公募研究 C01: X線を用いた マグネターの研究

マグネターの自由歳差運動と磁気変形
Free Precession and Magnetic Deformation of Magnetars

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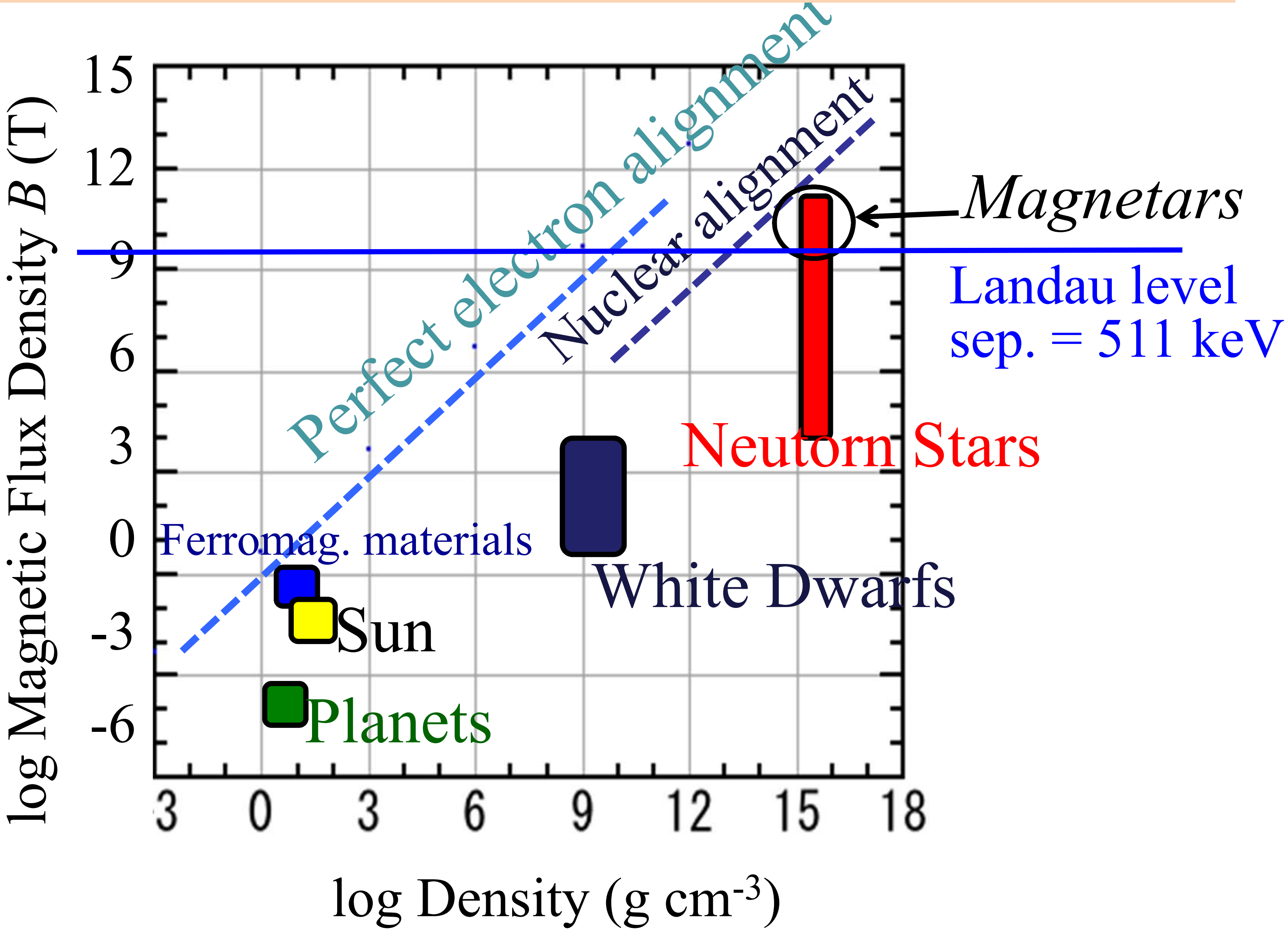
Magnetic Fields of Celestial Bodies



0. What are Magnetars?

- ✧ A subclass of isolated neutron stars. About 30 known in the Milky Way and Magellanic Clouds. New discoveries continue.
- ✧ Several are found in Super Nova Remnants: young.
- ✧ Pulse (=rotation) periods in the range 2-11 sec, with large spin-down rates. Assuming spin-down by emitting M2 radiation, these imply dipole mag. files of $10^{14\text{-}15}$ G. Exceeding the critical value of 4×10^{13} G. Many QED effects expected.
- ✧ Emitting in X-rays, with weak/no radio signals. Not rotation powered; $L_x \gg -\,\mathrm{d}E_{rot}/\mathrm{d}t$. Not accretion powered, either. Magnetically powered.
- ✧ Sporadic intensity changes on various time scales from msec to years. Sometimes behave like a “machinge-gun”, and produce “giant flares” which can even disturb the Earth’s ionosphere.

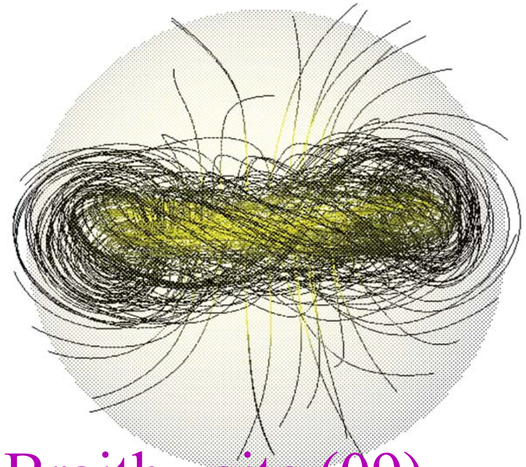
1. Toroidal Magnetic Fields of Magnetars

We expect magnetars to have toroidal field $\gg$ poloidal field

Theoretically:

✧Collapse and diff. rotation in progenitors wind up MF lines.

✧Some MF lines emerge from the surface to form multipoles.



Braithwaite (09)

Observationally:

Recently discovered *low-dipole-field* (6×10^{12} G) magnetar, SGR 0418+5729 (Rea +10):

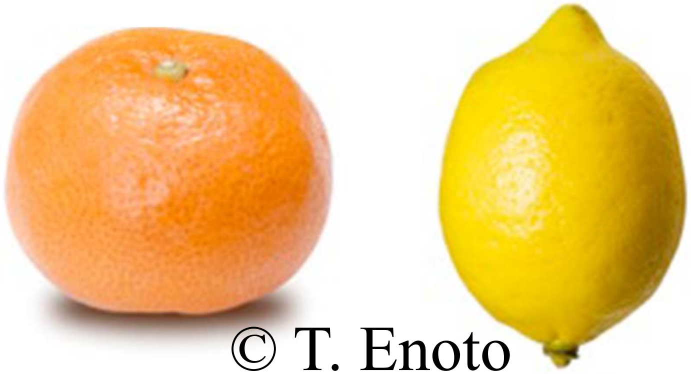
✧Requires much stronger B_t to sustain its burst activity

✧Shows spectral evidence for intense multipole surface fields with > 2×10^{14} G (Tiengo+13).

How can we measure toroidal MF?

2. Magnetic Deformation of an NS

Poloidal fields cause oblate deformation



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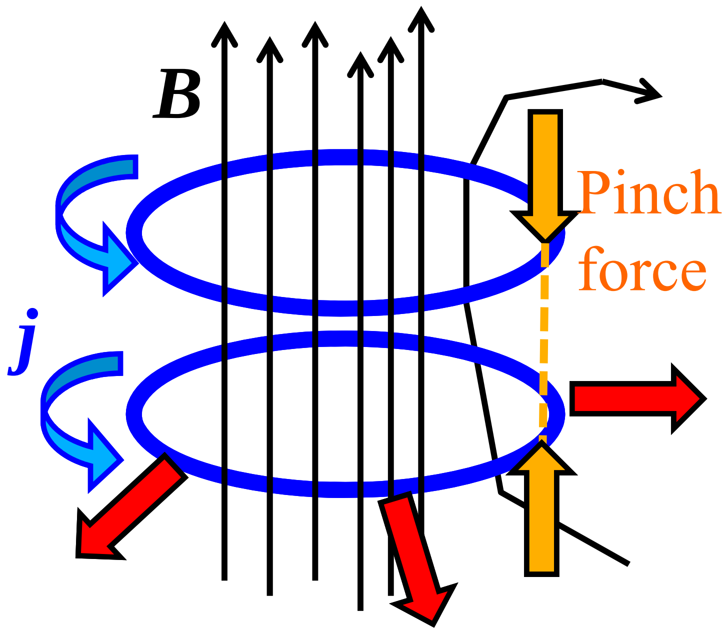
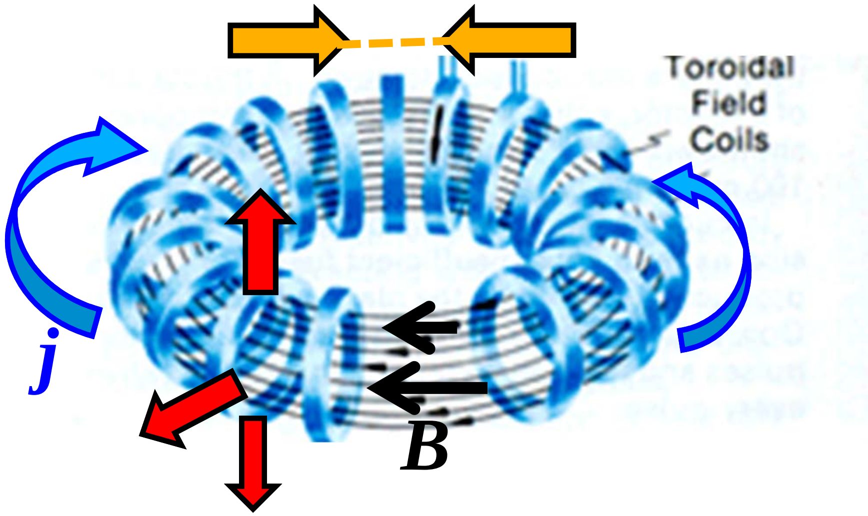
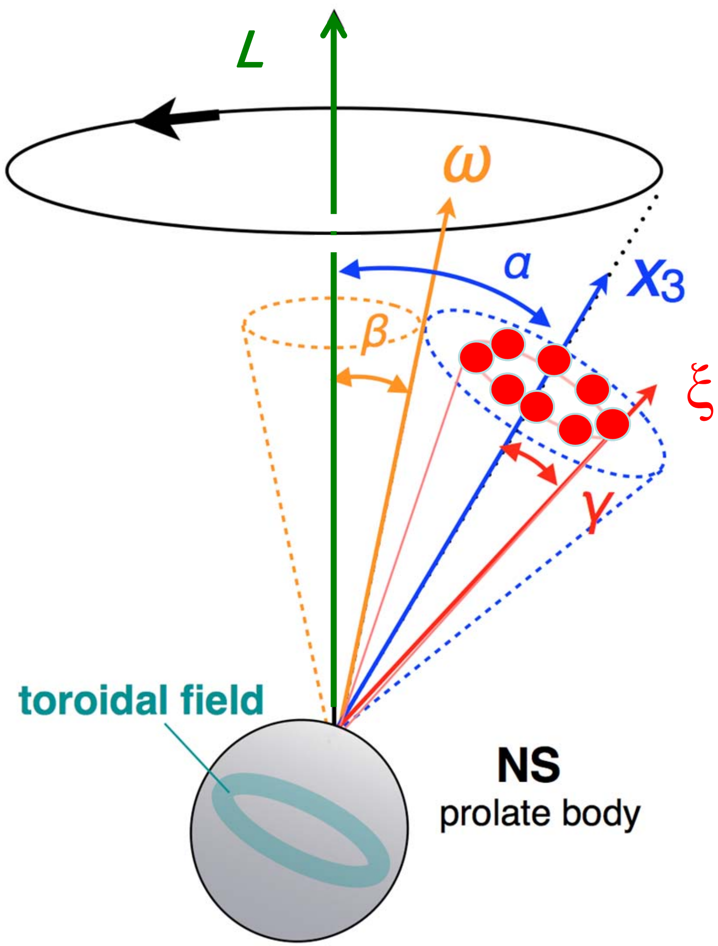
Toroidal fields cause prolate deformation





$\varepsilon \equiv \Delta I/I \sim$ a few $(B_t/1\mathrm{e}16\mathrm{G})^2 \times 10^{-4}$
(Gualtieri +2011)

3. Free Precession of an Axisymmetric Body



Mom. inertia $I_1=I_2>I_3$ (lemon shape), deviating from sphericity by $\varepsilon\equiv(I_1-I_3)/I_3$

✧L : ang. mom. fixed to inertial frame.

✧x_3: The body's symmetry axis. It rotates around L at a period $P_1 = 2\pi I_1/L$, with a constant wobbling angle α.

✧The body also spins around x_3 with a slightly different period, $P_3 = 2\pi I_3/L$.

✧ξ : the radiation direction. If it breaks the symmetry around x_3, it rotates w.r.t. the L-x_3 plane with slip period

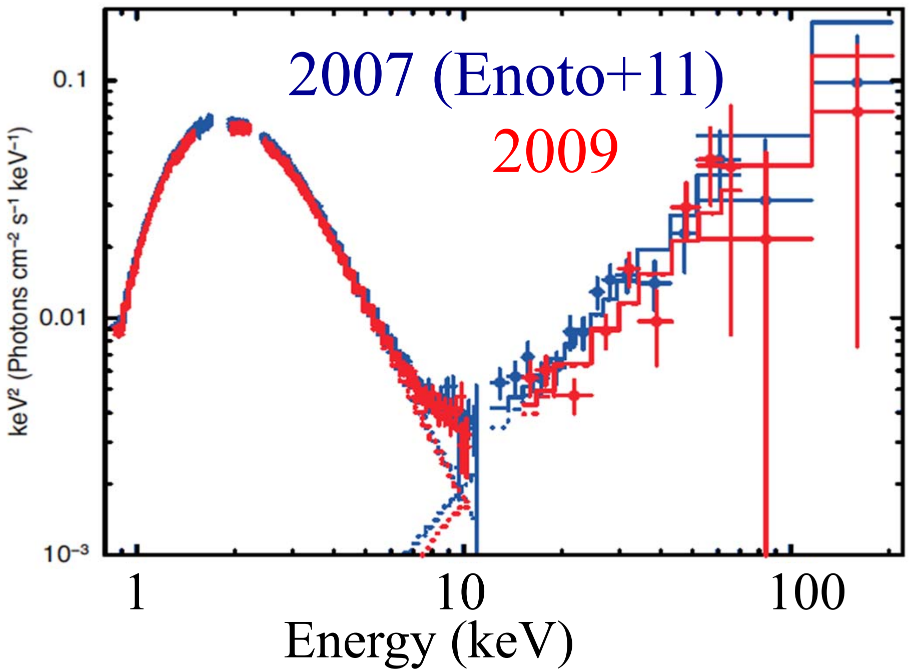
$$T=(1/P_3-1/P_1)^{-1}=P_1/\varepsilon$$

✧Then, the observed pulses (with period P_1) suffer phase modulations at T .

Any internal energy dissipation will make α increase with time if ε>0.

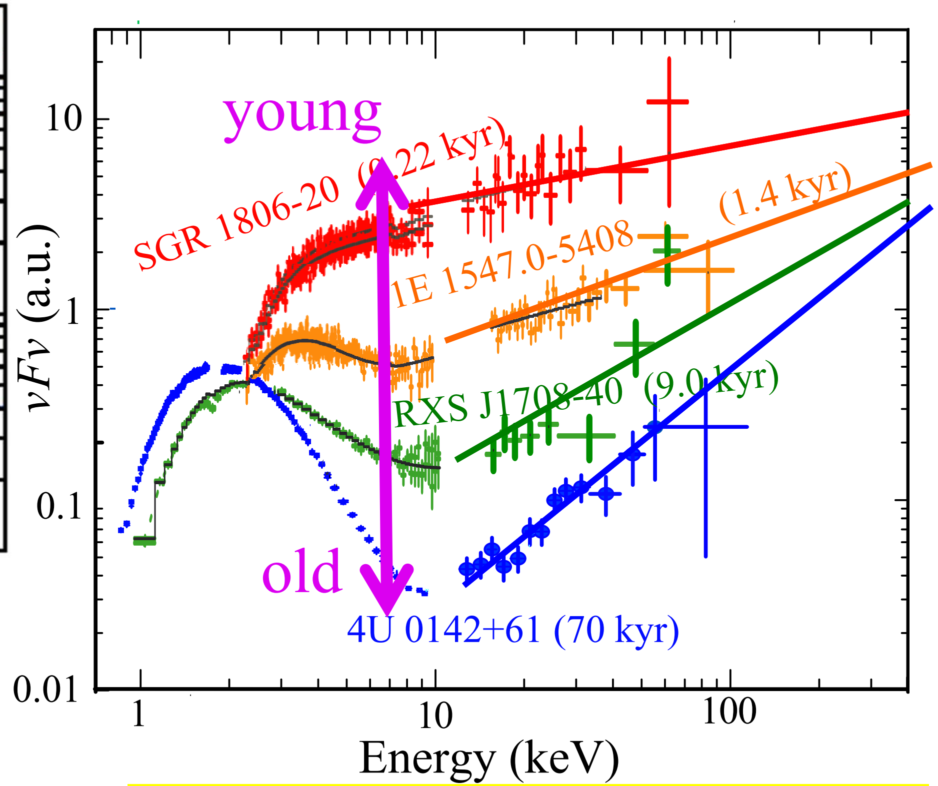
4. Two *Suzaku* Observations of 4U0142+61

νFν Spectra onTwo Occasions



Peculiar Hard/Soft 2-components, possibly with different emission regions (Enoto+10,11)

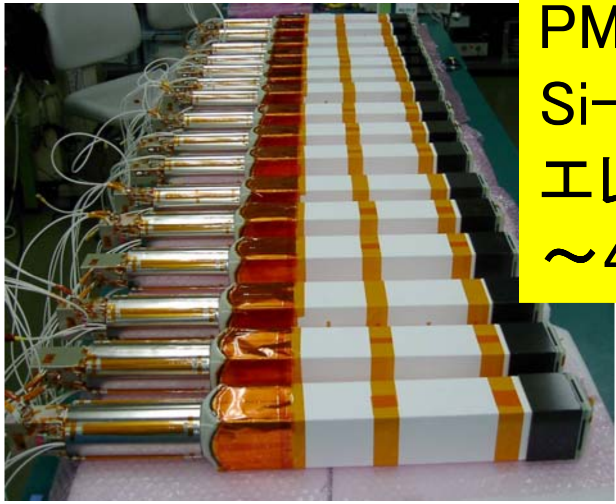
Clear spectral evolution with the characteristic age (Enoto+10)



The hard c. may result from QED splitting of 511 keV photons (Enoto+10)

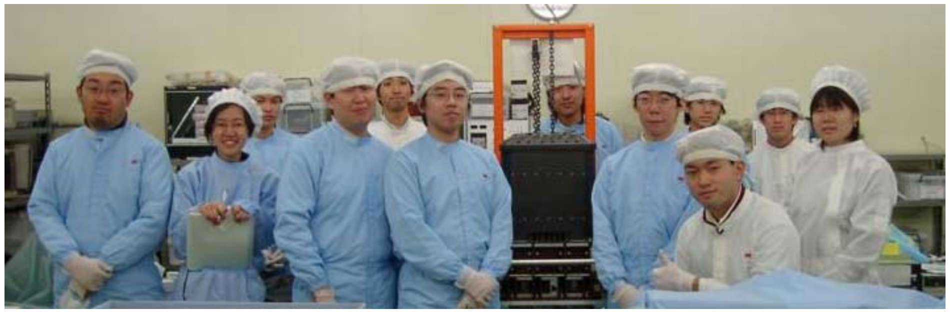
Final integration of HXD-S (2003)

16 Well units



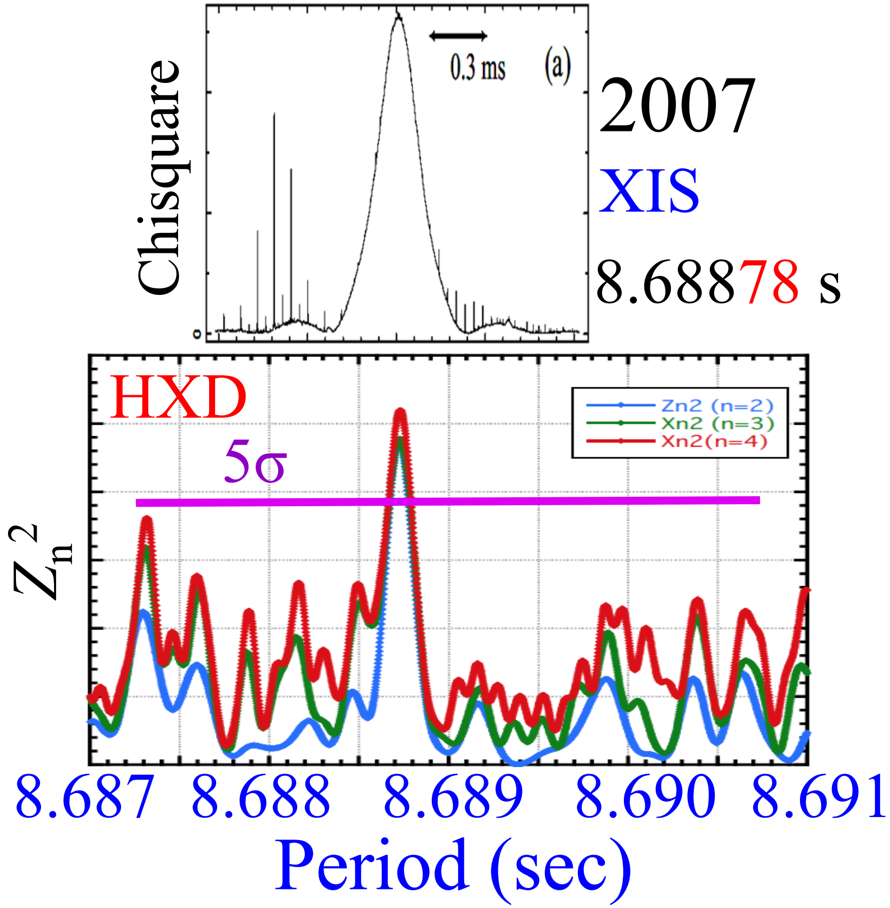
PMT 36ch
Si-PIN 64 ch
エレキまで含めて
～40 W

20 Anti units

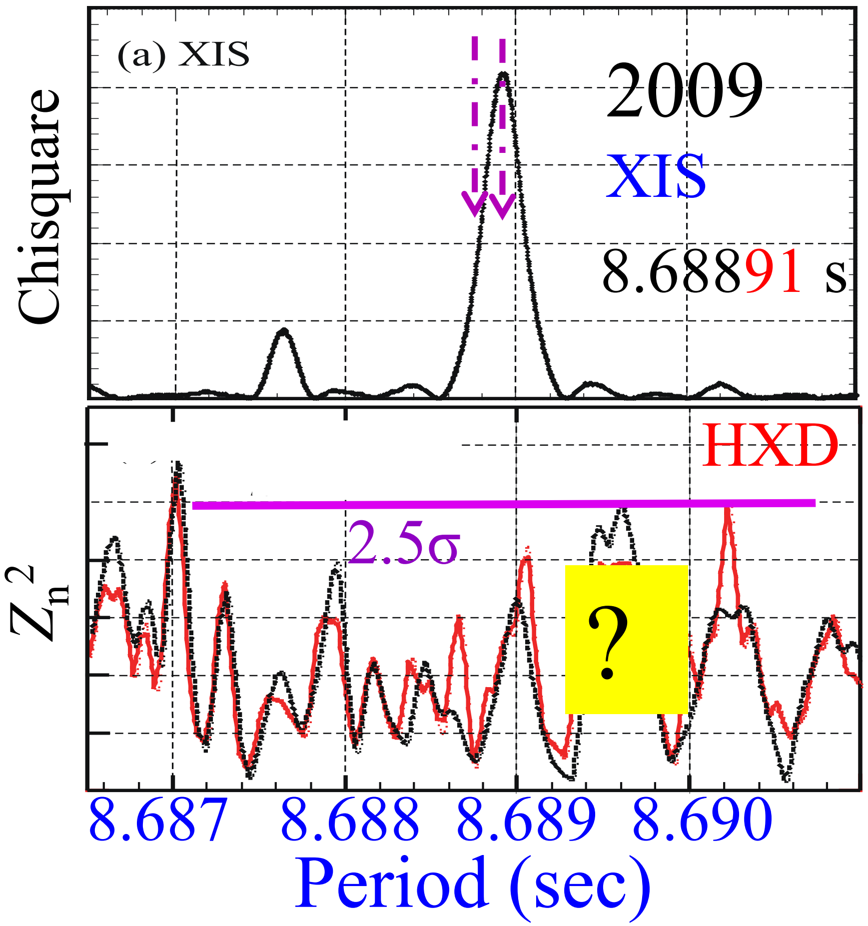


5. *Suzaku* Periodograms of 4U0142+61

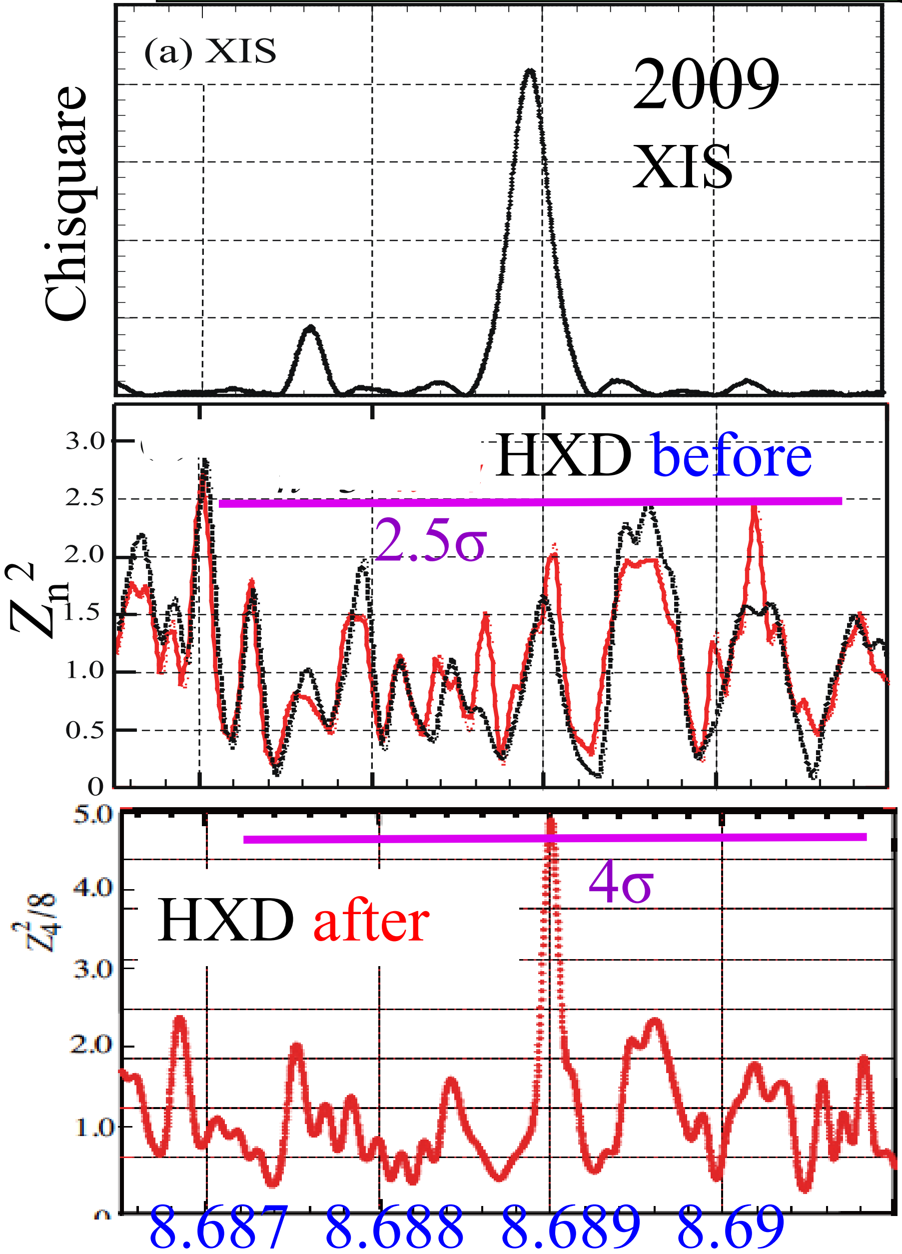
A steady spin-down, indicating $B_d = 1.3 \times 10^{14}$ G



(Enoto+11)



6. Detailed Analysis of the 2009 Data

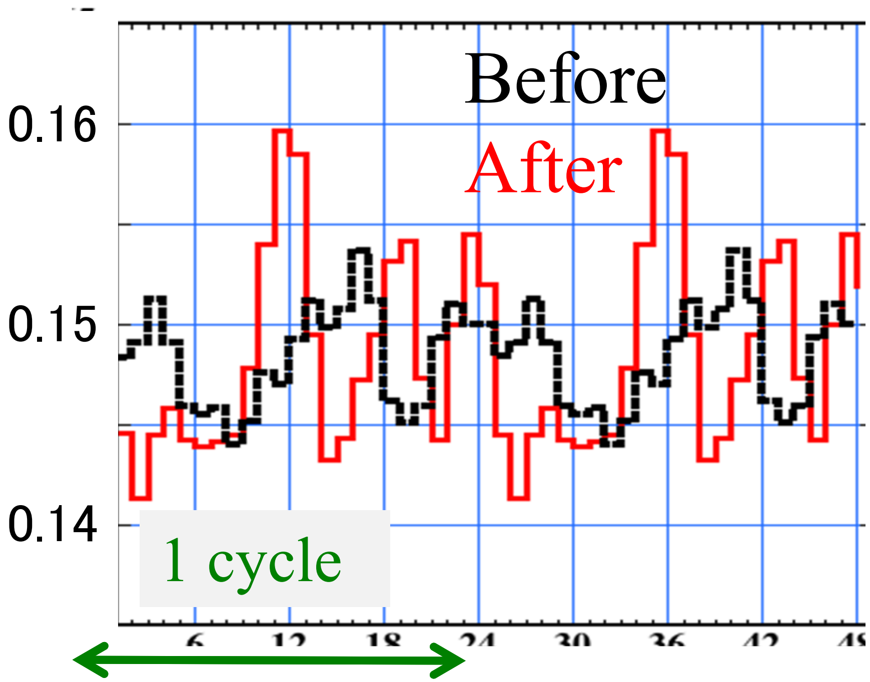


Assuming that arrival times of the HXD photons from 4U 0142+61 are periodically modulated by

$$\Delta t = A \sin (2\pi t/Q - \varphi),$$

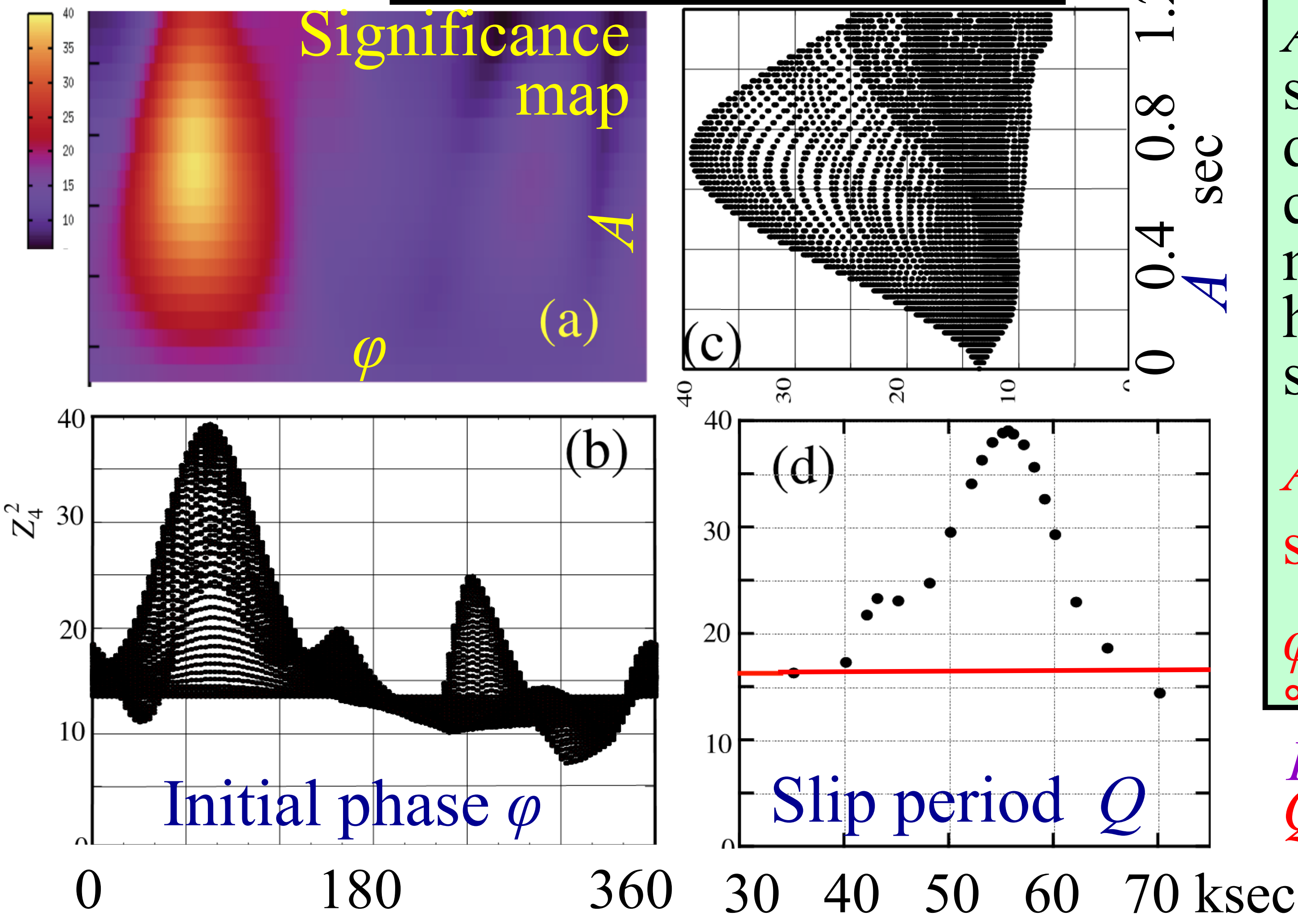
we corrected them by $-\Delta t$.

《15-40 keV pulse profiles》



7. Demodulation Search

$\Delta t = A \sin(2\pi t/Q - \varphi)$



Scanning over A, φ, and Q spaces, we determined the condition that maximizes the hard XR pulse significance.

A=0.7±0.3 sec

φ=70°±30°

Q=55±4 ksec

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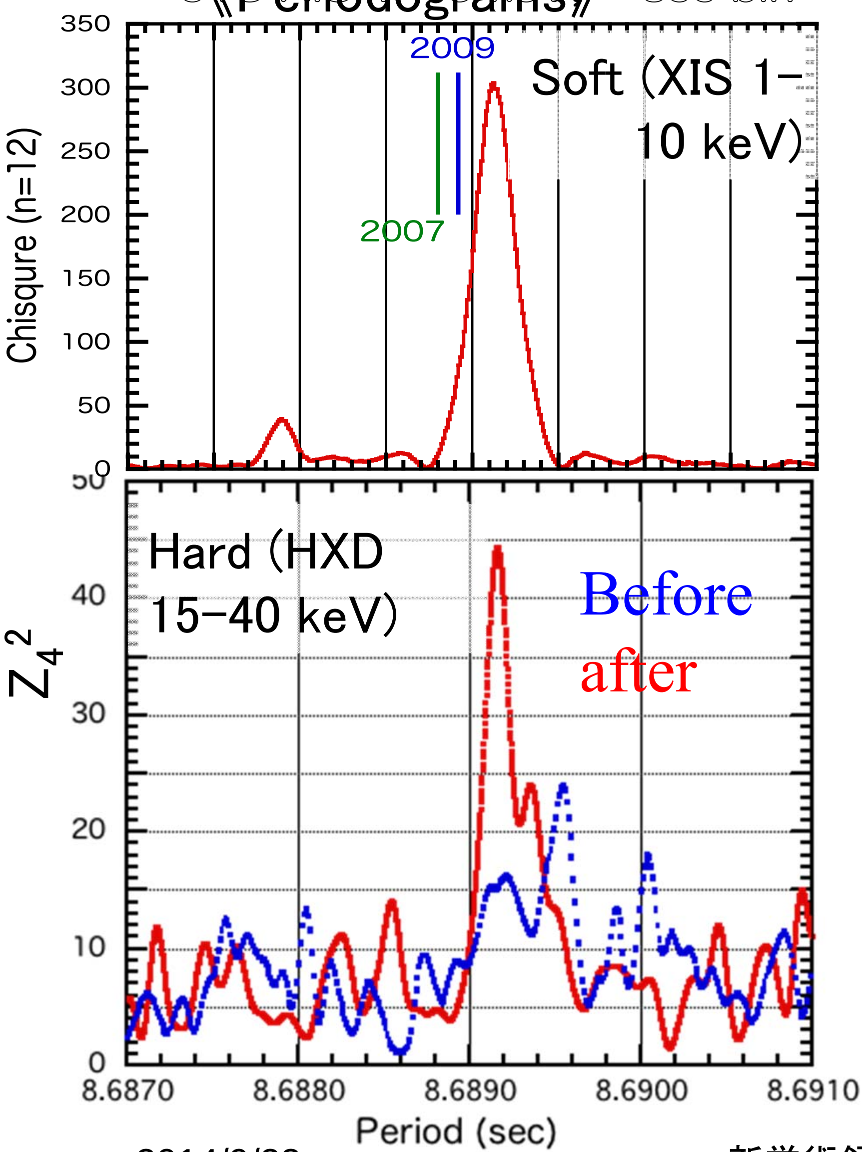
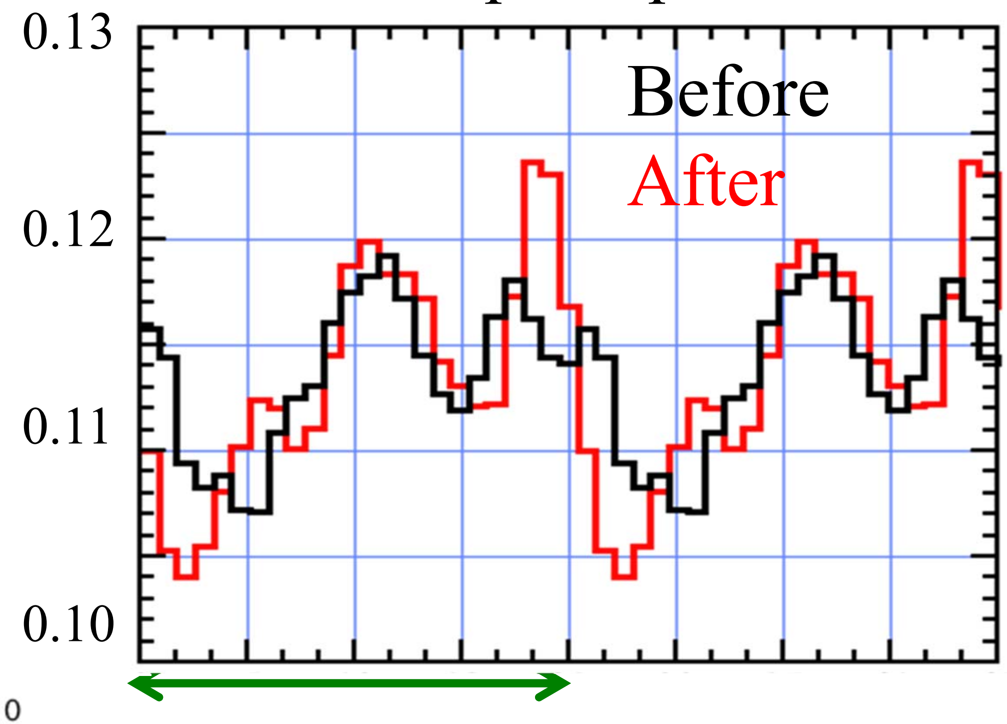
8. *Suzaku* Data in 2013 (Aug. 1-2)

《Periodograms》



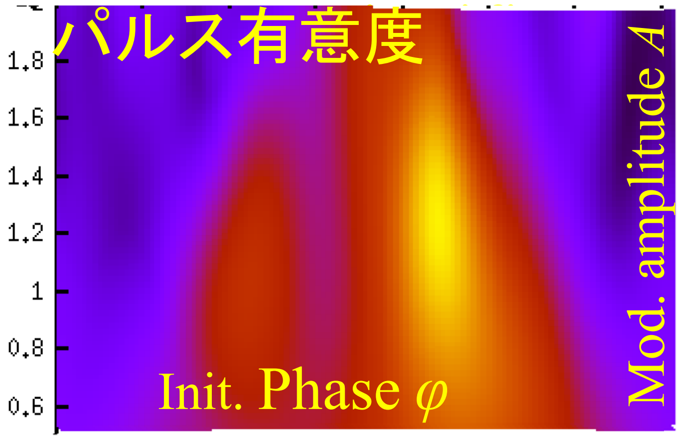
In the same way as in 2009, $\Delta t = A \sin(2\pi t/Q - \varphi)$ was assumed, and each photon arrival time was corrected by $-\Delta t$.

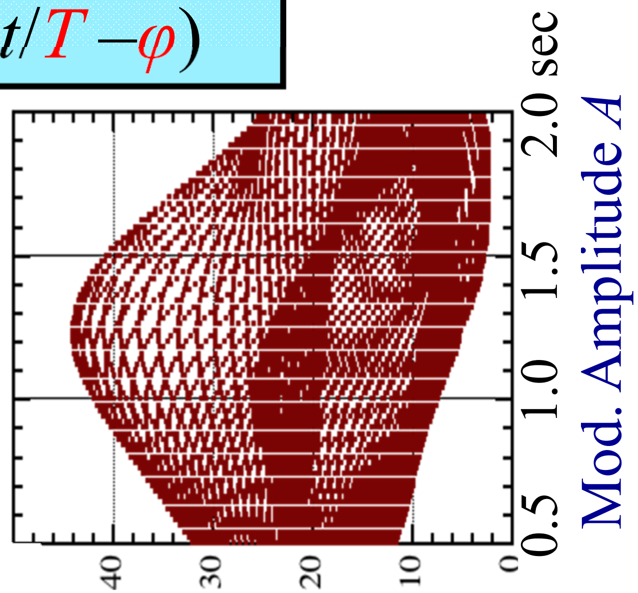
《15-40 keV pulse profiles》



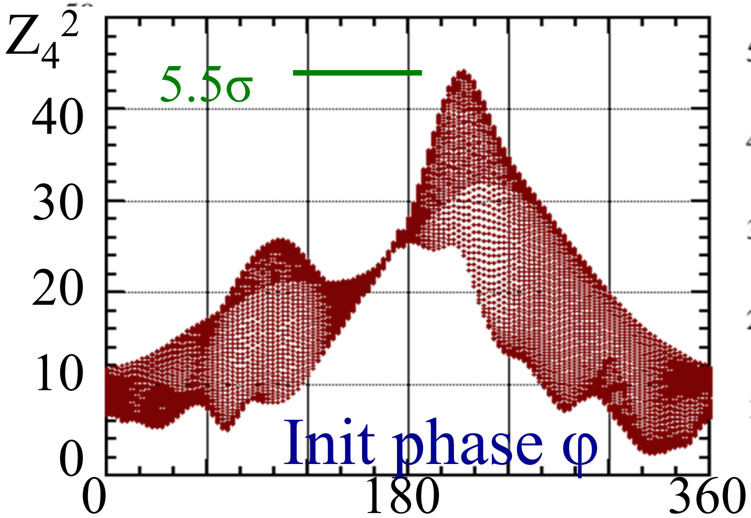
9. Demodulation Search in 2013

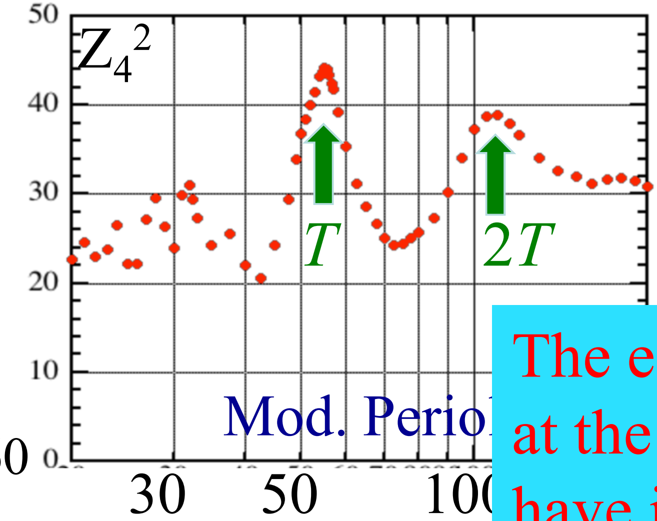
$\Delta t = A \sin(2\pi t/T - \varphi)$





- A=1.2±0.4 sec
- φ=215° ±25°
- T=56±4 ksec
- Z_4^2=44.3 (5.5σ)

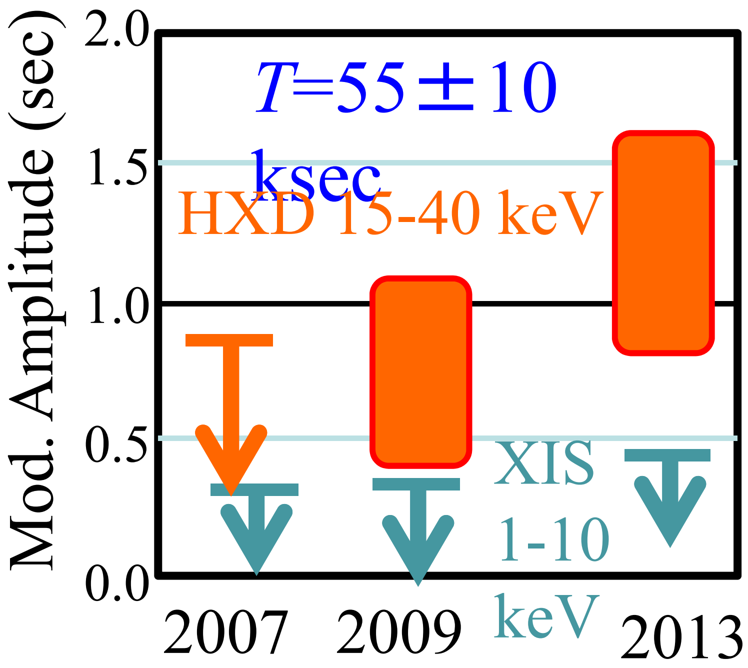




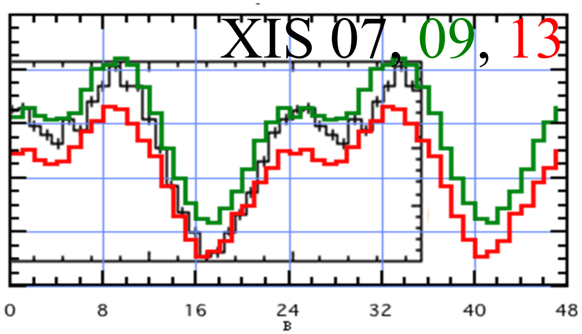
cf. 2009
Chance prob.0.03→0.1%
A=0.7±0.3 sec
φ=75° ±30°
T=55±4 ksec

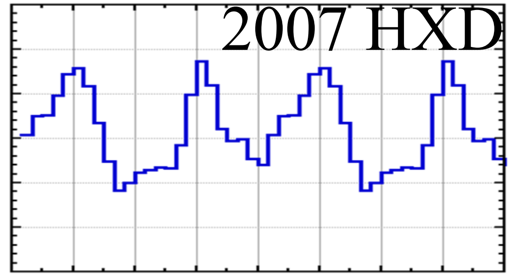
The effect reconfirmed at the same T. A may have increased.

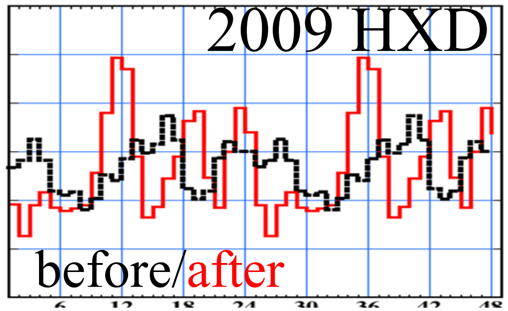
10. Comparing the 3 Data Sets

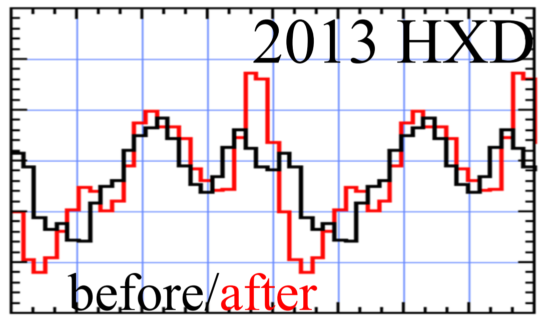


- ✧ The T=55 ksec pulse-phase mod. is seen only in hard XR.
- ✧ Its amplitude A may be variable.
- ✧ Pulse profiles are stable in soft XR, while variable in hard XR.





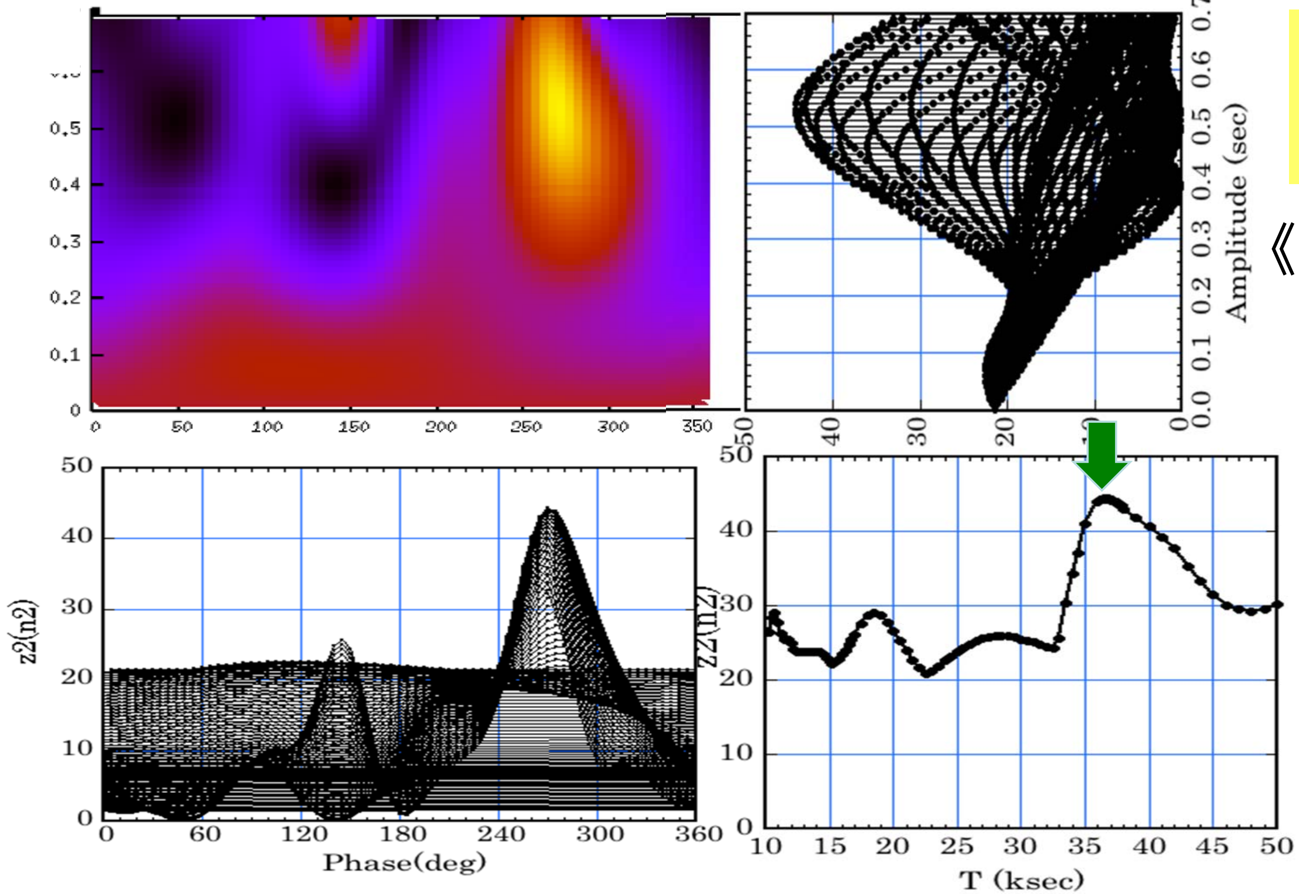




The results cannot be explained by the presence of a binary companion; then, it should also be detected in soft XR.

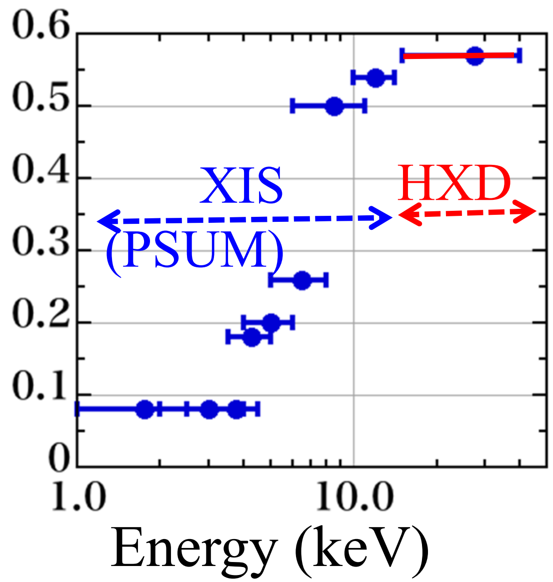
11. Magnetar 1E1547-54: a 2nd Example

2009 Jan. 28-29, observed with *Suzaku* in an outburst

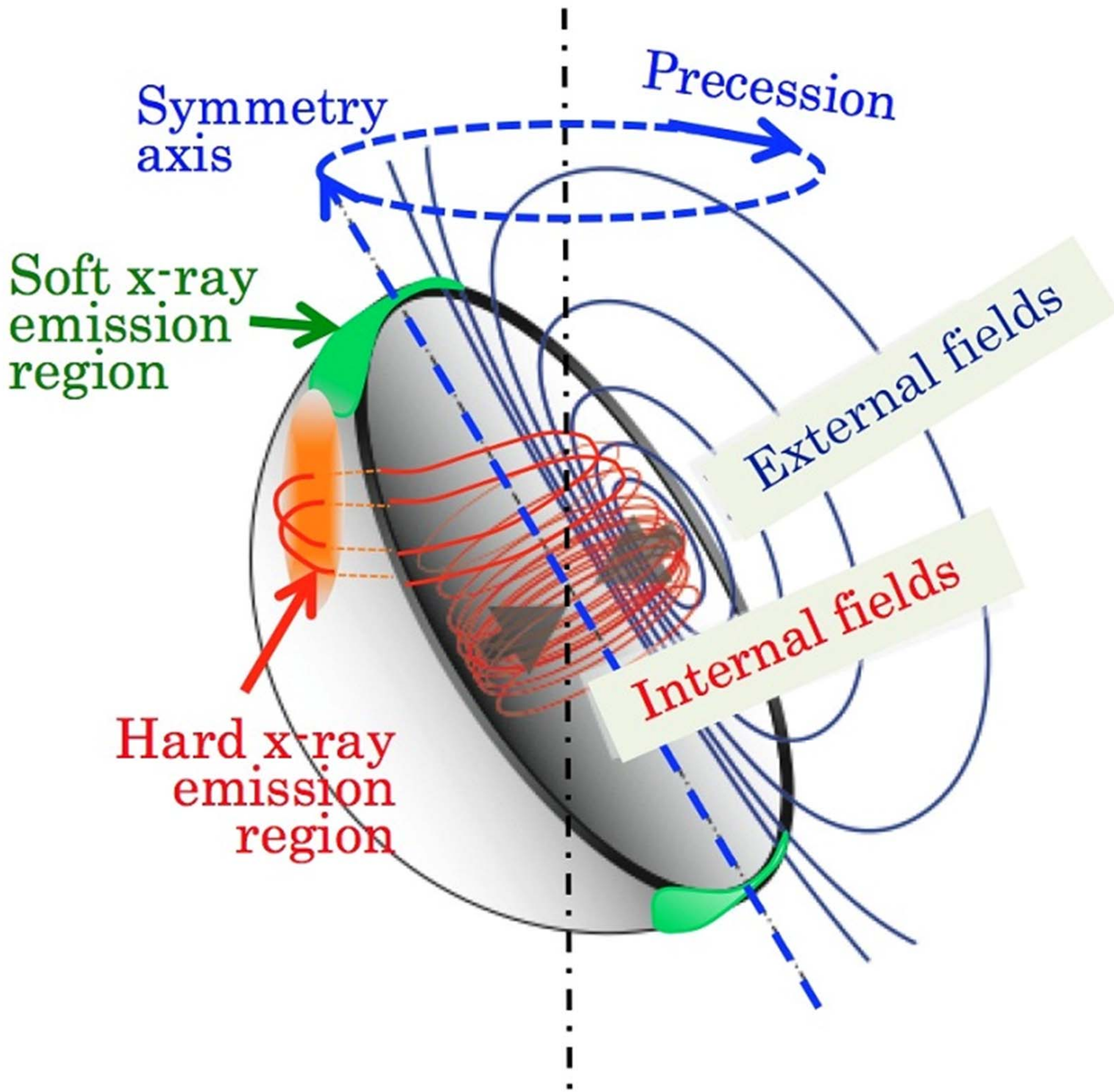


The effect confirmed with the XIS as well.

《Energy dependence of *A*》



	P (sec)	*A* (sec)	*T* (ksec)	ε≡*P*/*T*
1E1547	2.072137	0.56±0.03	37±4	0.6e-4
4U 0142	8.68916	1.2±0.4	56±4	1.6e-4


Symmetry
axis
Precession
Soft x-ray
emission
region
External fields
Internal fields
Hard x-ray
emission
region

12. Discussion & Conclusion

- In the magnetar 4U 0142+61, the P=8.69 sec hard X-ray pulses were phase-modulated at a period of T~55 ksec and with a variable amplitude A. The periodical nature was confirmed.
- The pulse-phase modulation was absent (A<0.3 sec) in soft X-rays on any occasion. The soft/hard components are implied to have different emission regions, and/or different beam patterns.
- These results can be consistently interpreted in terms of "free precession of a slightly non-spherical neutron star" plus "a hard X-ray emission pattern that breaks axial symmetry of the star". The variation in A can be attributed to changes in the latter.
- The same effect was detected from another magnetar 1E 1547-54.
- In both objects, the implied asphericity is ε~1e-4, which further suggests deformation by toroidal magnetic fields of $B_t \sim 10^{16}$ G. This provides the first observational estimate of B_t.
- Further studies form an ideal subject for *ASTRO-H*, which is scheduled for launch in FY2015.