Spectral and timing analysis of the Be/X-ray binary A0535+26 in outburst

Isabel Caballero

Institut für Astronomie und Astrophysik
Universität Tübingen

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Outline

1. Introduction
   - Be/X-ray binary system
   - Production of X-rays
   - Spectral properties
2. Observations and Data Analysis
   - INSTRUMENTS
3. Results
   - Timing analysis
   - Spectral analysis - Broad band spectra

Outline

Compact Object and Binary Companion

Neutron Star

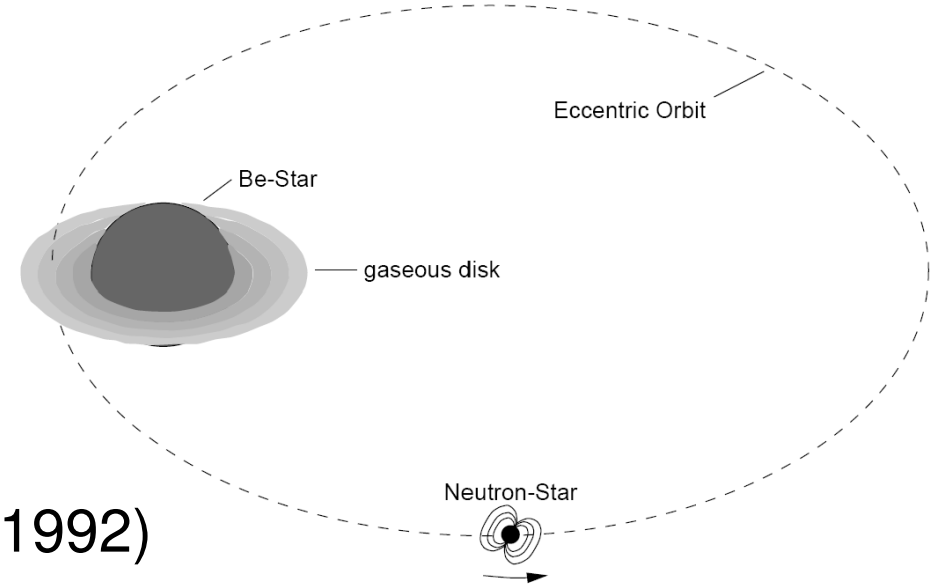
- typical parameters: $R = 10\mathrm{km}$, $M = 1.4\mathrm{M}_\odot$
- $P_{spin} \sim 103\mathrm{s}$
- $B \sim 4 \times 10^{12}\mathrm{G}$

HDE 245770 - O9.7, IIIe

- $14\mathrm{M}_\odot$
- $14\mathrm{R}_\odot$
- $1.41\mathrm{L}_\odot$
- $T_{eff} = 26000\mathrm{K}$

Orbital Parameters

- $P_{orb} = 111\mathrm{days}$
- $e = 0.47$



$d \sim 2\mathrm{kpc}$
(Review in Giovanelli&Graziati, 1992)

(Figure: Kretschmar, 1996)

Transient Source

The source has shown 5 giant outbursts since its discovery

- April/May 1975 - $L_{(3-50\mathrm{keV})} \sim 1.2 \times 10^{37}\mathrm{ergss}^{-1}$ (Rosenberg et al. 1975)
- October 1980 -$L_{(1-22\mathrm{keV})} \sim 3 \times 10^{37}\mathrm{ergss}^{-1}$ (Nagase et al. 1982)
- June 1983 -$L_{(32-91)\mathrm{keV})} \sim 2 \times 10^{37}\mathrm{ergss}^{-1}$ (Sembay et al. 1990)
- March/April 1989 -$L_{(23-52\mathrm{keV})} \sim 1.3 \times 10^{37}\mathrm{ergss}^{-1}$ (Makino et al. 1989)
- February 1994 -$L_{(20-40\mathrm{keV})} \sim 3.6 \times 10^{37}\mathrm{ergss}^{-1}$ (Finger et al. 1994)
- May/June 2005 - $L_{(15-195\mathrm{keV})} \sim 4.8 \times 10^{37}\mathrm{ergss}^{-1}$ (Tueller et al. 2005)
  Too close to the sun to be observed!!

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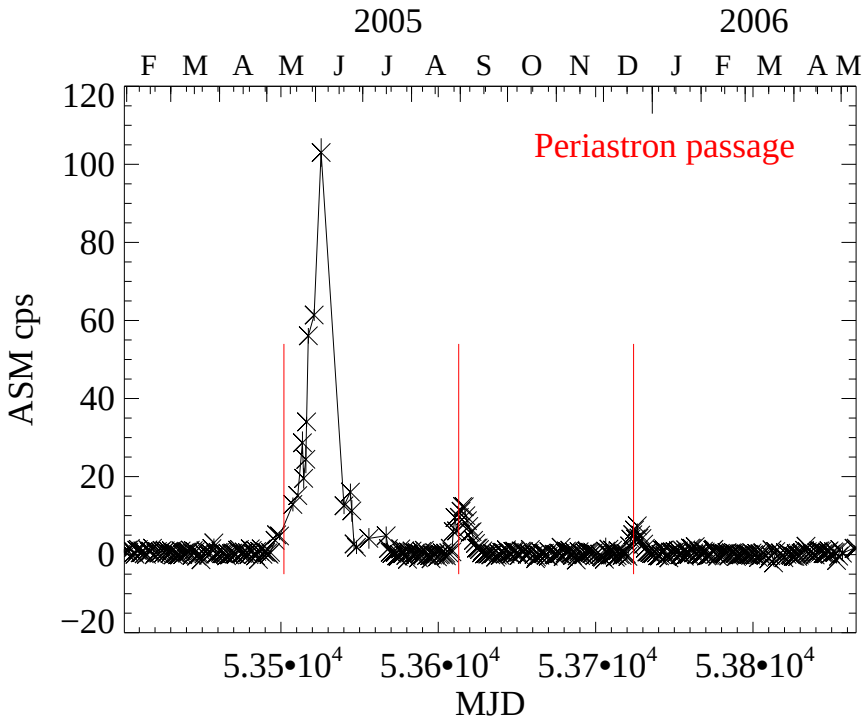
but...

The source became newly active in August/September 2005 showing a normal outburst observed by INTEGRAL and RXTE
$L_{(3-50\mathrm{keV})} \sim 0.9 \times 10^{37} \mathrm{ergss}^{-1}$



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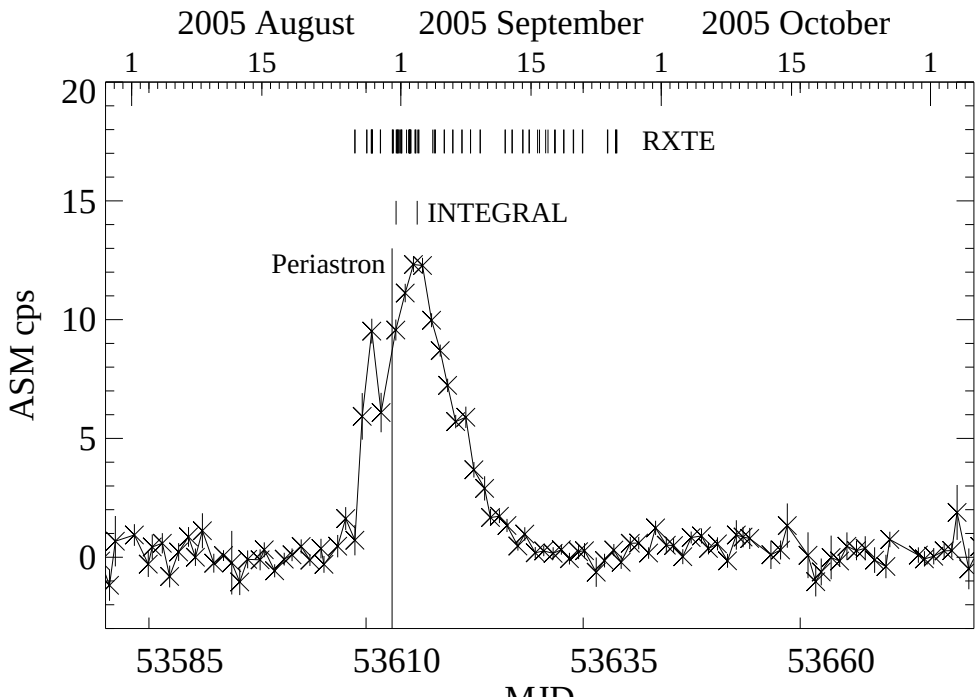
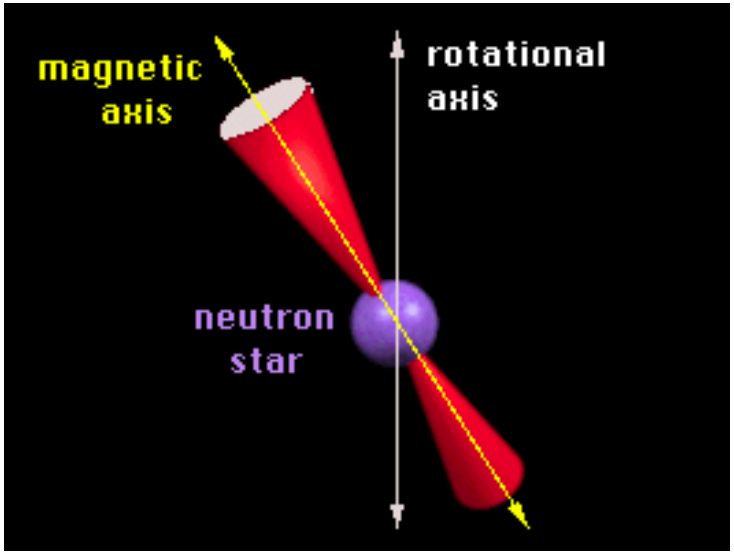
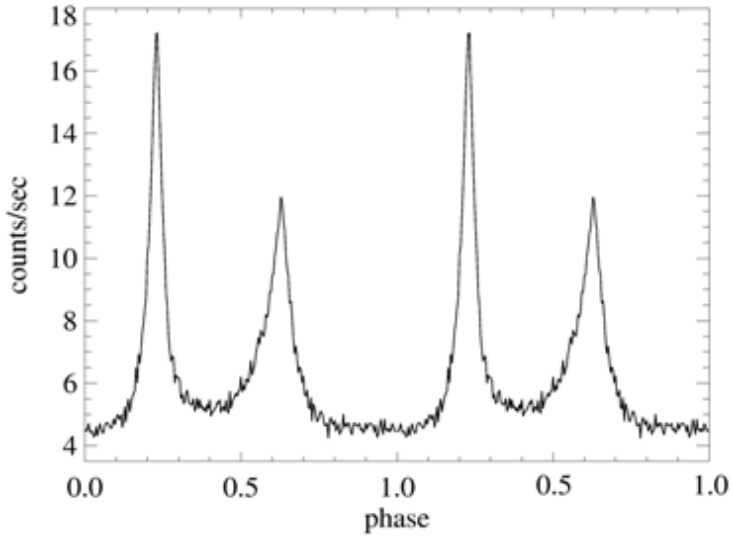


Pulsed emisison

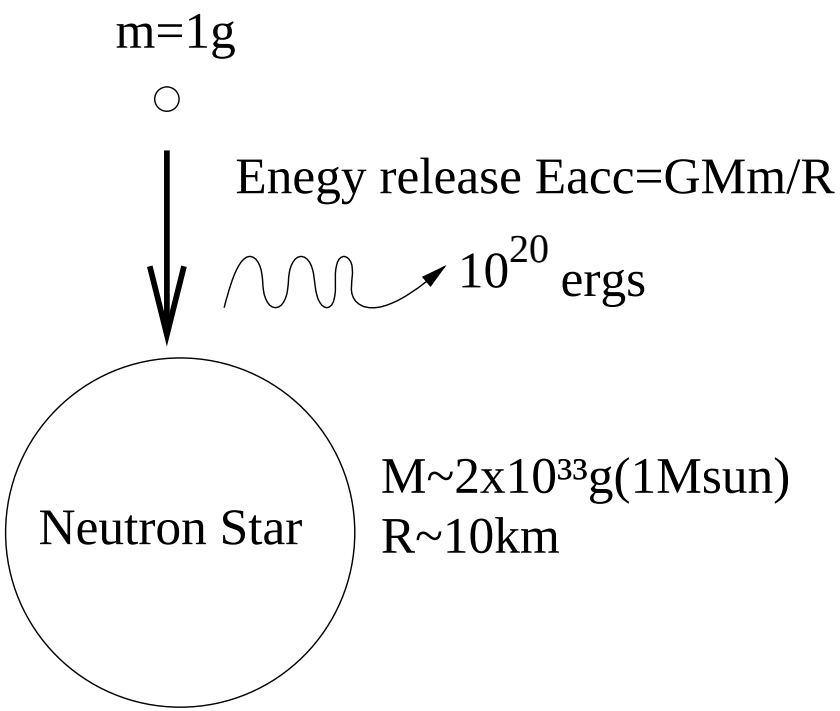
If magnetic axis and emission axis are misaligned we observe pulsed emission





Accretion

Conversion of gravitational energy into kinetic energy.
X-ray emission :
energy release when matter from companion falls into the NS



Most efficient way for energy production known in the universe!!

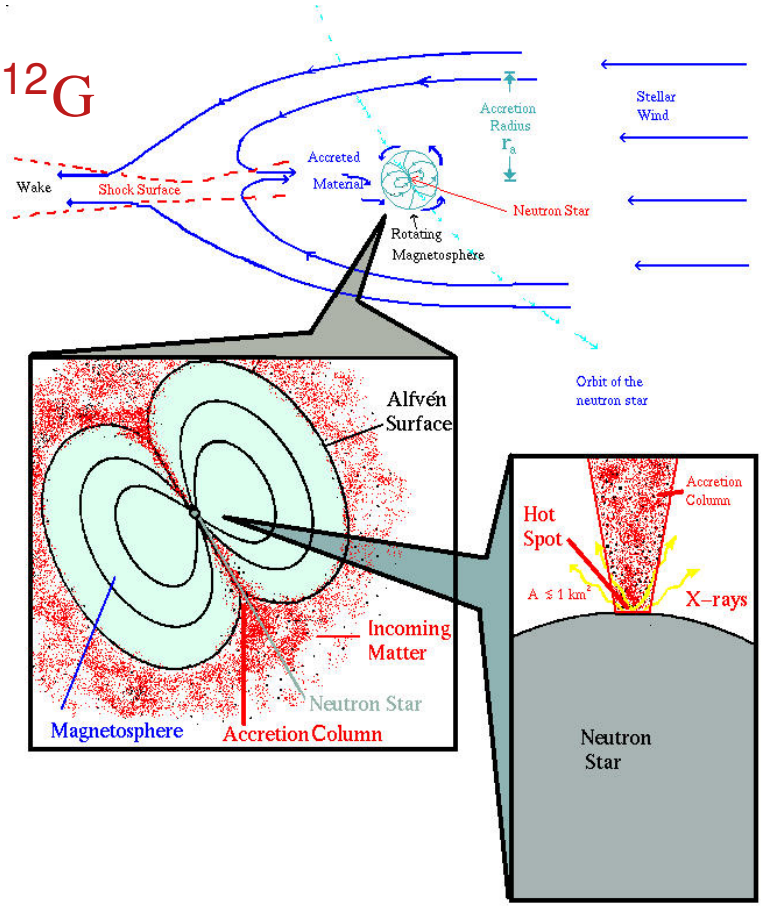
Luminosity of accretion

$$L_{acc} = \frac{GM}{R}\frac{dm}{dt} = \frac{GM\dot{m}}{R} \qquad (1)$$

Accretion

Process dominated by strong magnetic fields.
Matter couples to B field lines close to the NS surface.

$B \sim 10^{12}$G



Formation of accretion columns close to the polar caps

(Image: Negueruela)

Accretion luminosity

Inward and outward forces:

- Gravitational force acting on infalling matter (protons)
- Radiation pressure onto electrons due to Thompson scattering

Assuming spherically symmetric accretion, the X-ray luminosity has an upper bound:

$$L_X \leq L_{Edd} = \frac{4\pi cGMm}{\sigma_T} \sim 1.3 \times 10^{38} \frac{M}{M_\odot} \mathrm{ergss}^{-1} \quad (2)$$

Critical accretion rate:

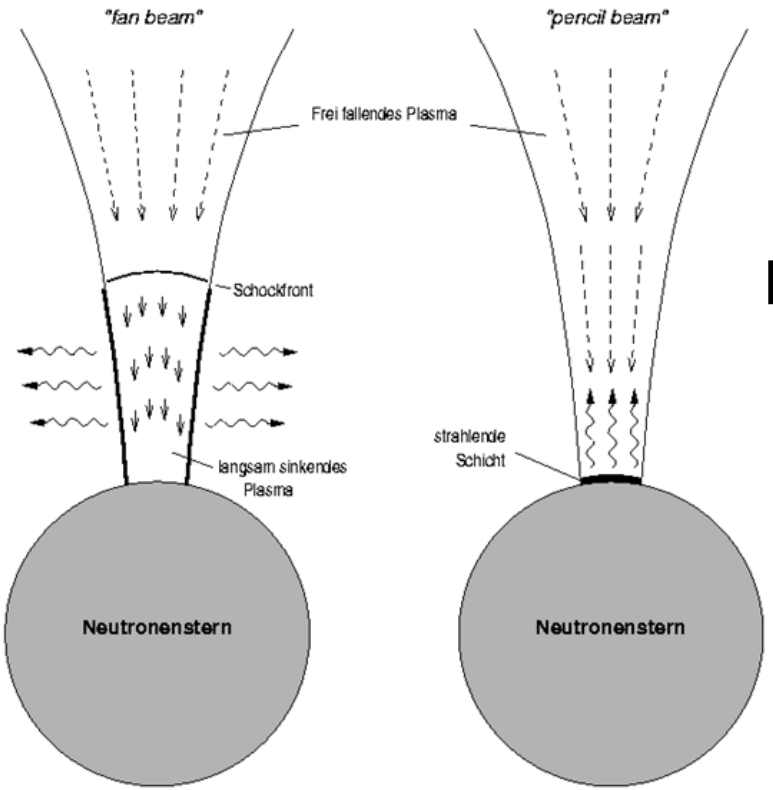
$$L_{acc} = L_{Edd} \Rightarrow \dot{m} = \frac{4\pi cmR}{\sigma_T} \sim 1.5 \times 10^{-8} R_6 \frac{M_\odot}{year} (_{R_6 = R \times 10^6 \mathrm{cm}}) \quad (3)$$

Accretion columns

Matter forced to follow the B field lines.
Extreme physical conditions in the accretion funnel:

- $B \sim 10^{12}$G
- relativistic plasma
- $L \sim L_{Edd}$

High accretion rates



Low accretion rates

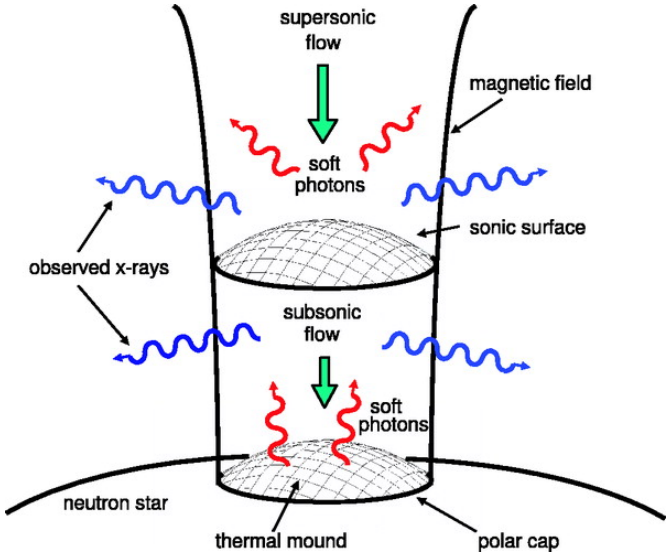
(Kretschmar, 1996 after Harding, 1994)

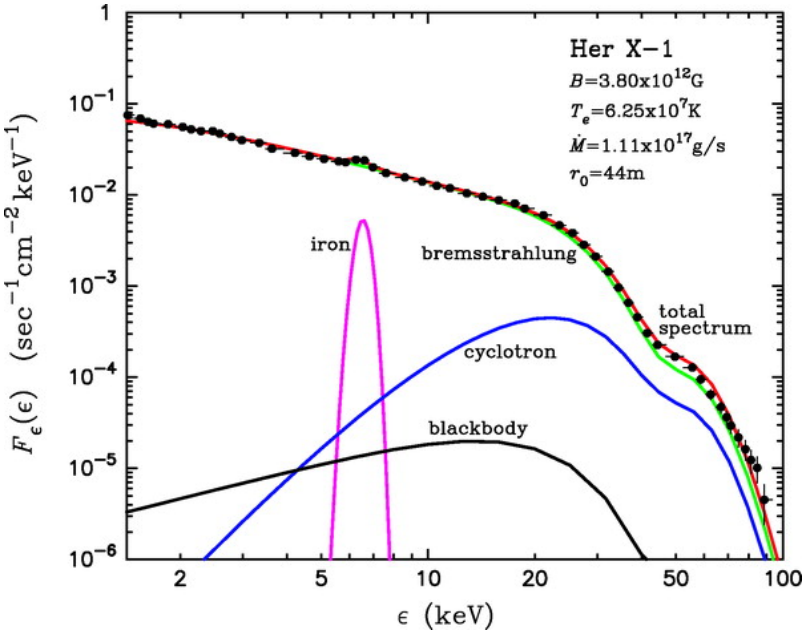
Emergent High Energy Radiation

X-ray spectra of accreting X-ray pulsars are usualy fitted with phenomenological models, typically

$$f(E) \sim E^{-\alpha} e^{-E/E_{fold}} \tag{4}$$

Recent model by Becker & Wolff, 2007



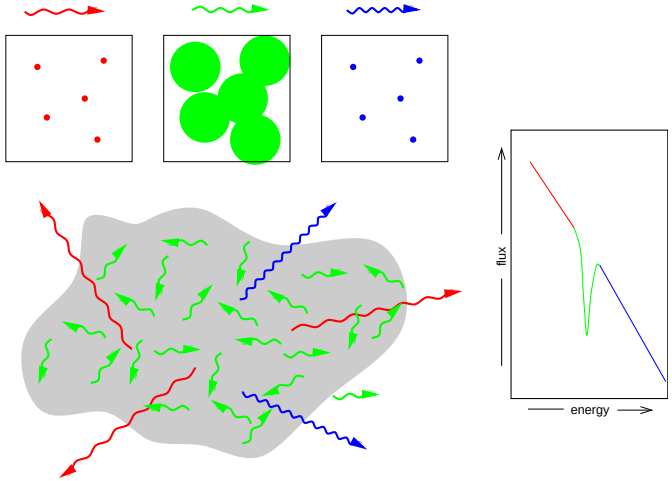


Cyclotron Resonance Scattering Features

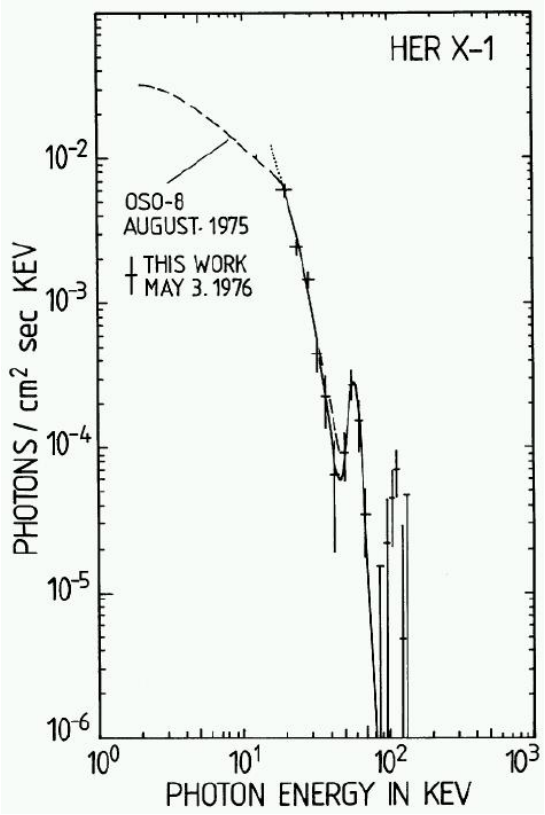
Very strong B fields: energy of electrons quantized into the Landau levels. Energy difference between two allowed eigenstates:

$$E_{cyc} = 11.6\mathrm{keV}B \times 10^{12}\mathrm{G} \tag{5}$$

Photons with $E \sim E_{cyc}$ can't leave the plasma.
Only direct way to determine B field of a NS!!



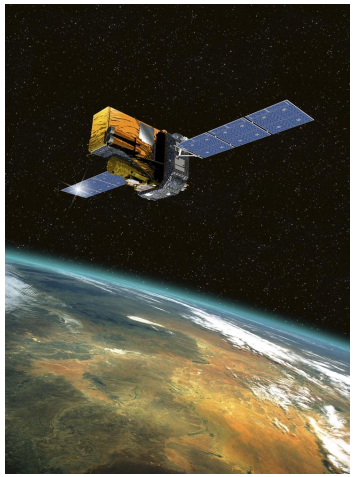
(Kretschmar)



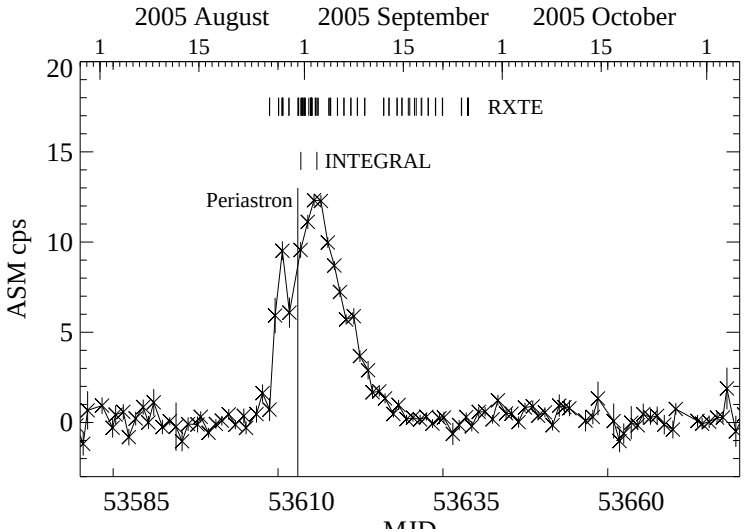
(Trümper et al. 1978)

Outline

INTEGRAL and RXTE



- JEM-X 3–35 keV
- IBIS 15keV–10MeV
- SPI 20keV–8MeV
  OSA 5.1



- ASM 2–10keV
- PCA 2–60keV
- HEXTE 20–200keV
  FTOOLS 6.0.2

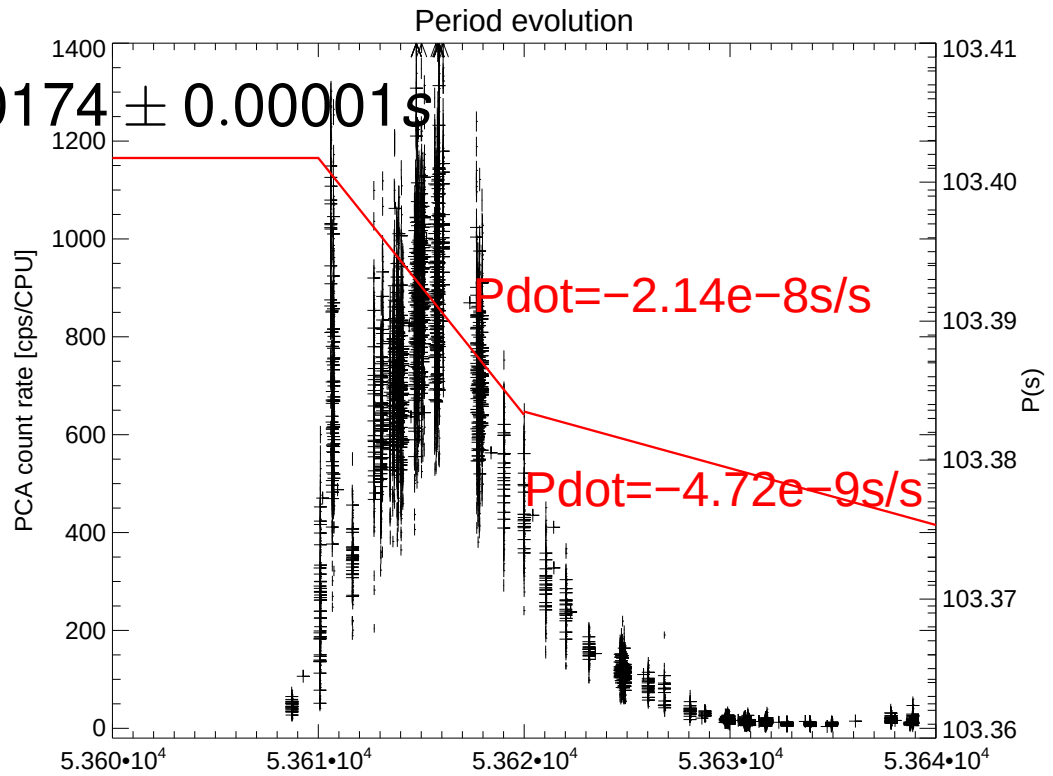
Exposure times:
RXTE $\sim$ 198.4ks
INTEGRAL $\sim$ 125.5ks

Outline

Period determination

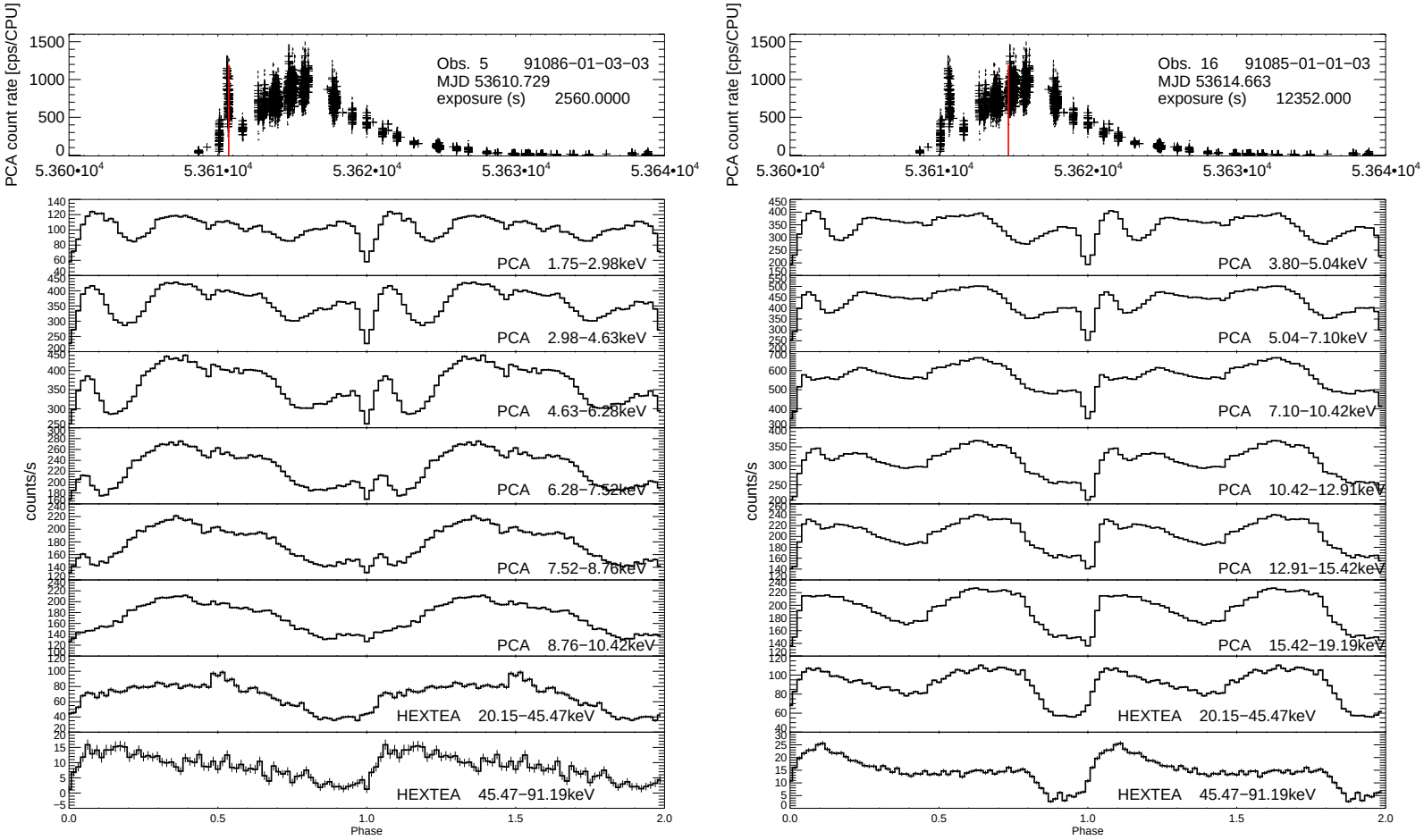
The pulse period and period derivative were determined with high accuracy using a “phase connection method”.
(Error analysis is ongoing)

$P = 103.40174 \pm 0.00001 s$



Pulse profiles

Dramatic pulse profile variation with the luminosity



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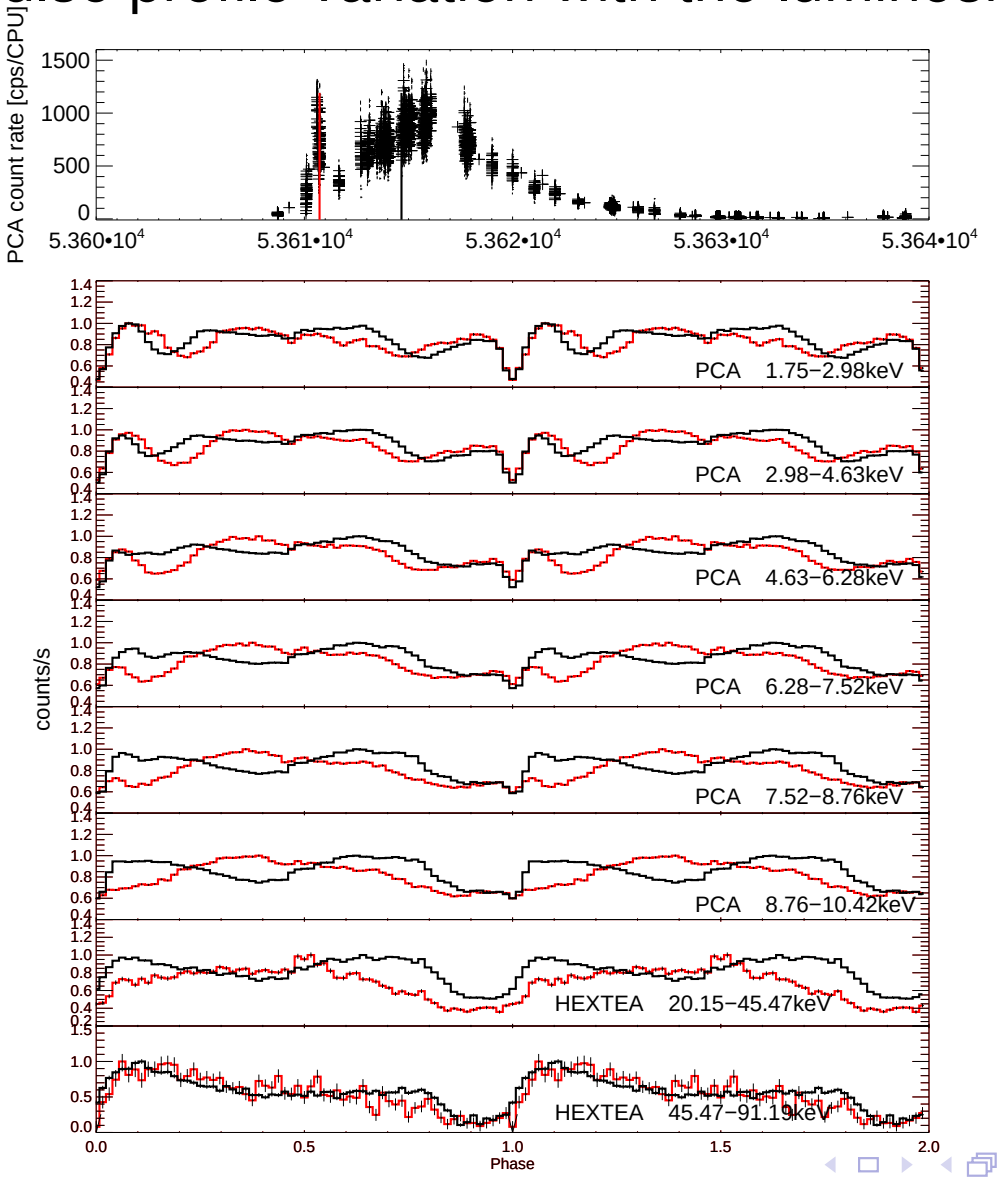
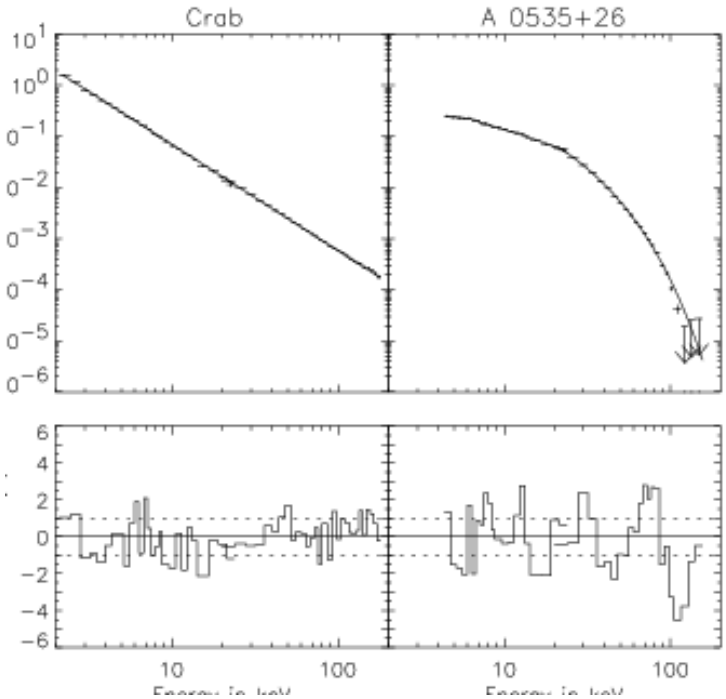


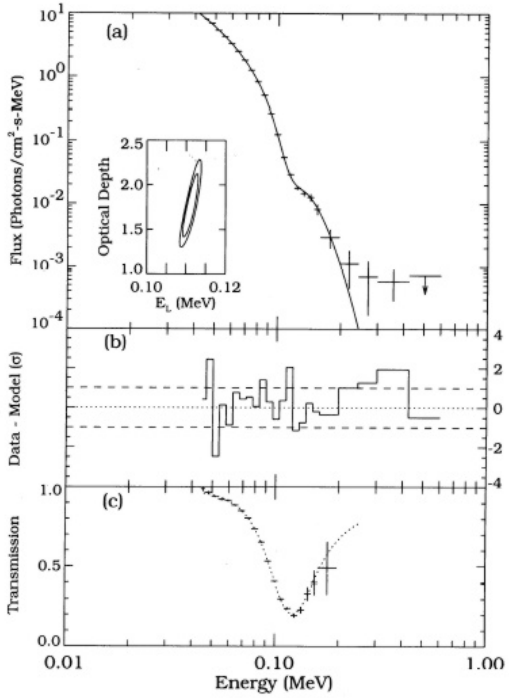
Previous results: Fundamental cyclotron line at 45keV or 100keV?

March/April 1989 giant outburst
TTM/HEXE observations
$E_1 \sim 45\mathrm{keV}$, $E_2 \sim 100\mathrm{keV}$
$\Rightarrow B \sim 4 \times 10^{12}\mathrm{G}$



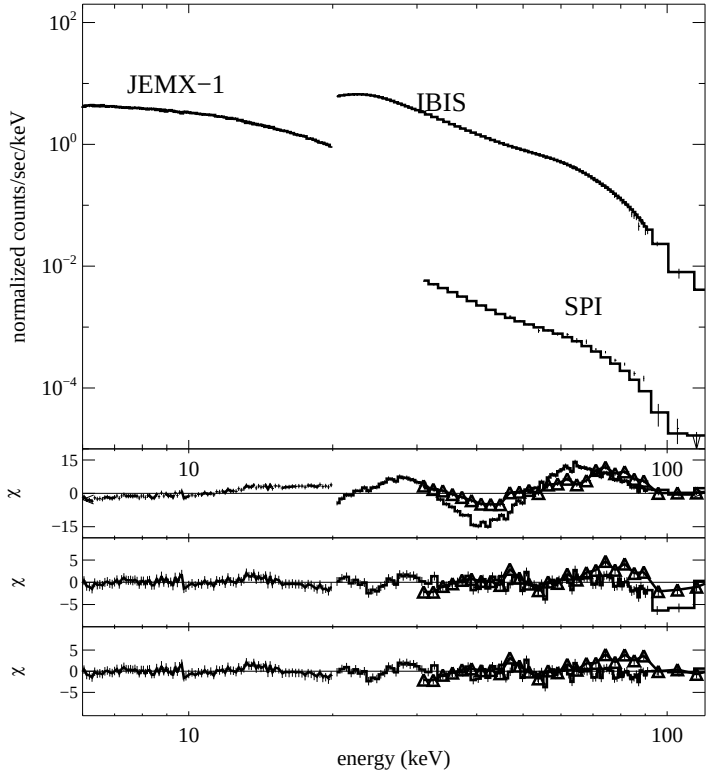
(Kendziorra et al., 1994)

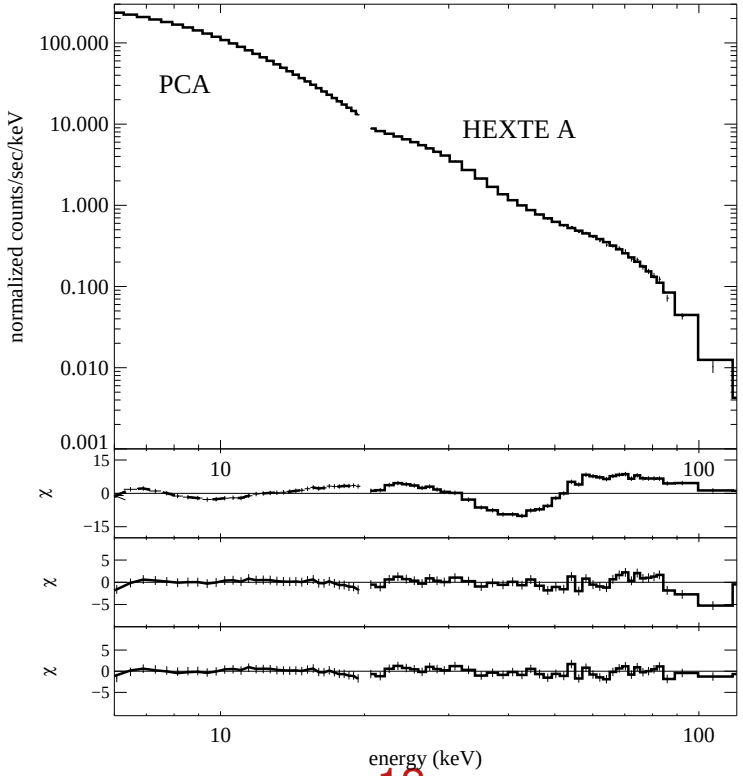
February 1994 giant outburst
OSSE observations
$E_1 \sim 100\mathrm{keV}$
$\Rightarrow B \sim 10^{13}\mathrm{G}$



(Grove et al., 1995)

Confirmation of two cyclotron lines at 45keV, 100keV





$$E_{cyc} = 11.6\text{keV}B \times 10^{12}\text{G} \Rightarrow B \sim 4 \times 10^{12}\text{G}$$

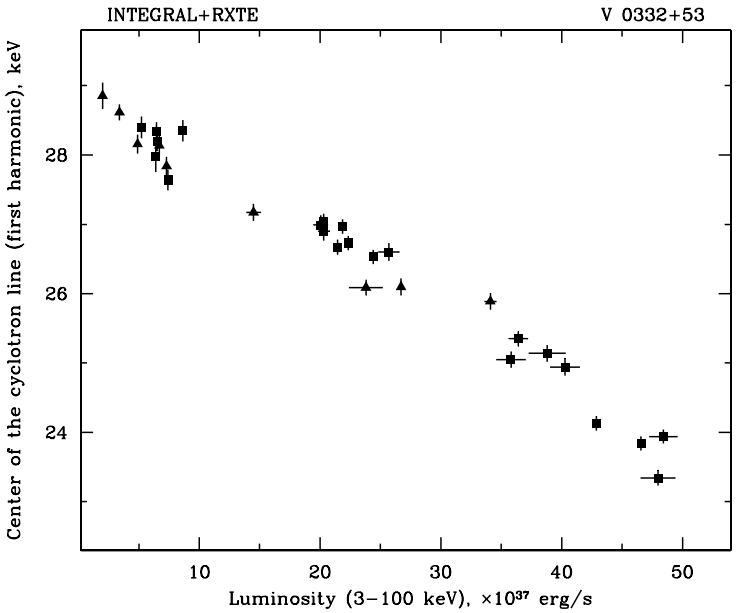
E_{cyc}(keV)	σ(keV)	τ
$45.9^{+0.3}_{-0.3}$	$9.5^{+0.3}_{-0.3}$	$0.415^{+0.015}_{-0.015}$
102^{+4}_{-3}	8^{+3}_{-2}	$1.1^{+0.4}_{-0.3}$

E_{cyc}(keV)	σ(keV)	τ
$45.9^{+0.4}_{-0.3}$	$10.3^{+0.5}_{-0.4}$	$0.500^{+0.002}_{-0.002}$
103^{+3}_{-3}	8^{+2}_{-2}	$1.1^{+0.4}_{-0.3}$

Cyclotron line position - luminosity

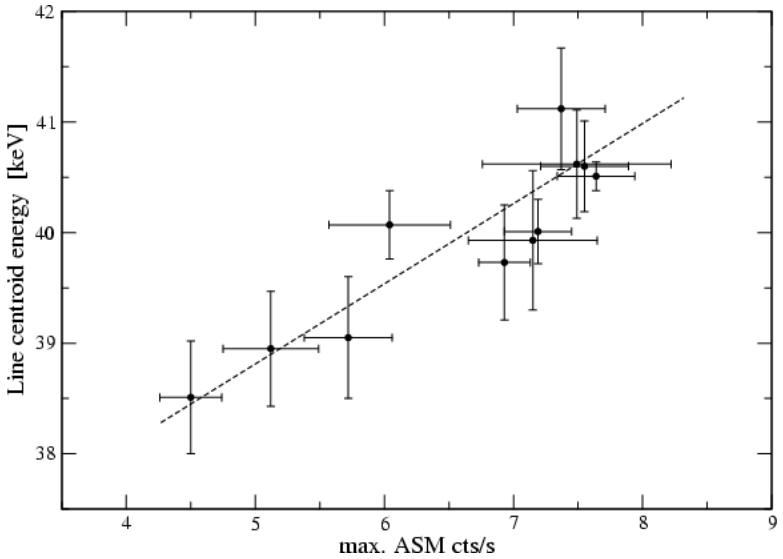
Super-Eddington regime
High accretion rates
Shock formation in accretion column
Height of schock $\propto \dot{m}$

Sub-Eddington regime
Low accretion rates
No shock is formed



(Tsygankov et al., 2006)

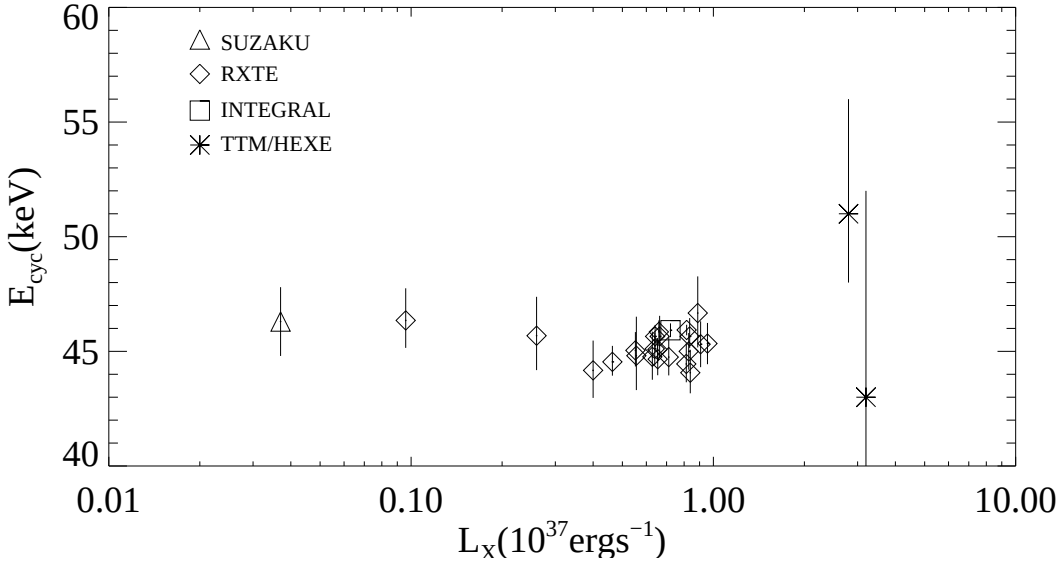
Her X-1



(Staubert et al., 2007)

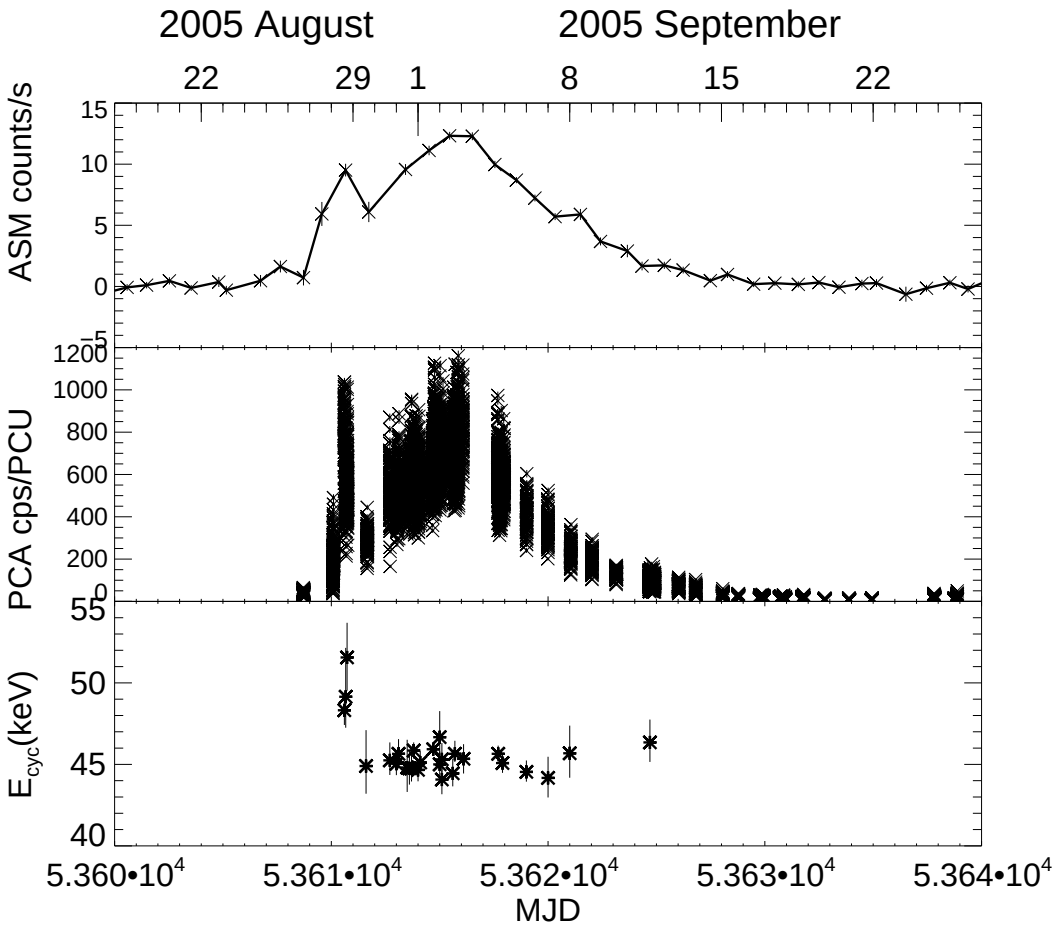
Cyclotron line position - luminosity

Energy of fundamental cyclotron line stays constant with the luminosity. This suggests that the line forming region does not change with the luminosity of the system.



(Caballero et al., 2007)

Change in the cyclotron energy?



Summary

- Confirmation of two cyclotron lines at $\sim 45\mathrm{keV}$ and $\sim 100\mathrm{keV}$
  We can firmly stablish the magnetic field at $B \sim 4 \times 10^{12}\mathrm{G}$
- Period determination with high accuracy
- Spin-up of pulsar during the outburst
- Energy of fundamental cyclotron line constant with luminosity: line forming region does not change during the outburst...
  Pre-outburst spike??

- Outlook
  - More investigation is needed
  - Work still ongoing