Evolution of Magnetic Fields of Magnetars (MGTs) Inferred from Observations

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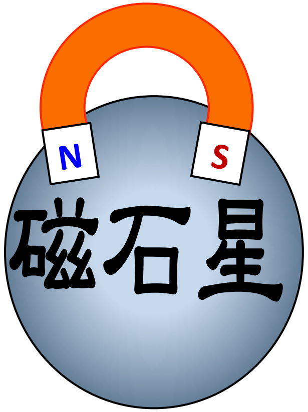


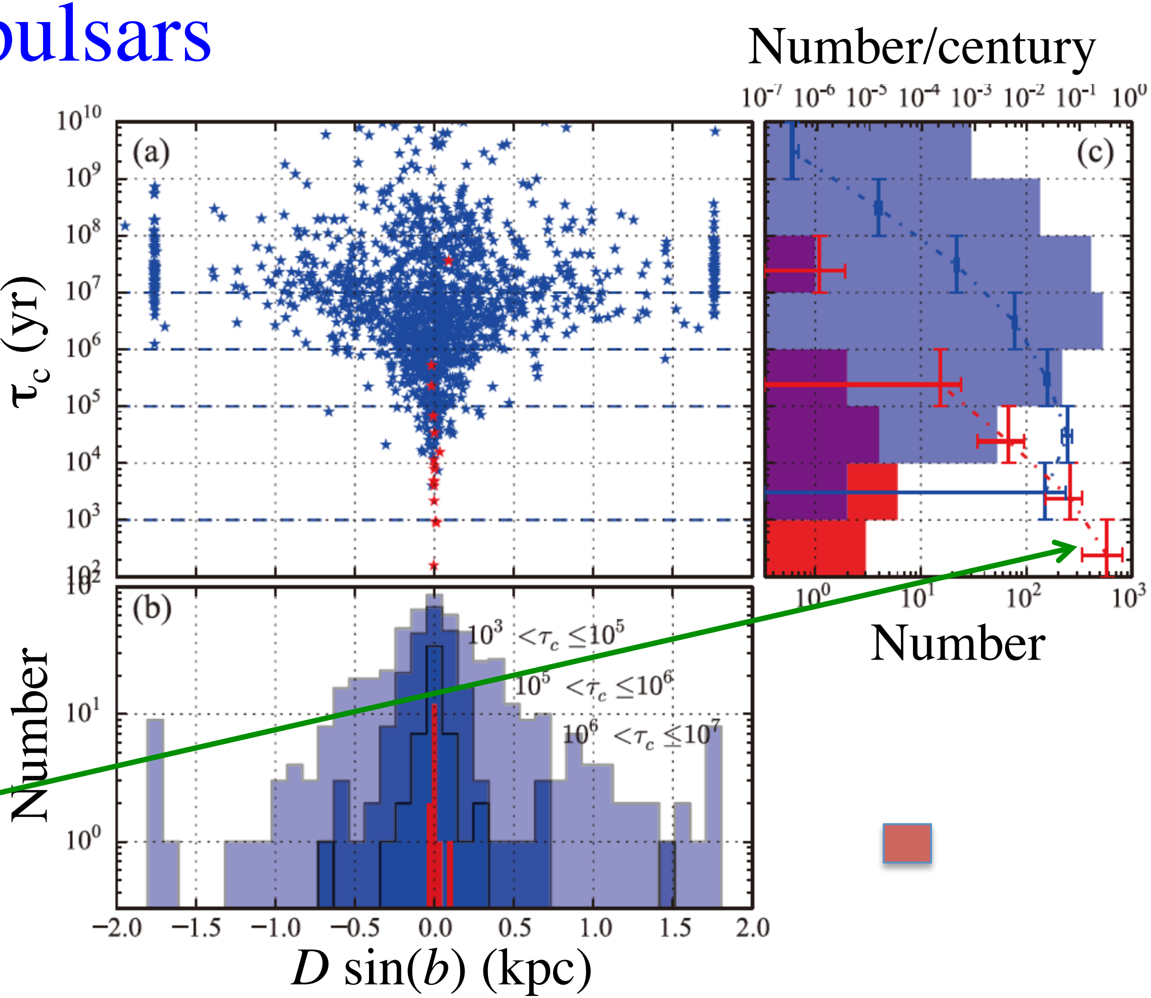
Q1: Do MGTs form a rare subclass of neutron stars (NSs)?

Q2: How do magnetic fields (MFs) of MGTs evolve?

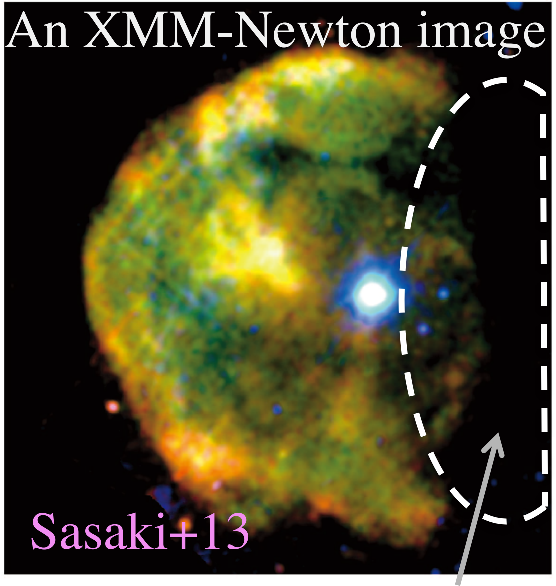
1. MGTs *vs*. radio pulsars

(Nakano+15, *PASJ* **67**, id.9)

1. For their τ_c, MGTs are much more concentrated to the Galactic plane than radio pulsars.
   - ➢ MGTs have lower run-away velocities? --> Unlikely (Tendulkar+13)
   - ➢ τ_c of MGTs are over-estimated?
2. MGTs and radio pulsars are born with comparable birth rates.



2. CTB109 and 1E 2259+586 : the age problem



✧ The host SNR, CTB 109 : age ~ 14 kyr

✧ The central MGT, 1E 2259+586: τ_c=230 kyr

This serious discrepancy was solved Nakano+15 (*PASJ* **67**, id.9) in a convincing way.

The characteristic age τ_c provides a good measure of the true age, only if (i) the initial *P* is very short, and (ii) the spin down occurs via mag. dipole rad. with a constant dipole filed B_d.

Clearly, (ii) is not the case with MGTs --> τ_c largely over estimates the true age.

High B_d at early phase makes *P* very long

$$\tau_c = P/2P_{dot}$$

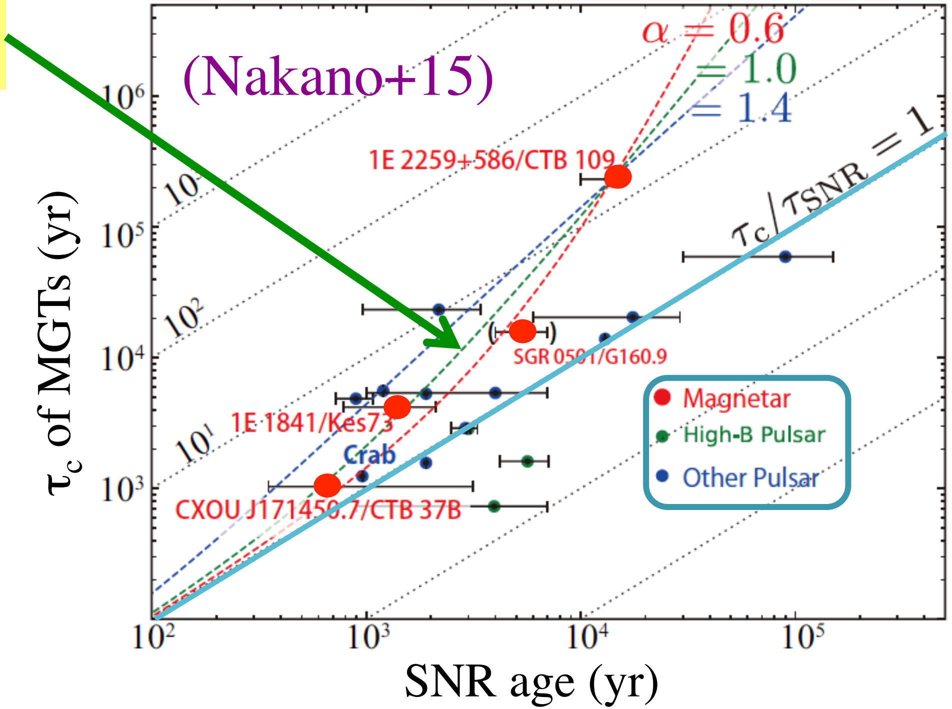
Low B_d at present means small P_{dot}

3. MGT ages considering MF decay (Nakano+15)

Assume $dB_d/dt \propto -B_d^{1+\alpha}$ ($\alpha \geqq 0$; Colpi+00)

- $B_d(t) = B_0\,(1+\alpha t/t_0)^{-1/\alpha}$ if $\alpha>0$
- exponential decay if $\alpha=0$

A good fit is obtained with $\alpha \sim 1$.
The *age problem* has been solved.

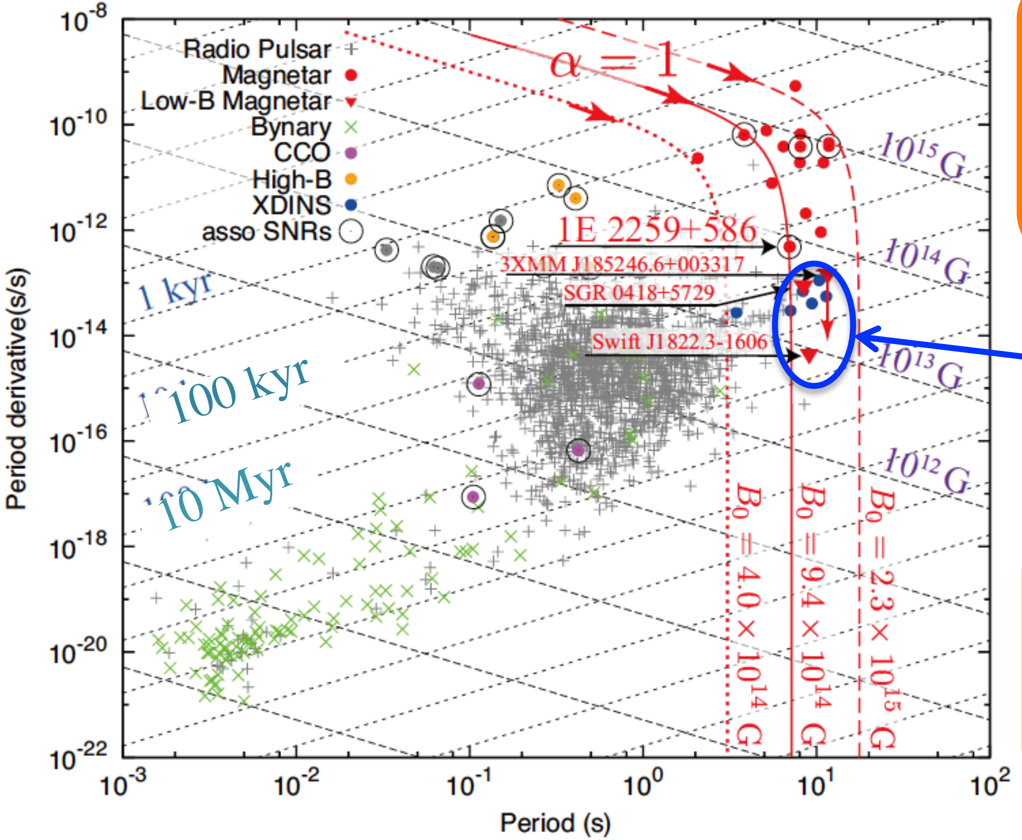


This simple idea implies:

- ➢ The basic postulate that *MGTs are powered by MFs* is reinforced.
- ➢ MGTs are much more short lived than usually thought. Many MGTs must have become inactive.
- ➢ MGTs must be born with a higher rate than ordinary NSs. MGTs are *not* a rare subclass. 🟩

4. Evolutionary tracks of MGT

(Nakano+15, *PASJ* **67**, id.9)



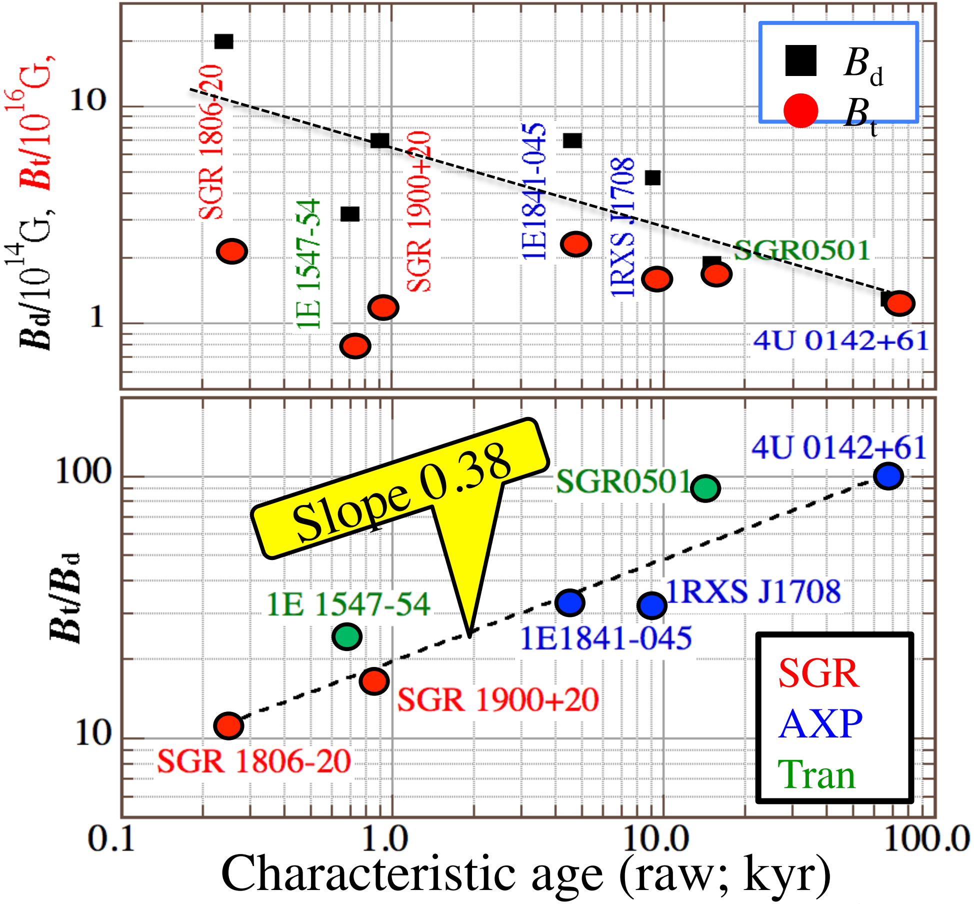
Assuming MF decay with α=1, MGTs evolve along curved tracks on *P*-*P*dot plane. They initially have B_d=(5-20) ×10^{14} G.

Weak-field MGTs ($B<5\times10^{13}$ G; Rea+13) can be explained simply as aged MGTs.

Like young MGTs, these aged objects still exhibit burst activity ==> they must be powered by internal toroidal MF (Rea+13).

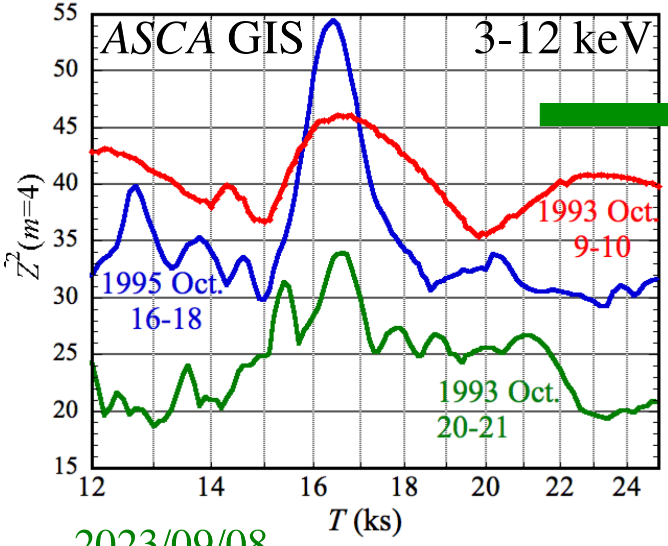
5. Evolutions of dipole and toroidal MFs

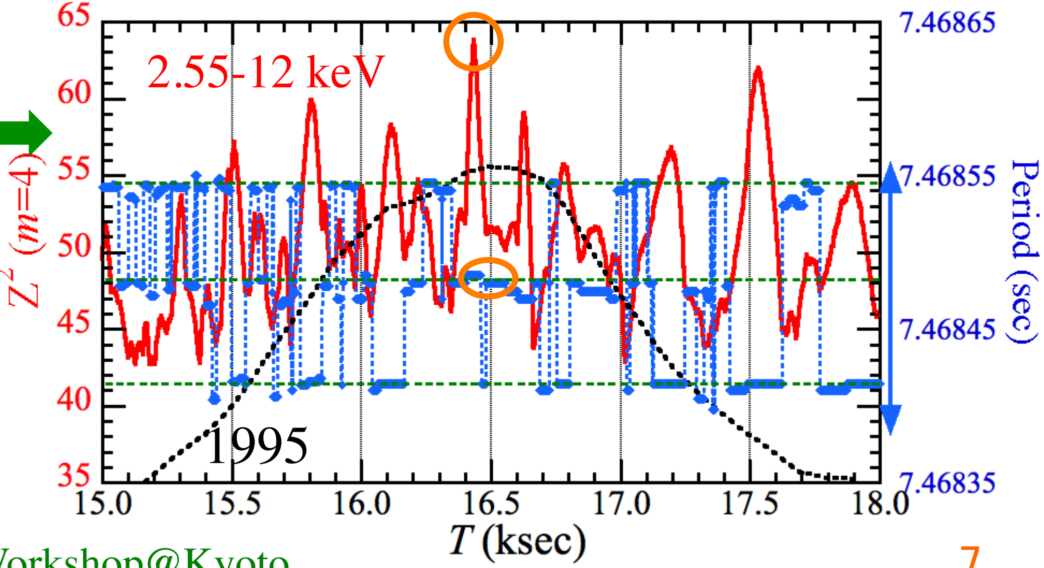
- From 7 MGTs, we detected *phase modulation* in the Hard-Component pulses, with a long period $T \sim 10^4 P$ (Makishima+14, 16, 19, 21a, 21b, 23).
- This T is beat between *rotation* and *free-precession* periods of a rigid body that is axial deformed by $\Delta I/I = P/T \sim 10^{-4}$.
- Ascribing the deformation to toroidal MF B_t, we can estimate it from a theoretical relation (Ioka & Sasaki 04) as $\Delta I/I \sim 10^{-4}(B_t/10^{16}\mathrm{G})^2$.
- As expected, B_t lasts longer than B_d



6. Coherence of the pulse-phase modulation

- ➢The prototypical MGT, SGR1806-20, was ID'd with an X-ray source by *ASCA* in 1993 (Murakami+94). Then, its 7-s pulsation discovered (Kouveliotou+98).
- ➢Demodulation analysis to three *ASCA* GIS data sets in 1993/1995. Photon arrival times are changed as *t*--> *t*-*A*sin(2πt/*T*-*ψ*); *T*, *A*, and *ψ* are varied to maximize pulse significance.
- ➢The 3 data sets all prefer *T*~16.5 ks.
- ➢Combining the two 1993 data sets, 16.5 ks periodicity was phase-connected across 11 day interval (interference pattern)---> high coherence, as expected form celestial mechanics.





7. The Gas Imaging Spectrometer (GIS) onboard *ASCA* (1993-2001)

- Wide FoV, high sensitivity (2-10 keV), moderate ΔE and $\Delta\theta$, high Δt (60 μs), low dead time, and low bkgd. Its data are easy to use, and suited to timing studies.
- Led by Ohashi-san, it was developed at U. Tokyo and ISAS, mainly by 6 generations of graduate students.
- A series of troubles in developments; gas cell leaked, quartz window cracked, discharge inside a phototube, mysterious charge-up of gas cells, a flight phototube damaged by Helium gas, re-fabrication of 8kV high voltage power supply, a fatal logic error in digital circuit (discovered only 4 months before launch), *etc*.
- In orbit, it worked all right through the mission life.


broken quartz window

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Fukazawa-kun soldering a test circuit

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Ohashi-san chipping of a flight gas cell.

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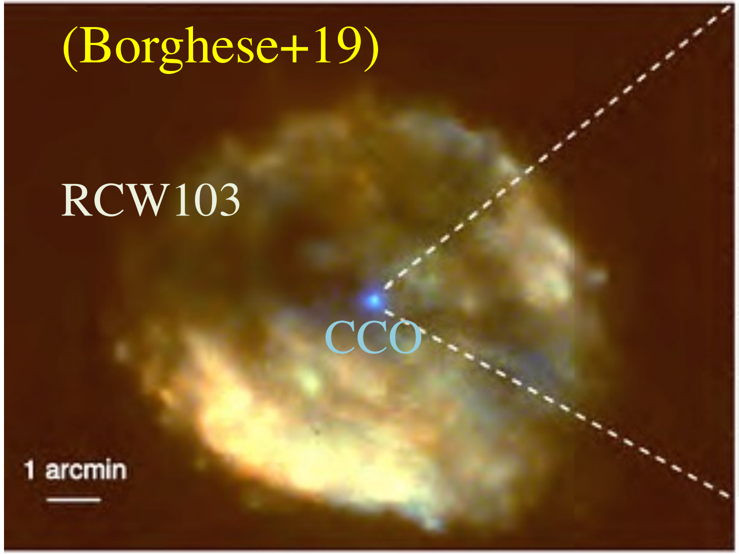
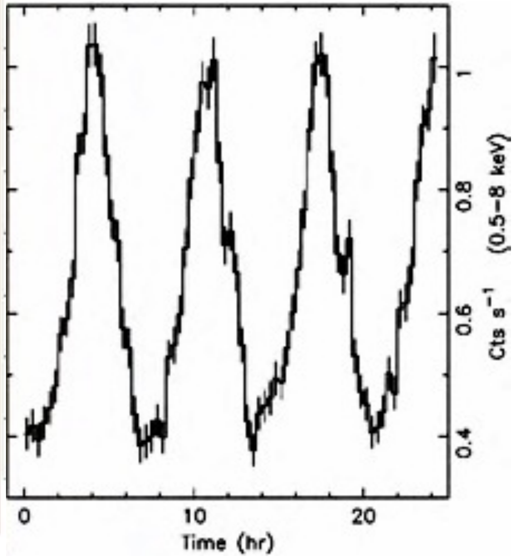
8. Enigmatic CCOs

A touchstone (試金石): CCO (Central Compact Object) in the SNR RCW103.

- A very long pulse period, 6.67 hr, or ~10^7 of break-up period, highly unlikely.
- Yet the periodicity is stable. A sudden brightening observed (Esposito+19).



6.67 hr periodicity



Possibly, 6.67 hr is the beat period *T*, and the true pulse period may be at *P*~1 s.

Demodulation analysis would prove this idea.

$t \dashrightarrow t - A\sin(2\pi t/T - \psi)$

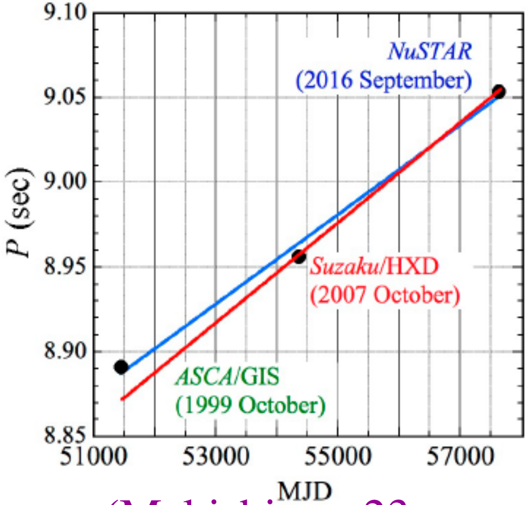
Now, *T* is known but *P* is unknown.

9. MGTs' birth conditions

MGTs may be produced by some physics built-in to the NS formation scenario?

- MGTs are suggested to dominate young NSs.
- SNRs hosting MGTs may be more circular than those hosting radio pulsars.
- MGT are likely to reside also in binaries.

1. The Be/X-ray binary X Persei; P=840 s and low L_x. Long monitoring of P and L_x with MAXI, combined with accretion torque theory of Ghosh & Lamb (1979), gives $B = (0.4\text{-}2.5) \times 10^{14}$ G (Yatabe+18).
2. The gamma-ray binary LS 5039. Pulsation with $P \sim 9$ s, discovered using *Suzaku* and *NuSTAR* (Yoneda+20), was reconfirmed with the *ASCA* GIS. $B > 10^{13}$G.
3. X-Persei has M=2.03±0.17, and LS 5039 $1.79 \pm 0.56 M_\odot$ Somewhat heavier NSs?



(Makishima+23, *ApJ*, submitted)

10. Conclusions

1. MGTs are much younger than their τ_c. They may be born with a higher rate than radio pulsars, but quickly become dim.
2. Aged MGTs are still powered by their B_t~10^{16} G toroidal field, which may last longer than their B_d as deduced from observations of their free precession.
3. The extremely long period, detected from some CCOs, could be the beat period T, and the true pulse period may be at ~$10^{-4}\,T$ ~ 1 s.
4. MGTs may reside in binaries as well; they provide a valuable info on the MGT mass, which could be ~2 $M_{\odot}$ rather than 1.4 $M_{\odot}$.
5. MGTs are not a rare subclass of NSs, and may represent basic physics intrinsic to the NS formation (*cf*. talk by 山本直希さん).