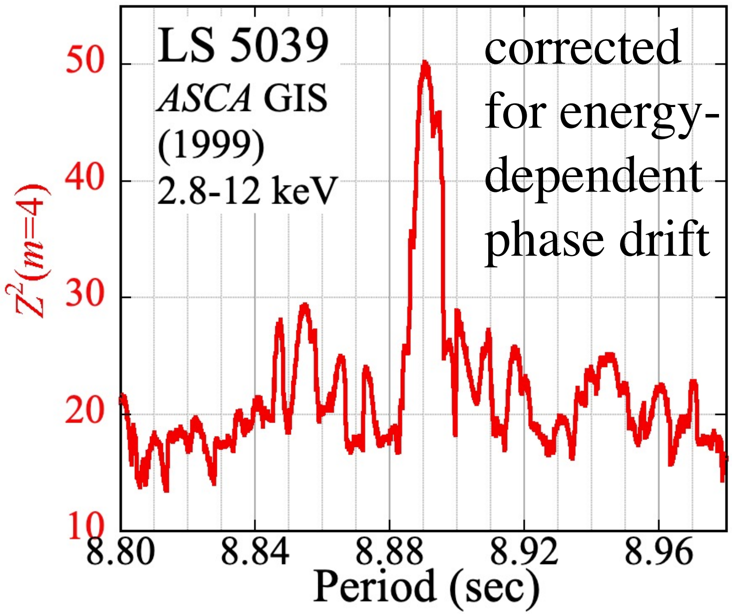
1a. The case of LS 5039

- LS 5039 is the MeV-brightest gamma-ray binary, in an eccentric (e~0.3) 3.9-d orbit with a massive star.
- Its nature (NS or BH) was unsettled. No pulses had been detected via orbital corrections on the photon timing.
- With corrections to >10 keV events, we detected pulses at P=8.957s (*Suzaku* 2007), and 9.054 s (*NuSTAR* 2016) [Yoneda+20]. From energetics *etc.*, it is a magnetar*!*
- At<10 keV, the pulse phase drifts with E [KM+23]. This must have hampered previous pulse detections
- Correcting for this peculiar E dependence, the pulse was detected in <10 keV with *NuSTAR* and *ASCA* [KM+23].

Magnetars can be efficient accelerators,
but the nature of pulse-phase drift is unclear.

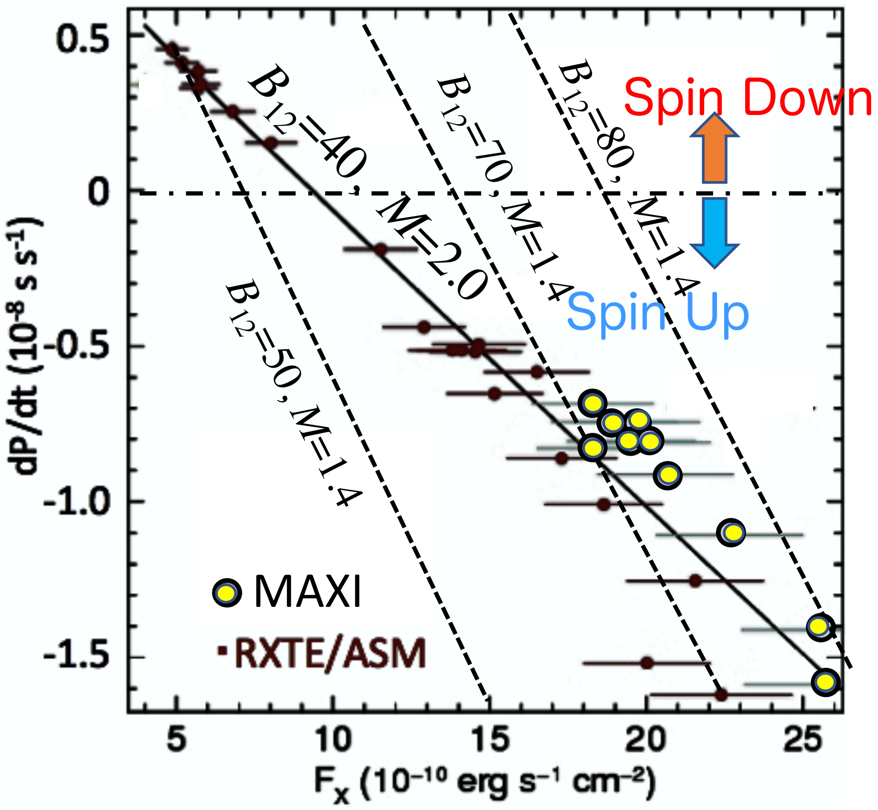




1b. Magnetars in Binaries

X-Per: P=835 s, 250-d binary with a Be star.

- Using *RXTE*/ASM and MAIX data for 1996-2017, correlation between P-dot and the X-ray flux was studied [Yatabe+18, PASJ,70,89] .
- Using the Ghosh-Lamb model for accretion torque, $B = (0.4\text{-}2.5)\times 10^{14}$ G was derived.



The binary environment also provides a rare chance to estimate the mass of magnetars.

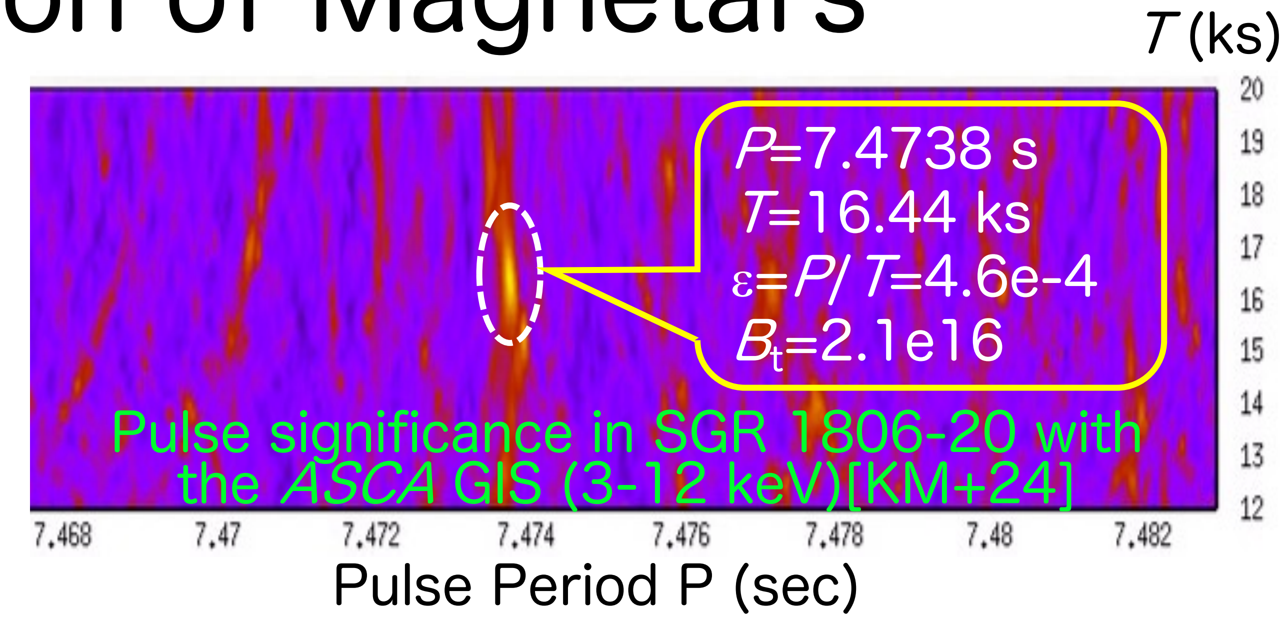
・X-Per : $M = 2.03 \pm 0.17 M_{\odot}$ [Yatabe+18]

・LS 5039: $M = 1.8 \pm 0.6\ M_{\odot}$ [Yoneda+20]

Sometimes magnetars can be found in binaries.
Magnetars may be heavier than 1.4 $M_{\odot}$ → Under such conditions, nuclear matter may become ferromagnetic!

2a. Free Precession of Magnetars

- By the stress of toroidal field B_t, magnetars will be deformed to asphericity of $\Delta I/I=\varepsilon\sim10^{-4}(B_t/10^{16})$, and performs free precession.
- Rotation and precession periods become different by ε; their beat appears at a long period $T=P/\varepsilon$.



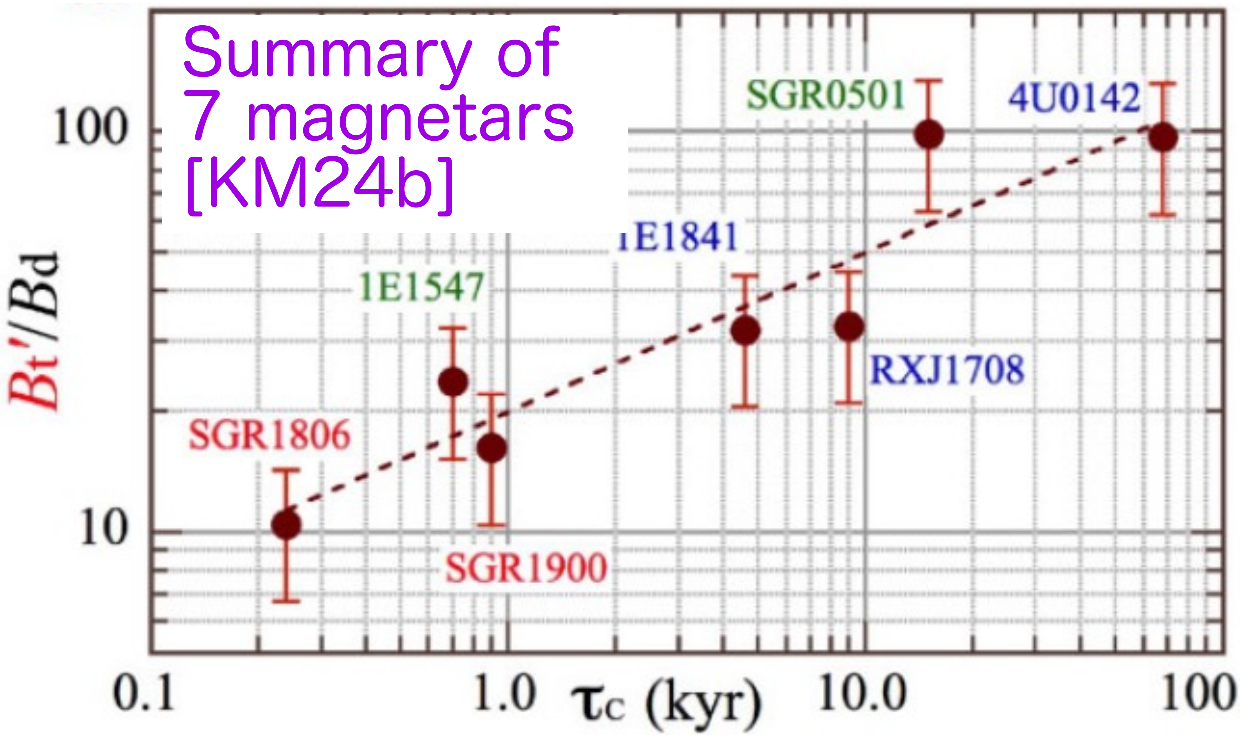
P=7.4738 s
T=16.44 ks
$\varepsilon=P/T$=4.6e-4
B_t=2.1e16

Pulse significance in SGR 1806-20 with the *ASCA* GIS (3-12 keV)[KM+24]

- Hard X-ray pulses are difficult to detect due to phase-modulatiom at T, but they can be recovered via a timing correction called “demodulation”.
- T is the period where demodulation is most effective → $\varepsilon=P/T\sim10^{-4}$. We derived $B_t\sim10^{16}\,\mathrm{sqrt}(10^4\varepsilon)\sim10^{16}$ G for 7 magnetars [KM+14,16,19, 21ab, 24ab]

Magnetars ubiquitously harbor ~10^{16} G toroidal fields.

2b. Decay of Dipole and Toroidal Fields


Summary of 7 magnetars [KM24b]

[Nakano+15, PASJ 67, 41]

Characteristic ages $\tau_c = P/2P_{\rm dot}$ of magnetars are often longer than their host SNR's age, $\tau_{\rm SNR}$.

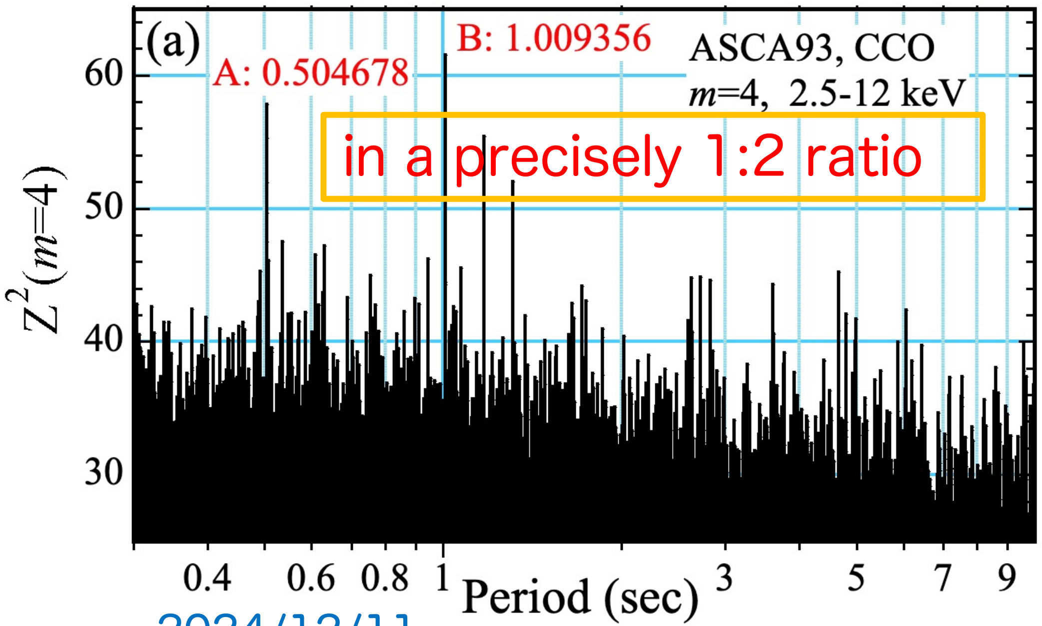
This is an artifact; when considering time evolution of τ_c due to the B_d decay, τ_c becomes consistent with $\tau_{\rm SNR}$.

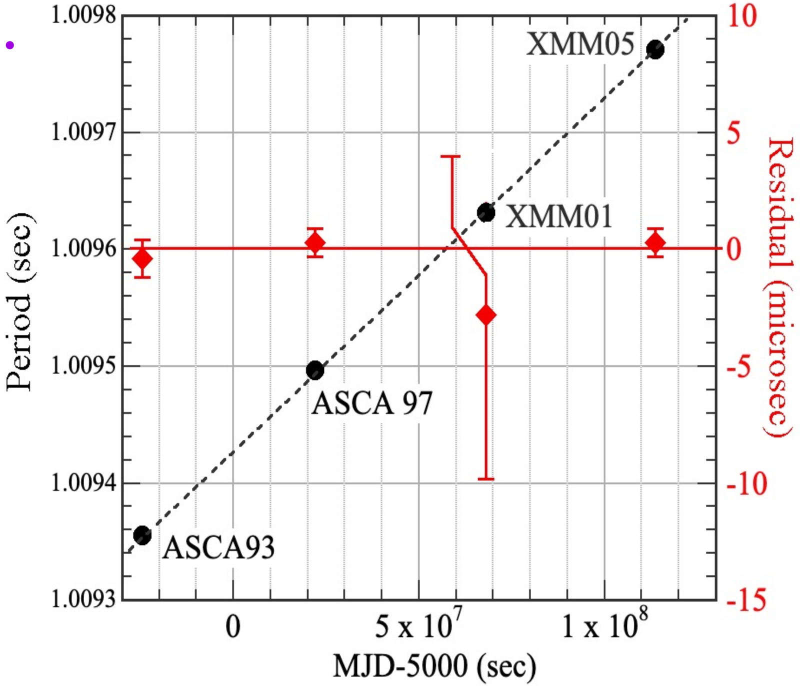
τ_c overestimates the magnetar age; they are younger than nominal τ_c.

- B_d of magnetars will decay more quickly than their B_t.
- Magnetars may dominate young neutron stars (over Crab-like ones), and there can be many aged magnetars.

3. The puzzling Long Periodicity in a CCO

- 1E 161348-5055, the CCO of the SNR RCW103, shows clear flux variations with a period of *T*=6.67 hr [De Luca +06]; too long for a spin period.
- Assuming *T* is beat period between precession and rotation, we demodulated 2.5-10 keV ASCA GIS data (1993) in outburst, and found pulses at *P*=1.0094 s.
- Reconfirmed with data from ASCA GIS (1997) and XMM-Newton (2001& 2005). The four measured periods precisely aligned on $P_{\rm dot}$ =1.09x10^{-12} s/s.
- Soon submitted to *ApJ* [KM+25].





It is a magnetar-like object, magnetically powered.

$B_{\rm d}$~4.6×10^{13} G

$L_{\rm sd}$=1.1×10^{33} erg/s

$\tau_{\rm c}$=14.7 kyr

$B_{\rm t}$~0.65×10^{16} G

4. Conclusions

Through timing analysis of many archival X-ray data sets,
we have derived the following new characterizations of magnetars.

Magnetars:

1. - ubiquitously harbor $B_t \sim 10^{16}$ G, and performs free precession.
2. - are found sometimes in binaries.
3. - can work as efficient accelerators.
4. - might be heavier than 1.4 $M_\odot$.
5. - may dominate young NSs, and there may be many aged magnetars.

In addition,

6. Magnetars' B_t may lasts longer than B_d.
7. Some CCOs are magnetar-like objects.

⬛ RXTE 🟥 Suzaku 🟦 NuSTAR 🟩 ASCA 🟨 MAXI

- 🟥 KM+14, *PRL*,**112**, 171102
- 🟥 Nakano+15, *PASJ*, **67**, 41
- 🟥 KM+16, *PASJ*, **68S**, 12
- ⬛🟨 Yatabe+18, *PASJ*, **70**, 89
- 🟦 KM+19, *PASJ*, **71**, 15
- 🟦🟥 Yoneda+20, *PRL*, **125**,111103
- 🟦 KM+21a, *MNRAS*, **502**, 2266
- 🟦🟥 KM+21b, *ApJ*, **923**, 63
- 🟩🟦 KM+23, *ApJ*, **959**, 79
- 🟥 KM+24a, *MNRAS*, **532**, 4355
- 🟩 KM+24b, *PASJ*, **76**, 688
- 🟩 KM+25, *ApJ*, in prep