Observation and appearance of magnetospheric instability in flaring activity at the onset of X-ray outbursts in A 0535+26

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Introduction

A0535+26

Transient Be/X-ray binary

- Type II outbursts (giant), $L_X > 10^{37} \mathrm{ergss}^{-1}$
- Type I (normal), associated with periastron, $L_X \sim 10^{36-37} \mathrm{ergss}^{-1}$
- quiescence states, persistent low luminosity, $L_X \lesssim 10^{36} \mathrm{ergss}^{-1}$

Discovered in 1975 during a giant outburst (Rosenberg et al. 1975)

Neutron star

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

HDE 245770 - O9.7, IIIe

- $14\mathrm{M}_\odot$, $14\mathrm{R}_\odot$
- $1.41 \times 10^5 \mathrm{L}_\odot$
- $T_{eff} = 26000\mathrm{K}$

- $P_{orb} = 111\mathrm{days}$, $e = 0.47$
- $d \sim 2\mathrm{kpc}$

Review: Giovannelli & Graziati 1992

Transient Source

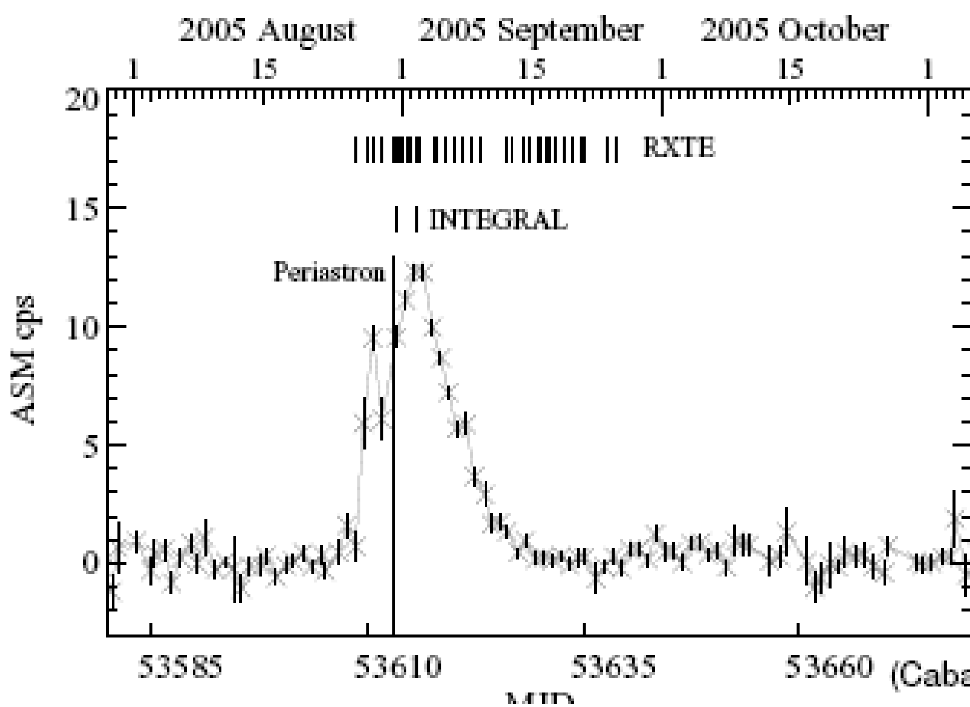
The source has shown 5 giant outbursts since its discovery

- 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!!

Transient Source

From 1994 until 2005 it has been in quiescence.

- May/June 2005: giant outburst, $L_{(15-195\mathrm{keV})} \sim 4.8 \times 10^{37} \mathrm{ergss}^{-1}$ (Tueller et al. 2005)
- Aug/Sept 2005: normal outburst, $L_{(15-195\mathrm{keV})} \sim 0.6 \times 10^{37} \mathrm{ergss}^{-1}$
- December 2005: normal outburst $L_{(15-195\mathrm{keV})} \sim 0.2 \times 10^{37} \mathrm{ergss}^{-1}$

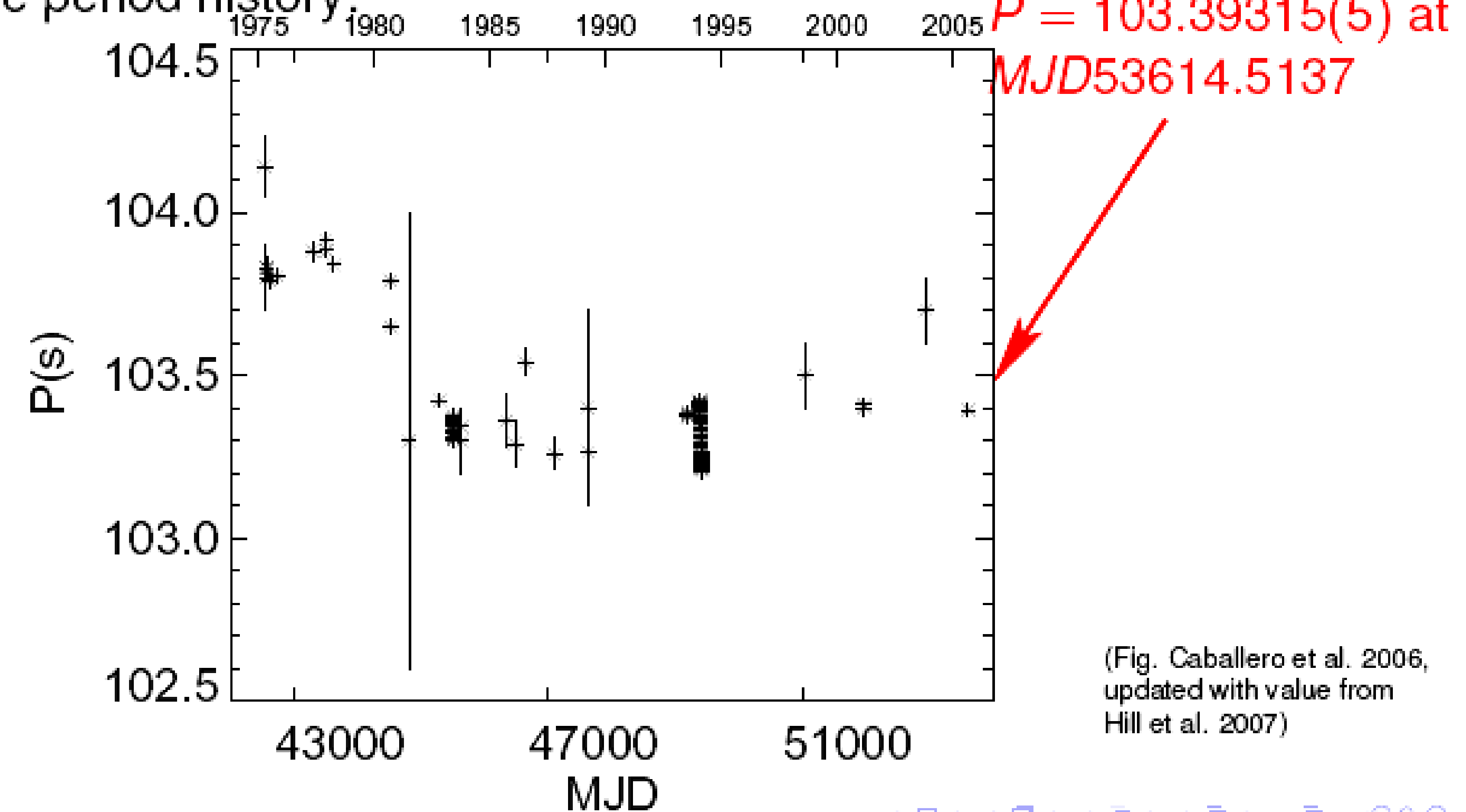


(Caballero et al. 2007)

Timing: pulse period search with INTEGRAL

Pulse period determined with high accuracy using IBIS-ISGRI data.

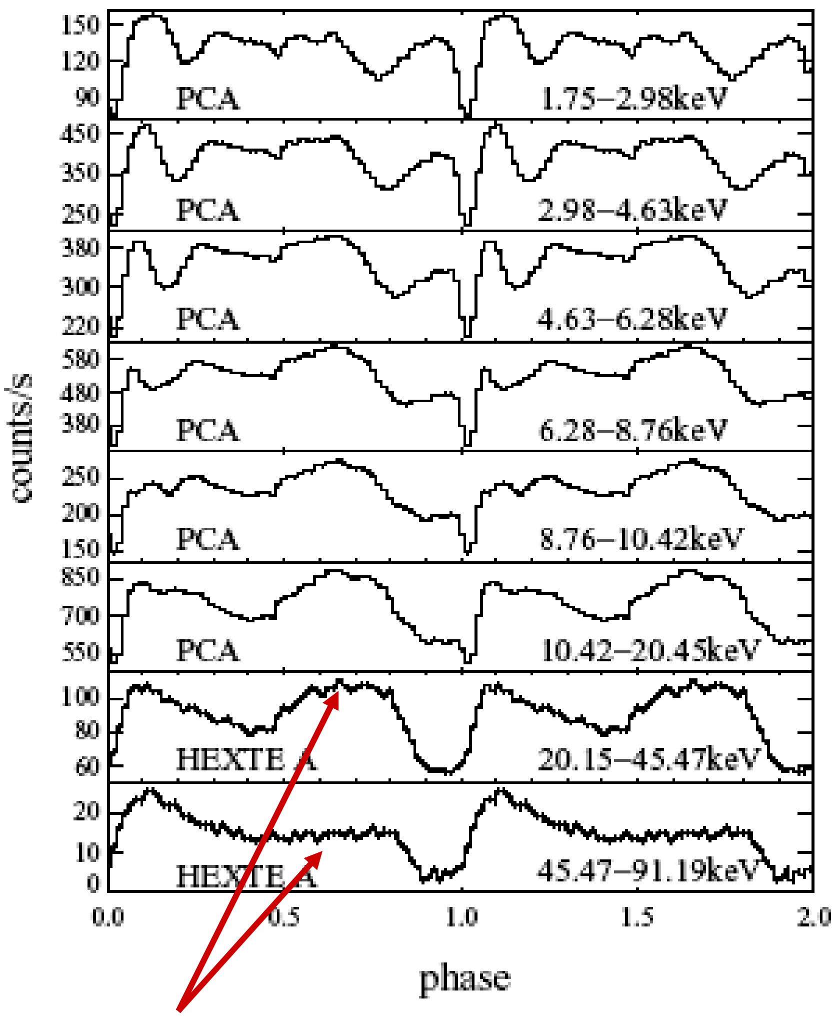
Pulse period history:



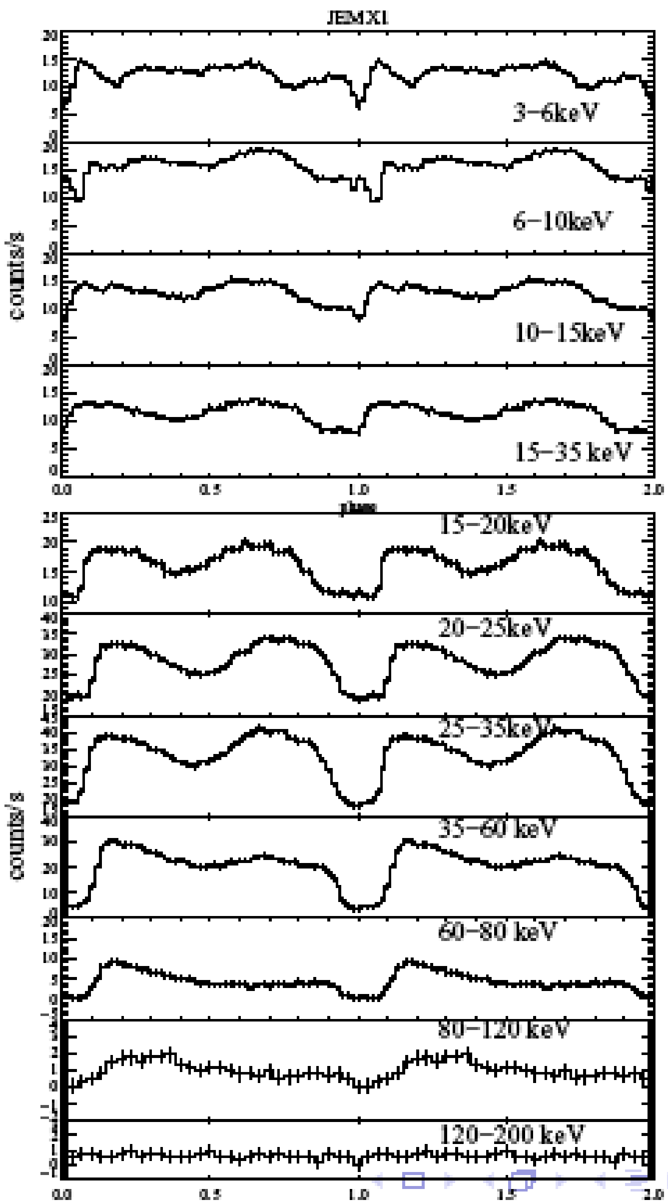
(Fig. Caballero et al. 2006, updated with value from Hill et al. 2007)

Timing: energy dependent pulse profiles

RXTE



INTEGRAL



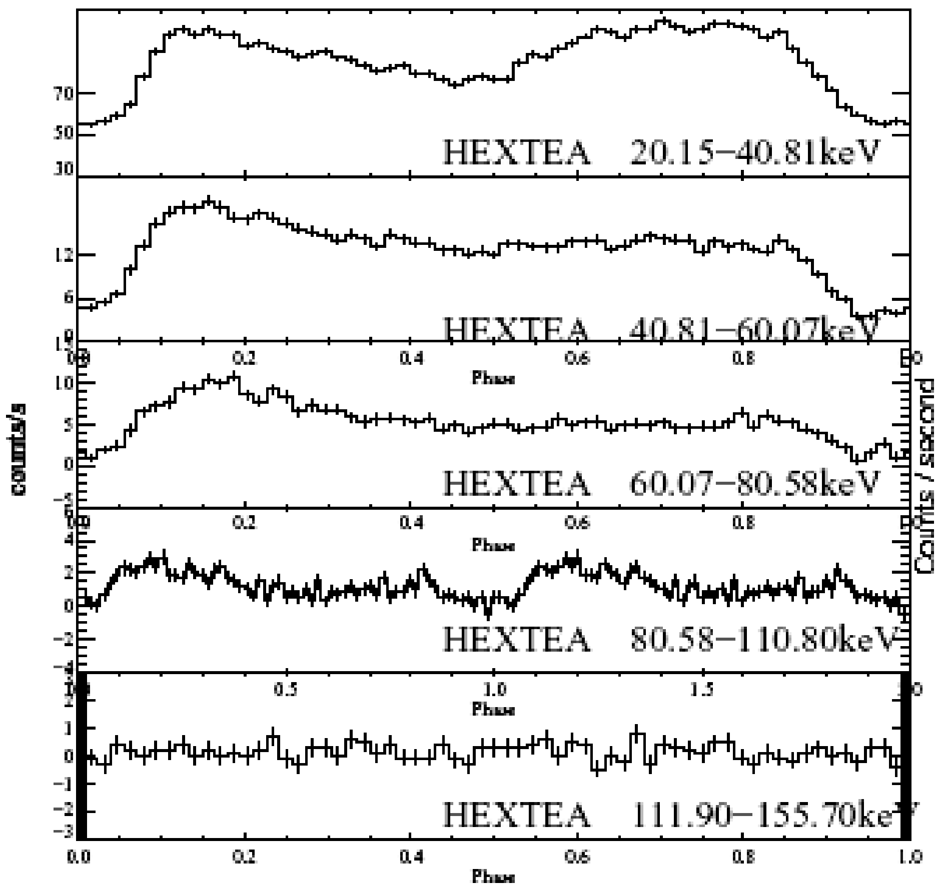
JEMX-1

IBIS

Timing: energy dependent pulse profiles

August/Sept.2005 normal outburst

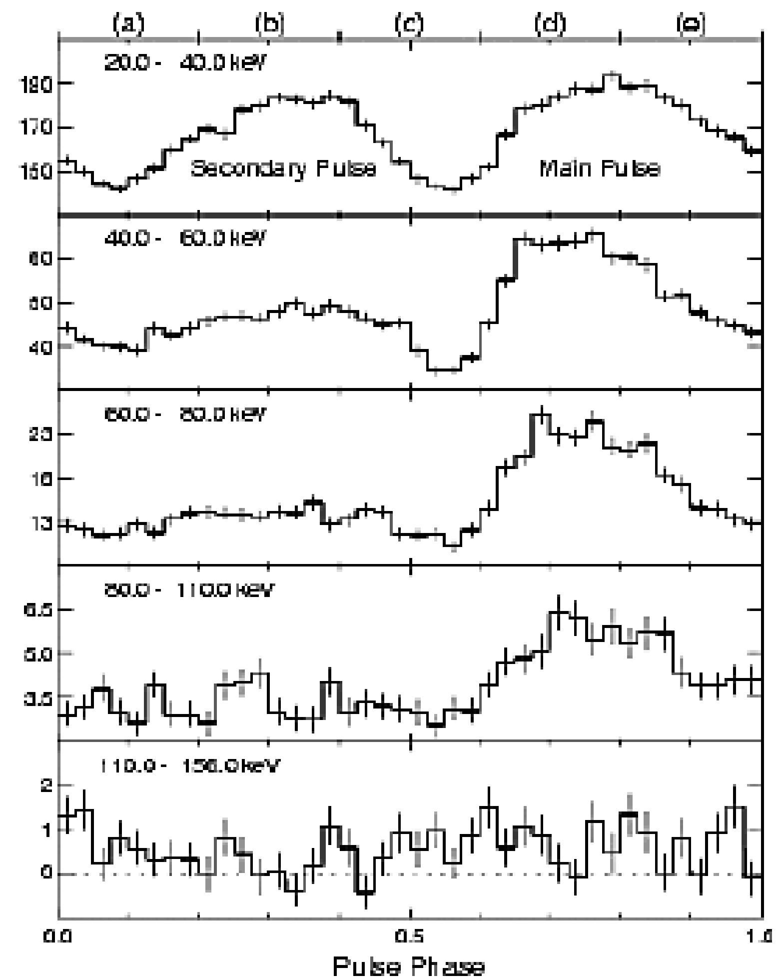
$L(23-53\mathrm{keV}) \sim 0.23 \times 10^{37} \mathrm{ergs}^{-1}$



March/April 1989 giant outburst

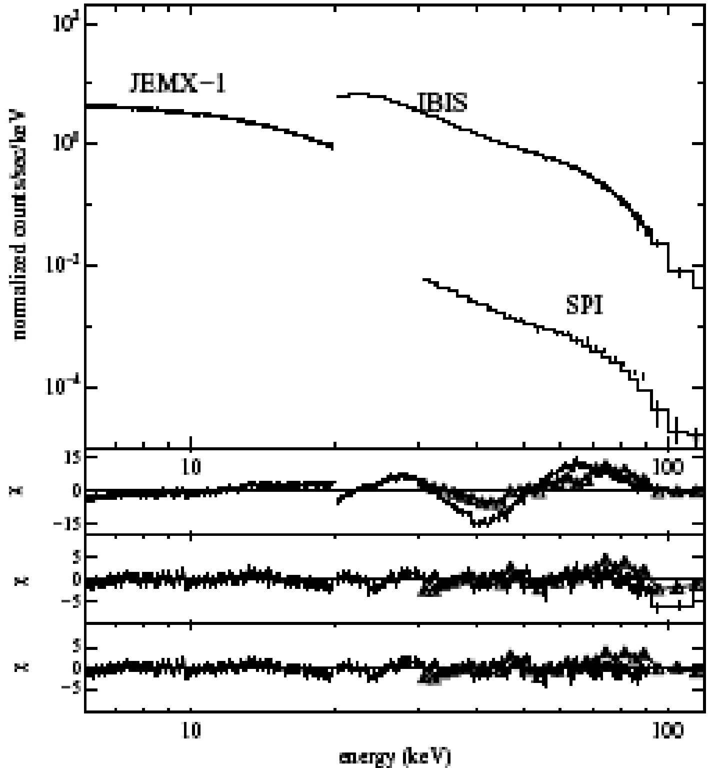
$L(23-53\mathrm{keV}) \sim 1.26 \times 10^{37} \mathrm{ergs}^{-1}$

TTM/HEXE observations (Kendziorra et al. 1994)

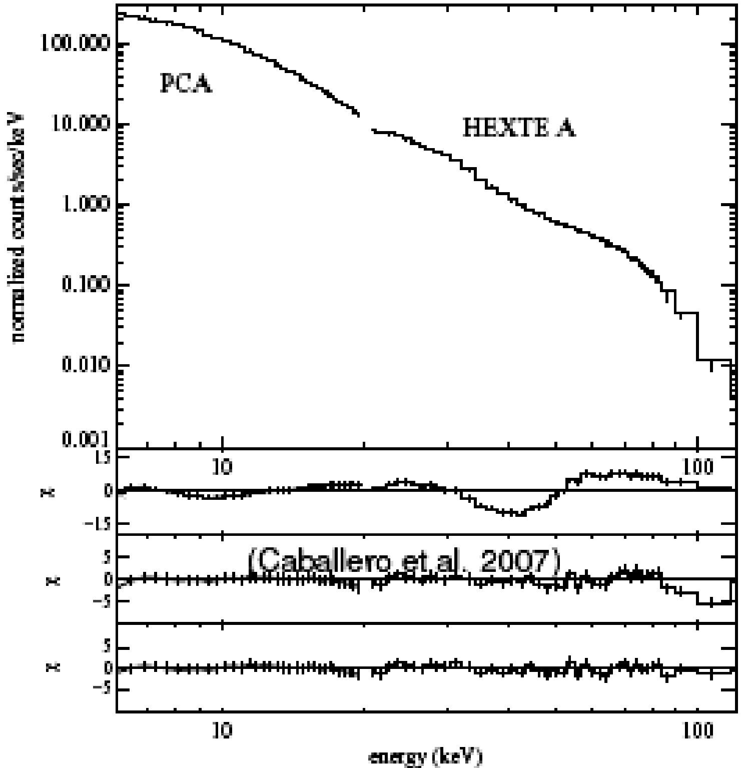


X-ray spectra: fundamental cyclotron line at 45keV

INTEGRAL



RXTE



$E_1 = 45.9^{+0.3}_{-0.3}\mathrm{keV}$

$E_2 = 102^{+4}_{-3}\mathrm{keV}$

$E_1 = 45.9^{+0.4}_{-0.3}\mathrm{keV}$

$E_2 = 103^{+3}_{-3}\mathrm{keV}$

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

Result confirmed by Suzaku (Terada et al. 2006): $E_1 = 46.3 \pm 1.5\mathrm{keV}$

X-ray spectra: Cyclotron line evolution with luminosity

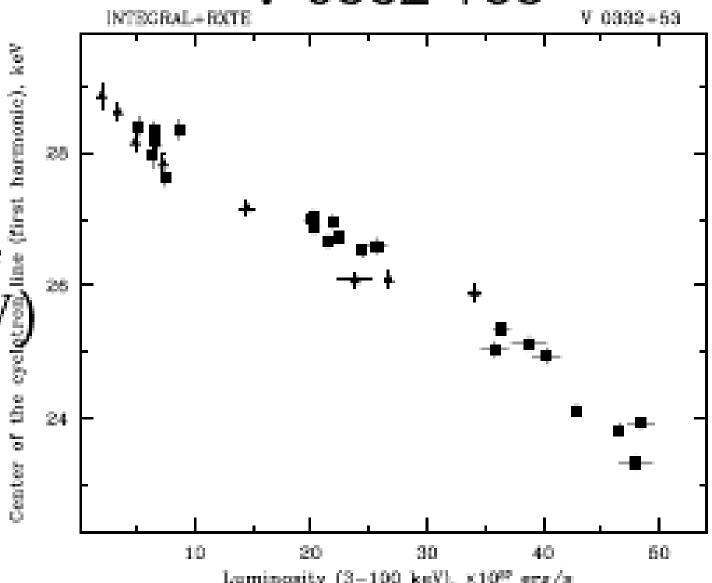
super-Eddington regime
High accretion rates
Shock formation in accretion column
Height of schock $\propto \dot{m}$

sub-Eddington regime
Low accretion rates
No shock is formed

(Basko & Sunyaev 1976)

V 0332 +53

E_{cyc} (keV)

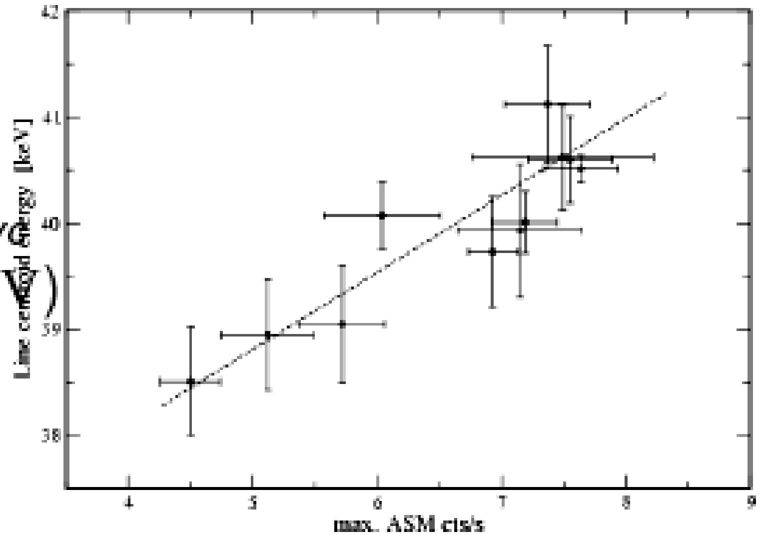


$L_{(3-100\mathrm{keV})} \times 10^{37} \mathrm{ergs}^{-1}$

(Tsygankov et al., 2006)

Her X-1

E_{cyc} (keV)



$\mathrm{max.ASMcts/s}$

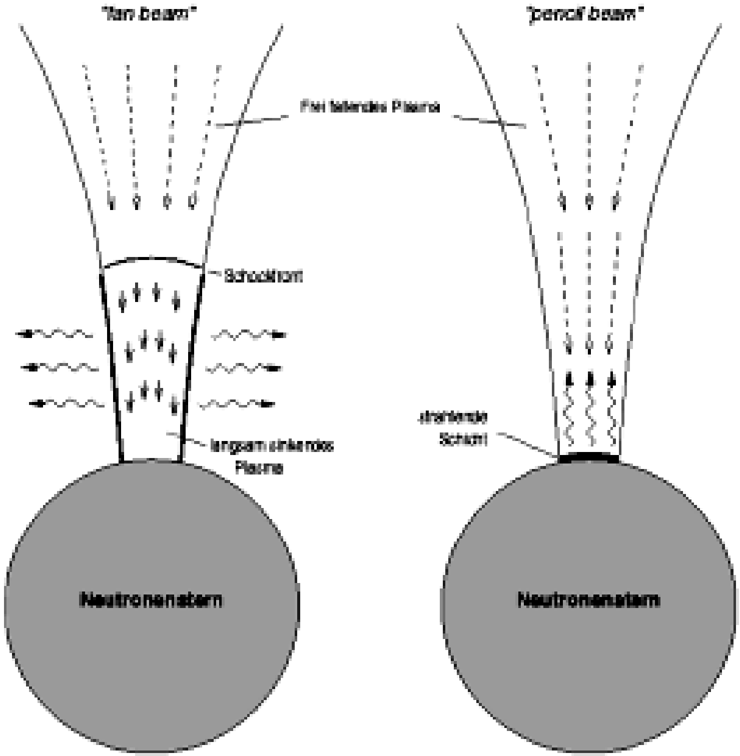
(Staubert et al., 2007)

Accretion columns

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

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

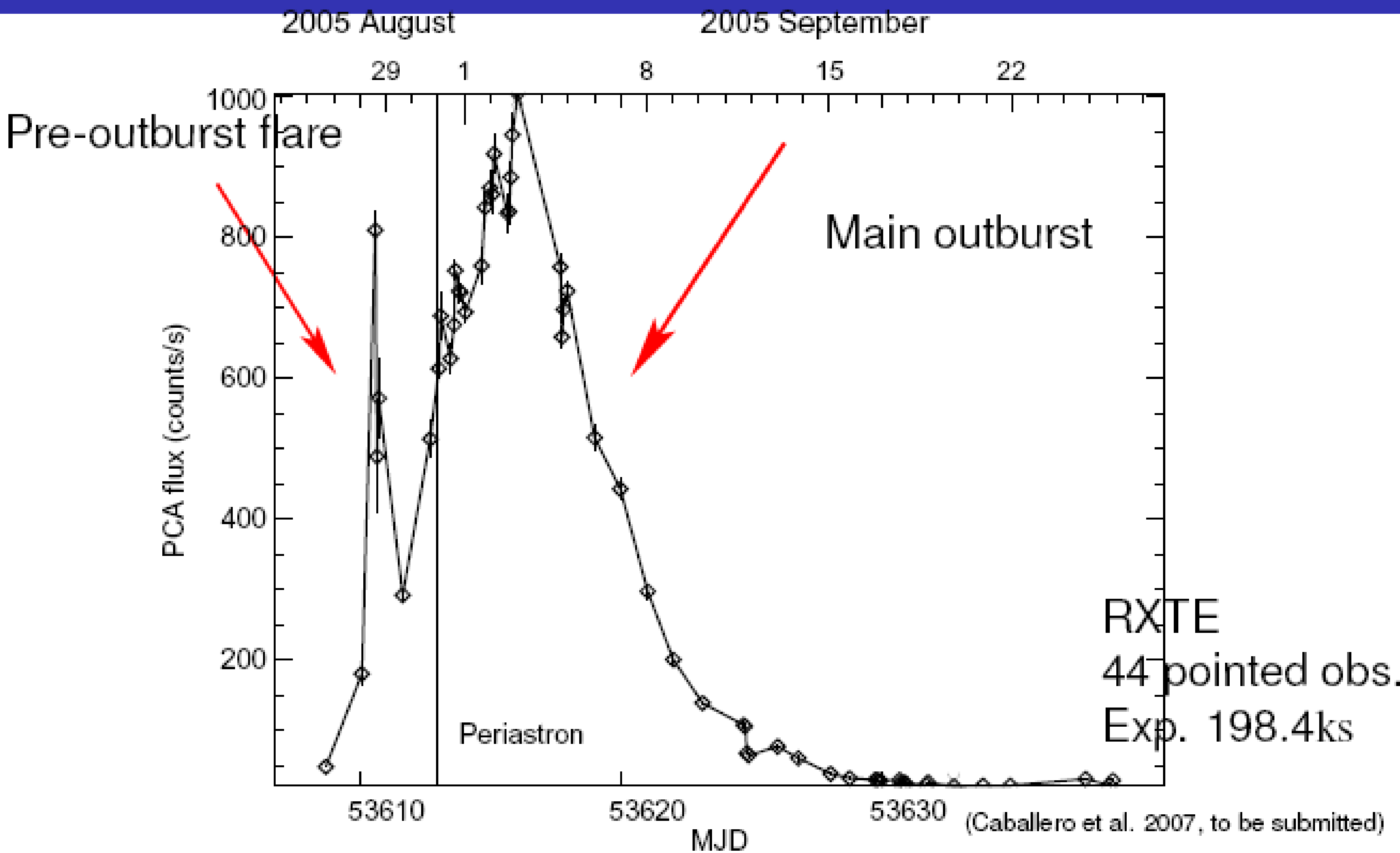
High accretion rates



Low accretion rates

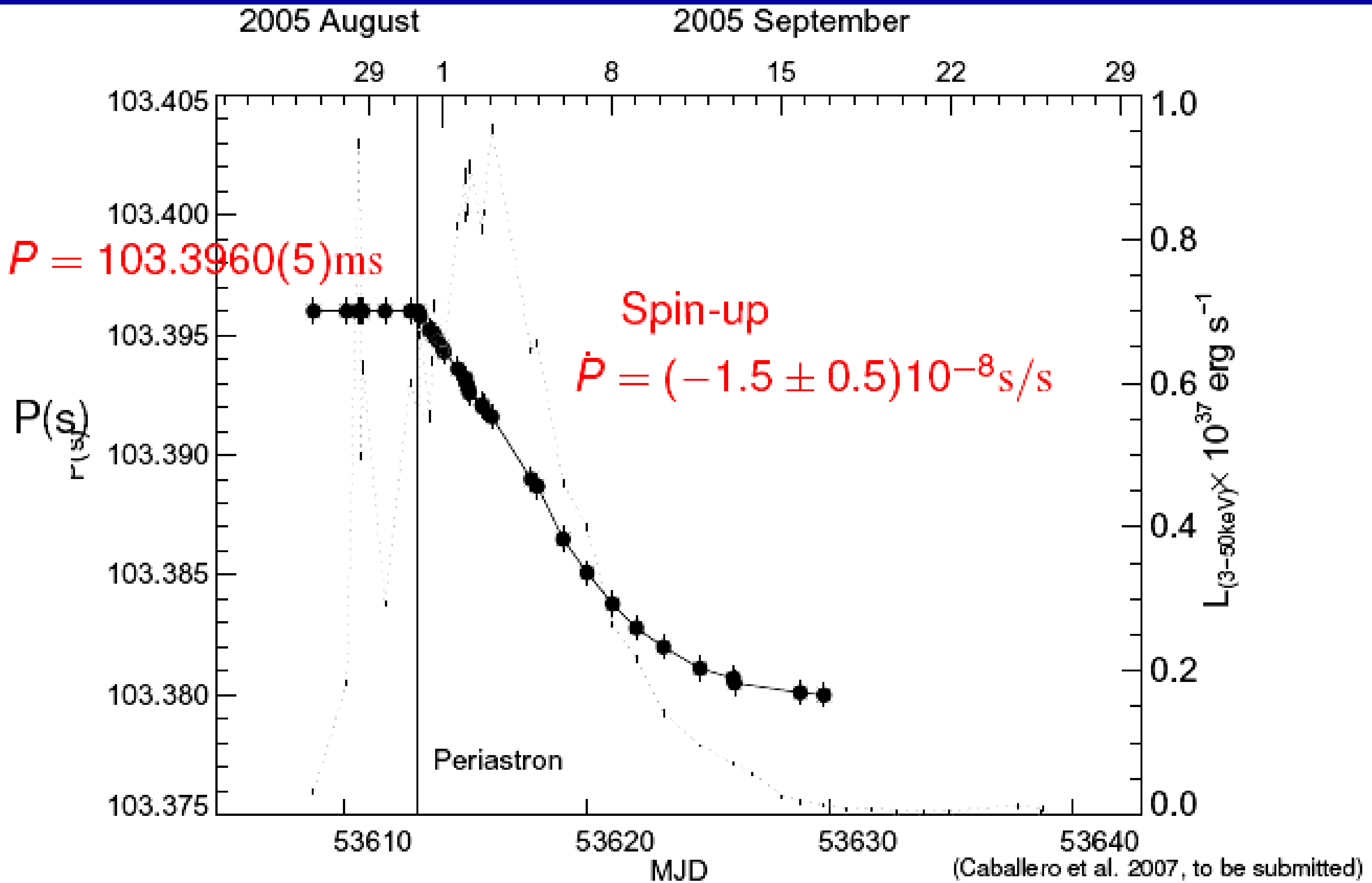
(Kretschmar, 1996 after Harding, 1994)

Evolution of timing and spectral parameters during the outburst - RXTE



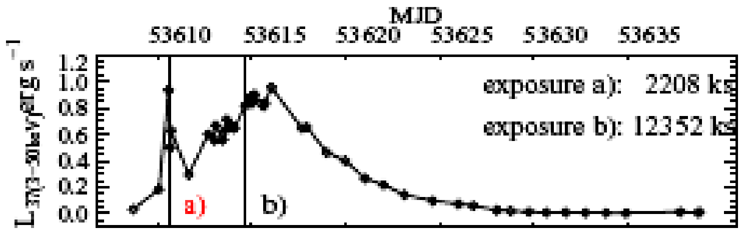
(Caballero et al. 2007, to be submitted)

Pulse period evolution



Pulse profiles evolution

Strong variation of energy dependent pulse profiles



a) FLARE b) NEAR MAXIMUM

PCA 1.75 – 2.98keV

PCA 2.98 – 4.63keV

PCA 4.63 – 6.28keV

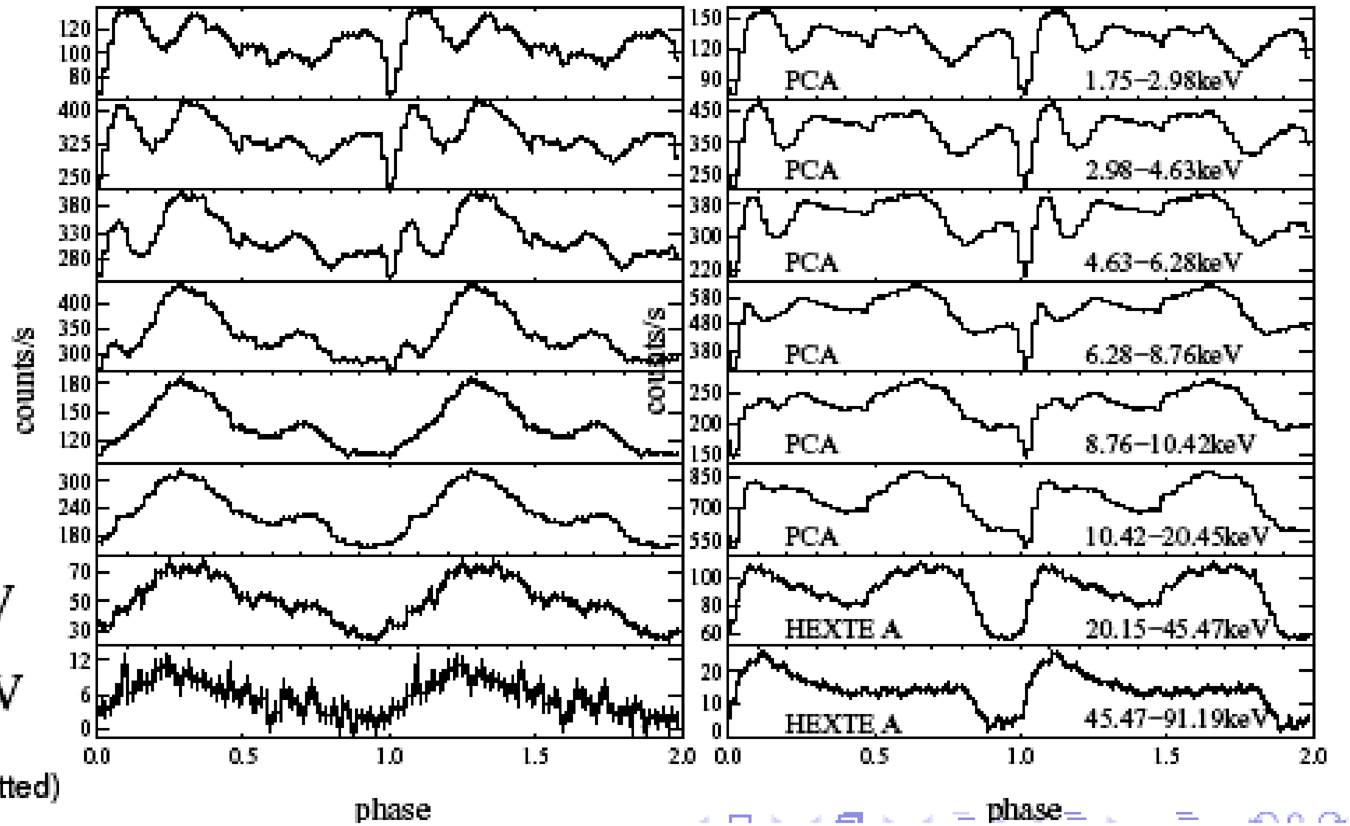
PCA 6.28 – 8.76keV

PCA 8.76 – 10.42keV

PCA 10.42 – 20.45keV

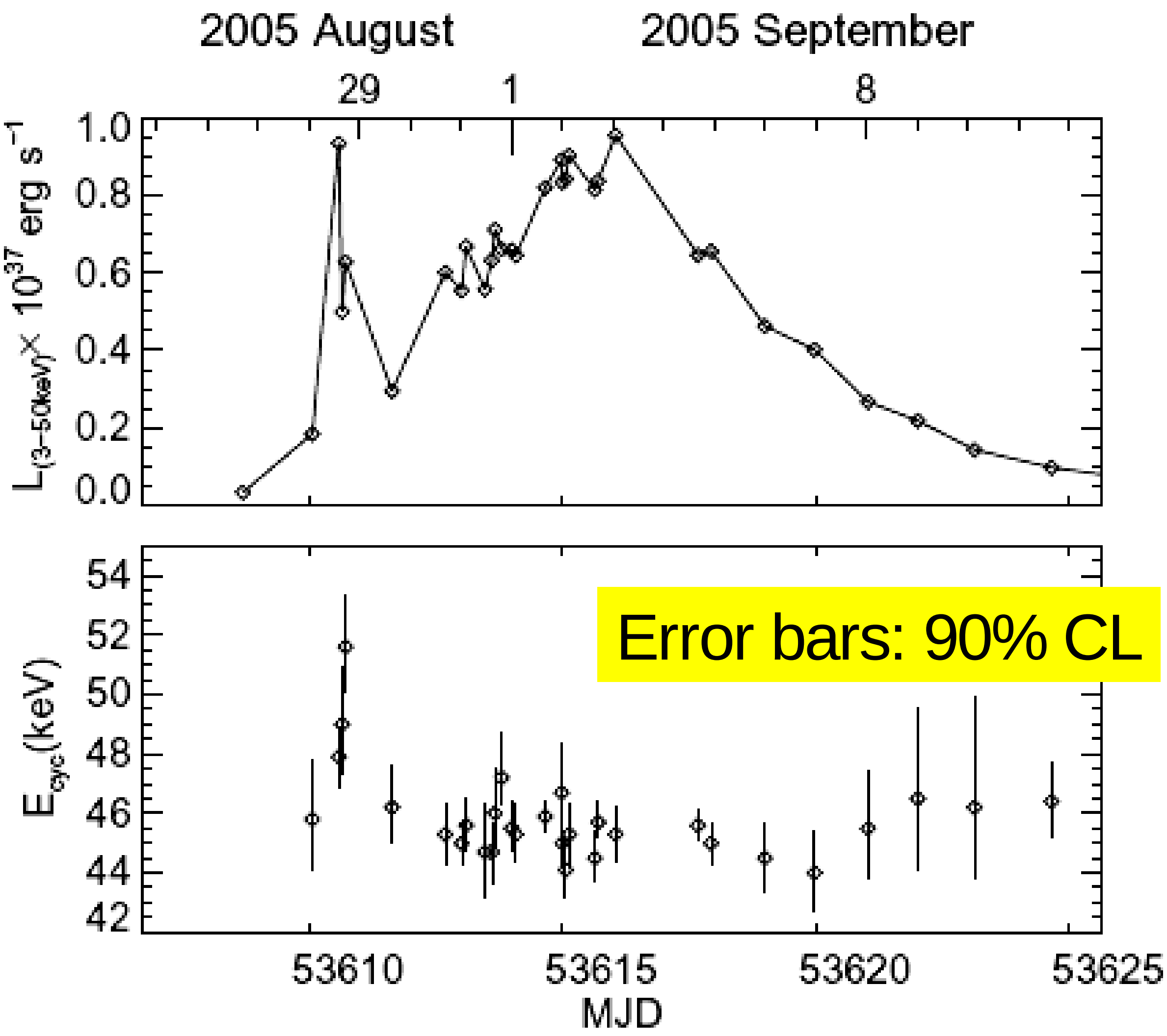
HEXTE A 20.15 – 45.47keV

HEXTE A 45.47 – 91.19keV



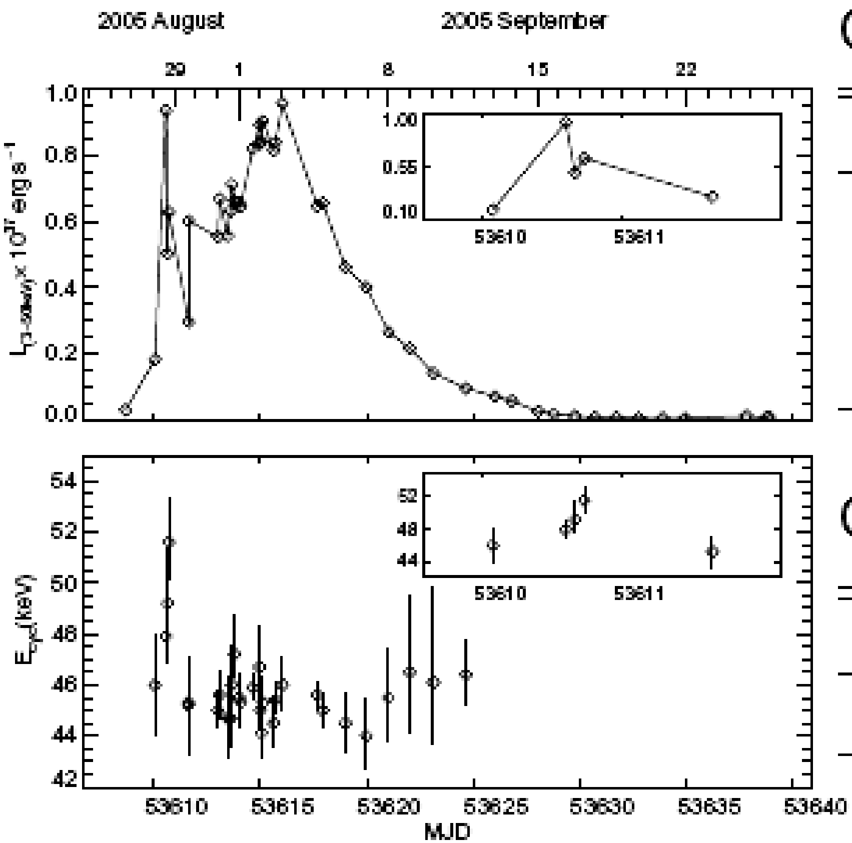
(Caballero et al. 2007, to be submitted)

Spectral evolution - cyclotron energy



Spectral evolution: cyclotron line energy

During the pre-periastron flare the energy of the centroid of the cyclotron line is measured at a higher position



Observations flare

E_{fund} (keV)	$L_{(3-50\mathrm{keV})} \times 10^{37} \mathrm{erg s}^{-1}$
$47.9^{+1.0}_{-1.0}$	0.94
$49.2^{+2.1}_{-1.6}$	0.50
$51.6^{+1.7}_{-1.5}$	0.63

Obs. close to maximum main outburst

E_{fund} (keV)	$L_{(3-50\mathrm{keV})} \times 10^{37} \mathrm{erg s}^{-1}$
$45.9^{+0.4}_{-0.3}$	0.82

(errors 90% confidence)

(Caballero et al. 2007, to be submitted)

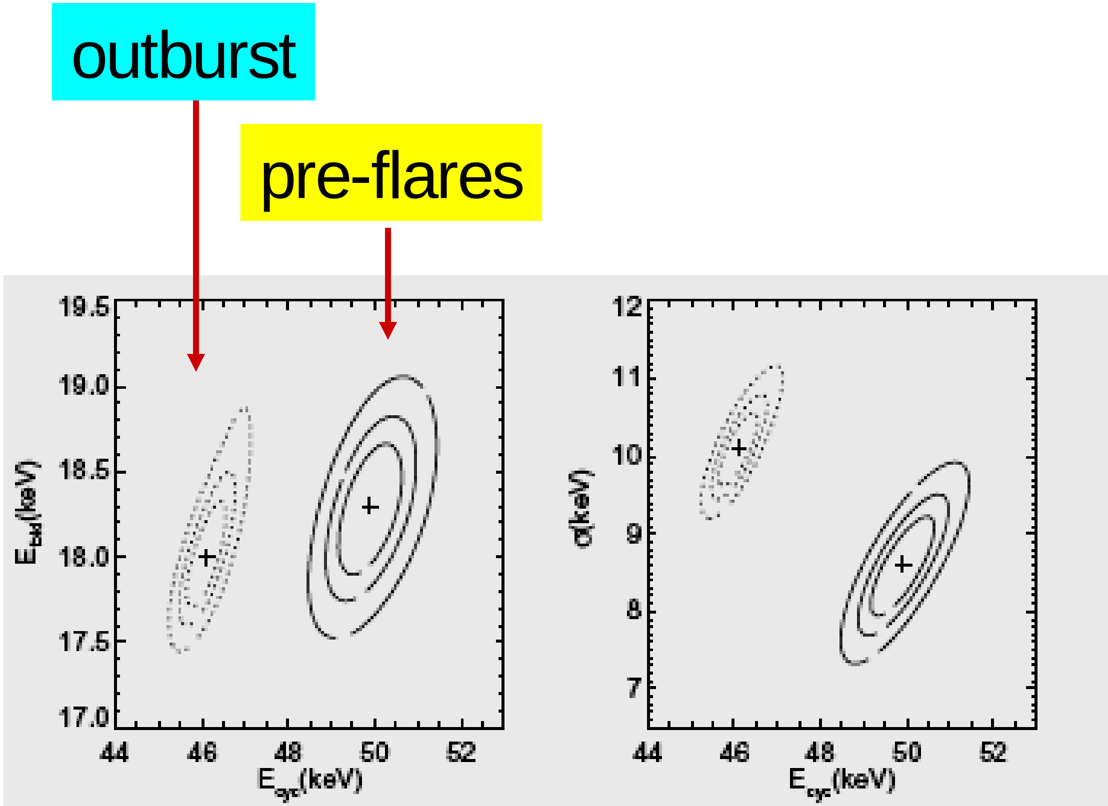
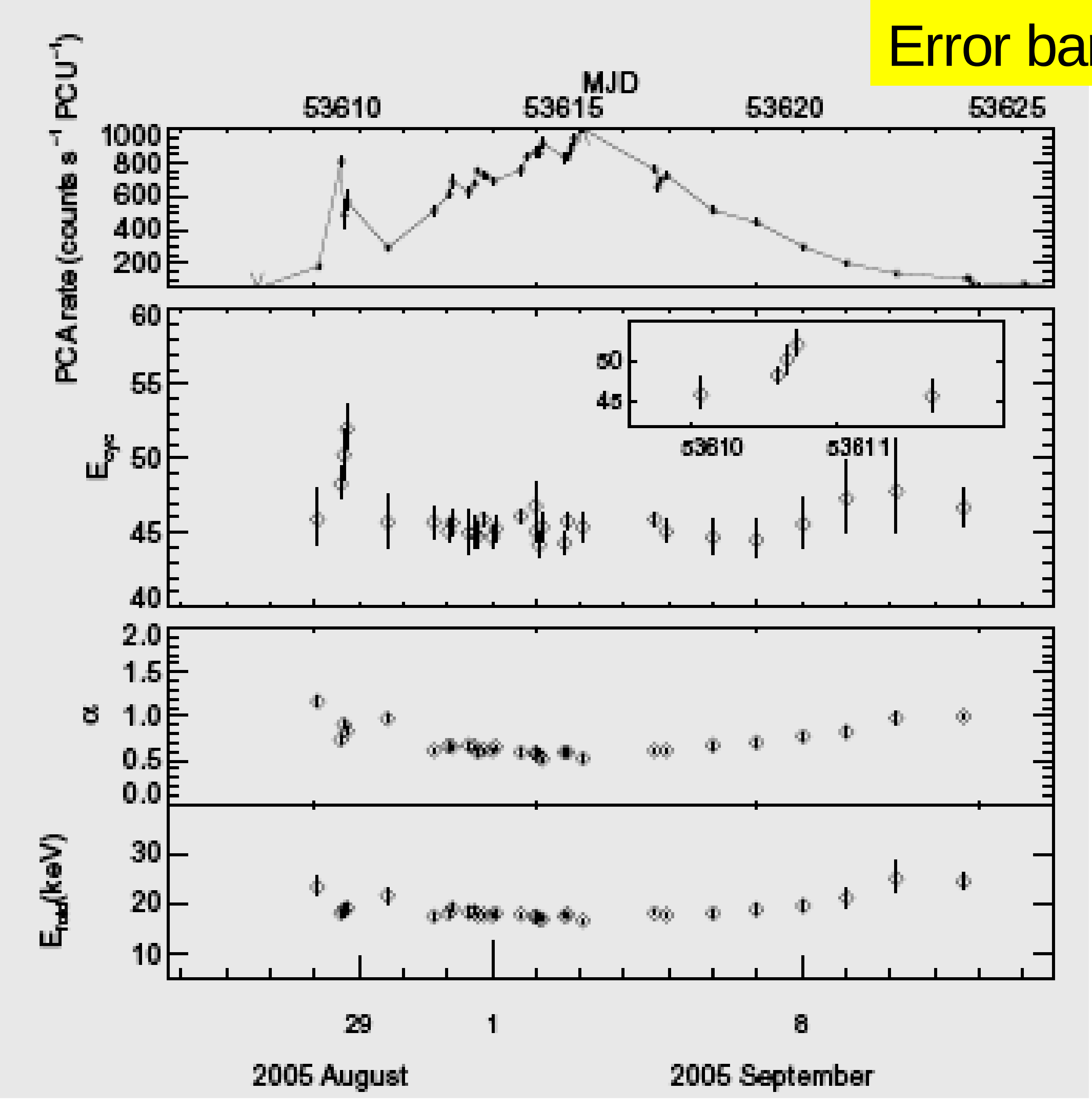


Fig. 3. $E_{\rm fold}$ vs $E_{\rm cyc}$ (left) and σ vs $E_{\rm cyc}$ (right) contour plots for one observation near the maximum (dotted lines, observation (b) in Fig. 2) and for the sum of the three available observations during the pre-outburst flare (solid lines). The contours indicate $\chi^2_{\rm min}$+2.30(68%), 4.61(90%), 9.21(99%) levels.

Spectral evolution: photon index -cutoff energy

Error bars: 90% CL

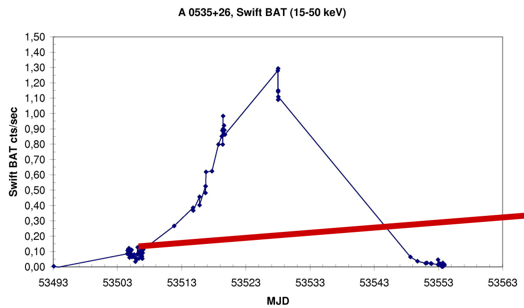


Summary of the RXTE/INTEGRAL analysis

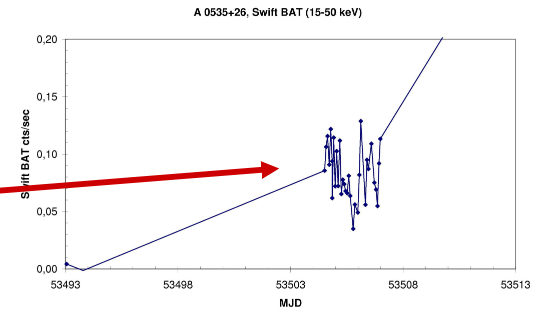
- Fundamental cyclotron line measured at $\sim 45\mathrm{keV}$ with INTEGRAL, RXTE. Result confirmed by Suzaku
- THREE MAIN DIFFERENCES PRE OUTBURST FLARE - MAIN OUTBURST
- **Constant period during pre-periastron flare Spin-up starts at periastron**
- **Strong pulse profile variation during the pre-periastron flare and the main outburst**
- **Centroid of cyclotron line higher during the pre-periastron flare, constant during the main outburst**

Swift BAT light curves

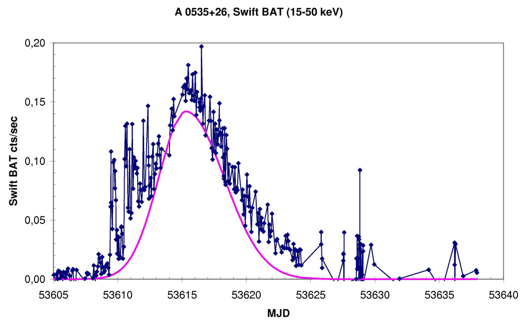
Giant o. Apr/May 05



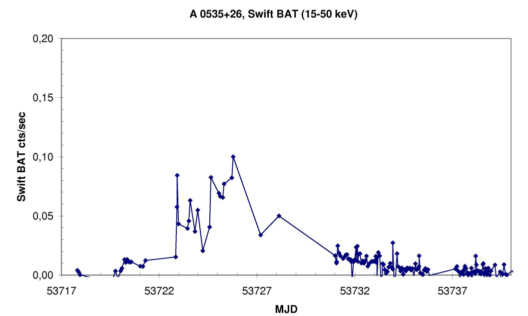
Look-up



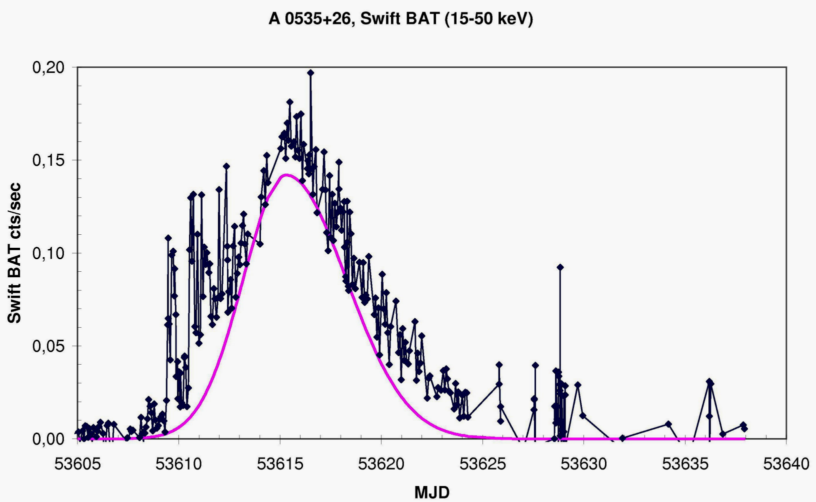
1st normal o. Aug/Sep 05

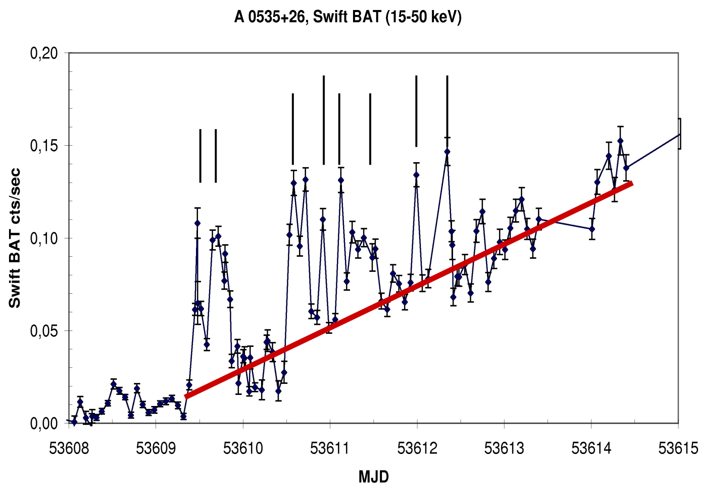


2nd normal o. Dec 05



Rising of the Aug/Sep 2005 outburst



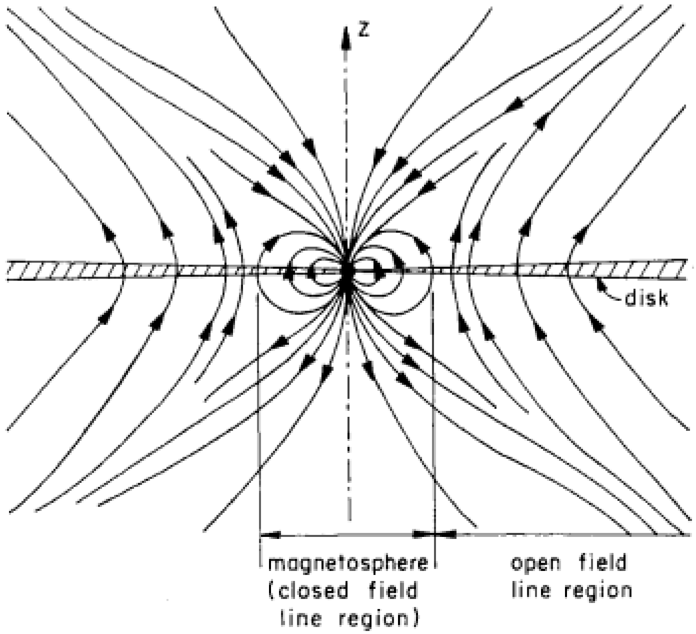


$$\Delta t = 10^4 - 3 \times 10^4 \, s$$

Typical mass in X-ray flares:

$$\Delta M = \Delta E / (0.1 c^2) \approx 3 \times 10^{20} - 10^{21} \, \mathrm{g}$$

Disk-magnetospheric interaction



Boundary layer:

$<20 c_s / \omega_K$ (Anzer & Boerner, 1983)

$\sim 5 c_s / \omega_K$ (Lovelace et al. 1995)

Lovelace et al. 1995

Estimate of mass in the boundary layer:

$$\Delta \approx h \sim 0.1 R_m$$

Standard Shakura-Sunyaev accretion disk:

$$\Delta M = \rho (2\pi R_m) \times \Delta \times 2h\ ;$$

$$(2 \times 10^{19}\,\mathrm{g})\ r_{m,9}^{7/5} \alpha^{-4/5} \dot{M}_{-10}^{3/5} (1 \quad \xi)^{3/5}$$

$$\xi = j / j_{in}, \qquad j = \dot{M}\sqrt{GMr}$$

At the beginning of outburst $\xi \approx 0$

$\alpha \sim 0.01,\ \dot{M}_{-10} \sim 3$ ⇒ $M \sim 10^{21}\,\mathrm{g}$

Disc accretion - Magnetospheric instabilities

For low accretion rates, Kruskal-Schwarschild instability can occur: plasma enters the magnetosphere in form of bubbles that fall onto the NS.

See Postnov et al 2007
Baan 1979
Fig. Arons & Lea 1976

Development of the instabilities

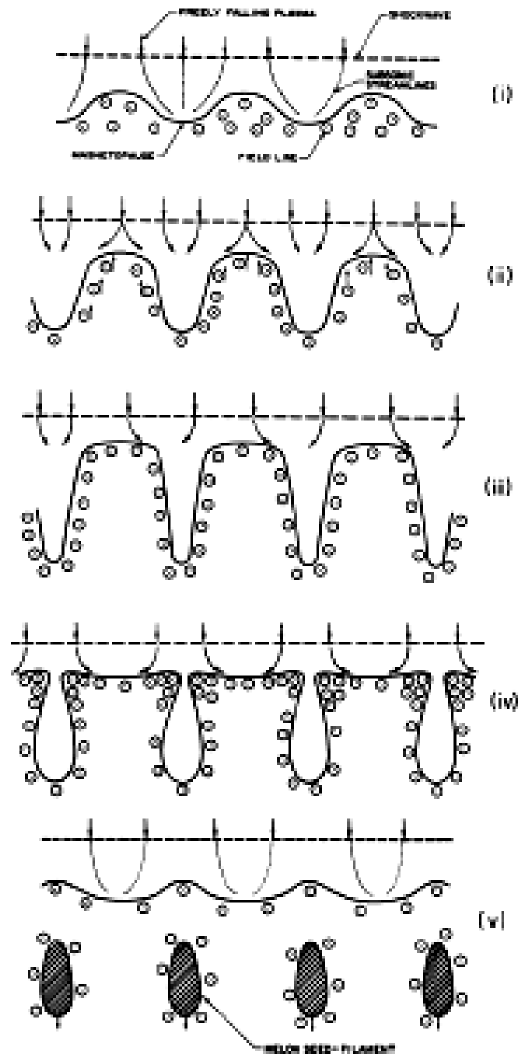


FIG. 4.—Cross section of the development of the interchange instability. (i) Initial nonlinear growth into the hydrostatic layer.

Linear analysis (Arons & Lea, 1976, Baan 1977, 79):

$$\delta\rho : \ \exp(\Gamma t),$$

$$\Gamma^2 = k g_{eff} \tanh(kz)$$

The effective acceleration near the equatorial plane:

$$g_{eff} \cong \frac{GM}{r_m^2} - \Omega^2 r_m - \frac{(\mathbf{k}\ \mathbf{Bu})^2}{4\pi\rho_m k r_m^6} - \frac{3\mu^2}{4\pi\rho_m R_c r_m^6} - \frac{\delta k \mu^2}{4\pi\rho_m r_m^6} - \frac{\Omega r_m}{4}\left|\frac{dV_\phi}{dz}\right|_{r_m}$$

Centrifug. force

m.f.line curvature

Bending of field lines due to instability

1st-order correction due to current sheet

$g_{eff} > 0$ ч instability; low-modes (large k) first instable

$g_{eff} < 0$ ч stability

At small $\dot{M}$, accretion is centrifugally prohibited

$$(R_m > r_{cor} = (GM/\omega_*^2)^{1/3}). \; g_{eff} \cong \frac{GM}{R_m^2}(1-\omega_*^2/\omega_K^2) < 0$$

When $\dot{M}$ increases, $R_m \propto \dot{M}^{-2/7}$ decreases

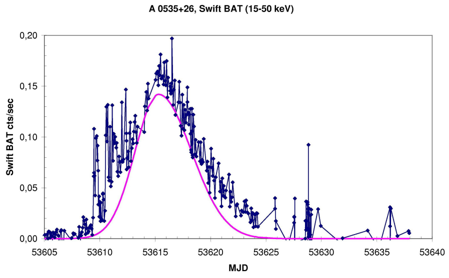
A the onset of accretion (when $R_m < R_{cor}$) g_{eff} can be positive $\Rightarrow$

unstable magnetospheric accretion can occur

(like in the rapid burster MXB 1730-335)

How does this explain the observed features of Aug/Sep 05 outburst?

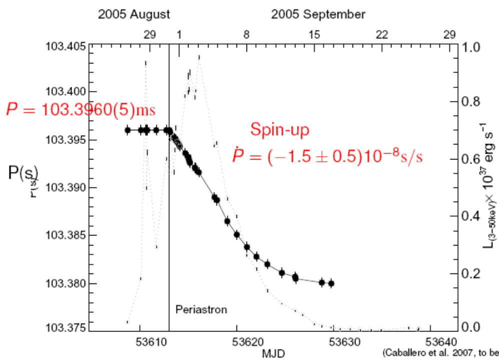
1)X-ray luminosity of flares are due to spasmodic accretion of matter from unstable NS magnetosphere



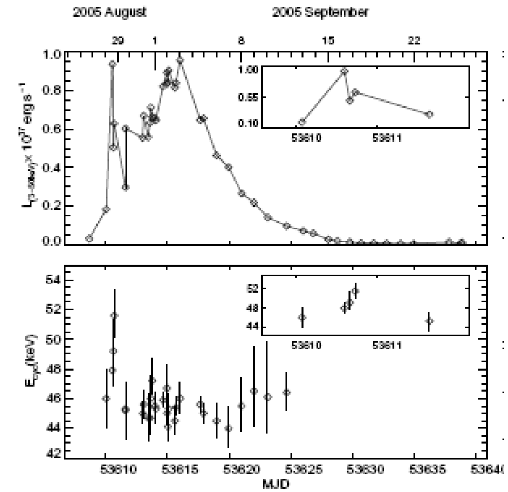
2) Blobs with $\Delta M \sim 10^{21}$g produce very small spin-up

$$\left|\frac{\Delta \mathrm{P}}{\mathrm{P}}\right|_{\max} = \frac{\Delta M\sqrt{GMR_m}}{2\pi I} \sim 7\times 10^{-6},$$

within period measurement errors



3) Plasma entering magnetosphere through KS-instability can be frozen closer to NS and falls along different lines   difference in the CRSF in flares and the main outburst

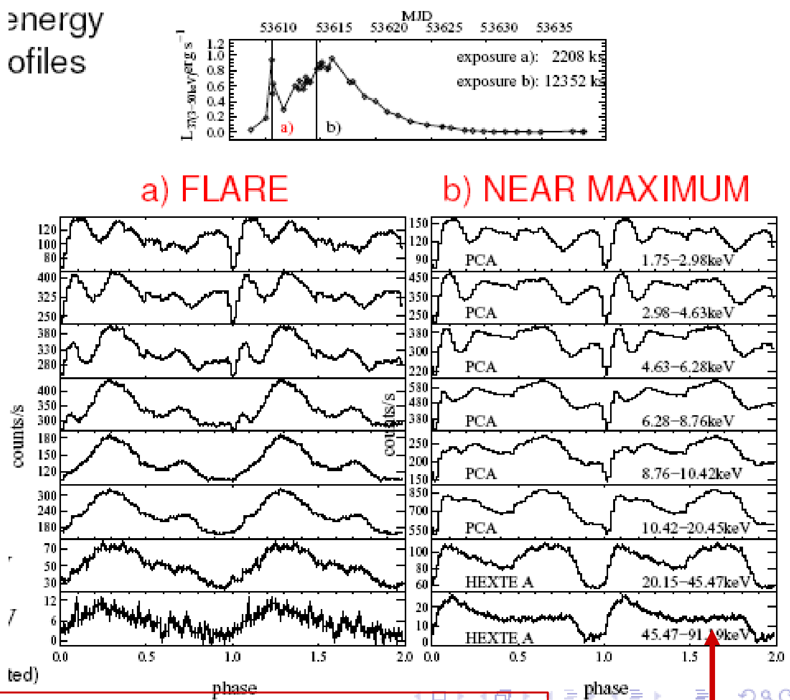


4) Independence of E_c on luminosity during the main outburst suggests the absence of radiation-dominated accretion column (like in Her X-1, Staubert et al. 2007). $\Delta E_c/E_c$~10% in the flare $\Delta B/B$~10% $\Delta R/R$~3% ΔR~300 m! Emission during the flare comes almost from the NS surface.

Explanation of the different pulse profile evolution

5) Smooth p.p. change with energy in the flare suggests pencil-beam emission diagram in the flares.

In the main outburst accretion column is higher and can have additional fan-beam formed by e-photons.



Only pencil-beam ?

Fan-beam due to e-photons disappears after crossing E_c

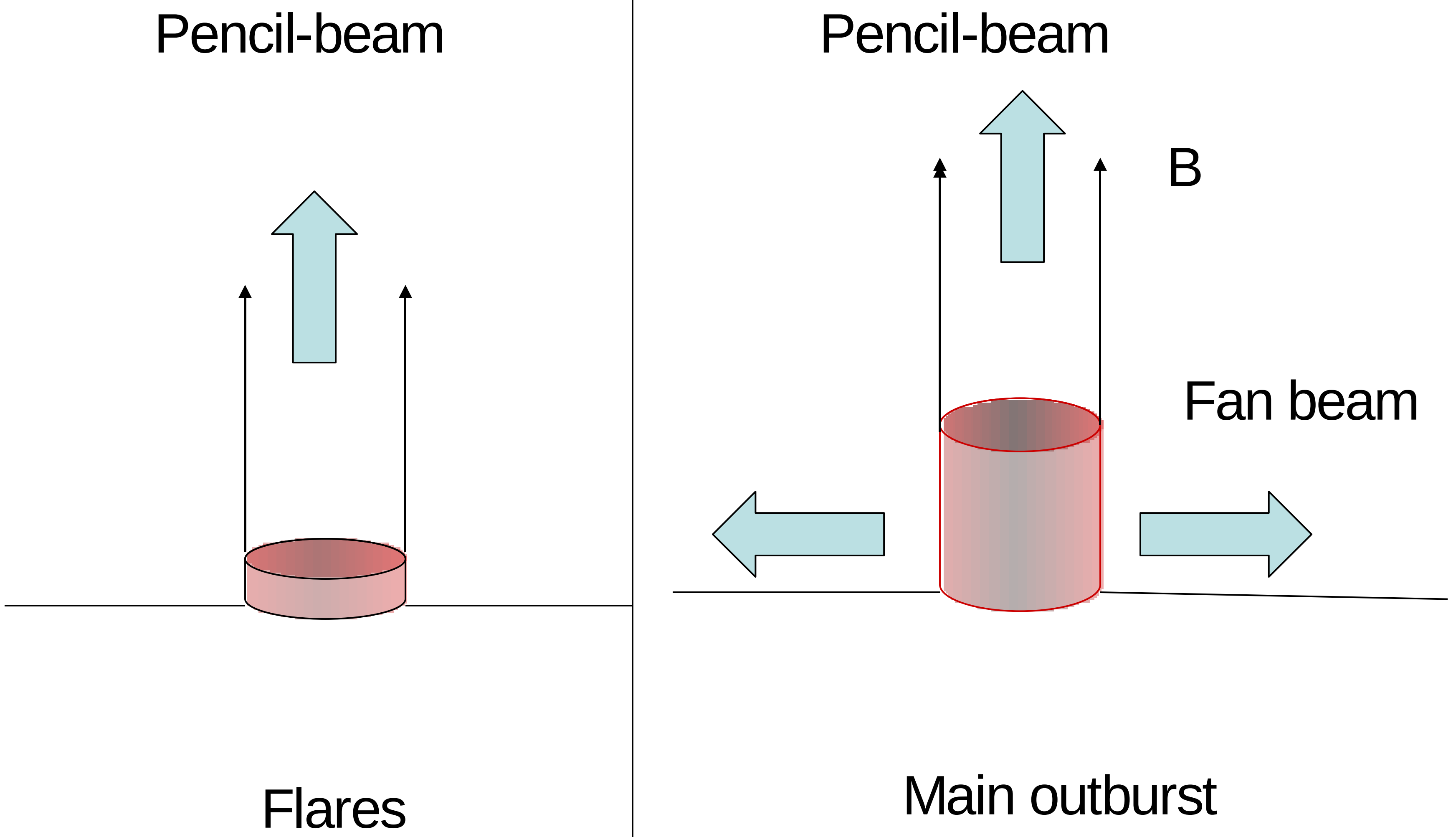
$$E = E_c :$$

$$\sigma_P \approx \sigma_T (E/E_c)^2 \quad (e)$$

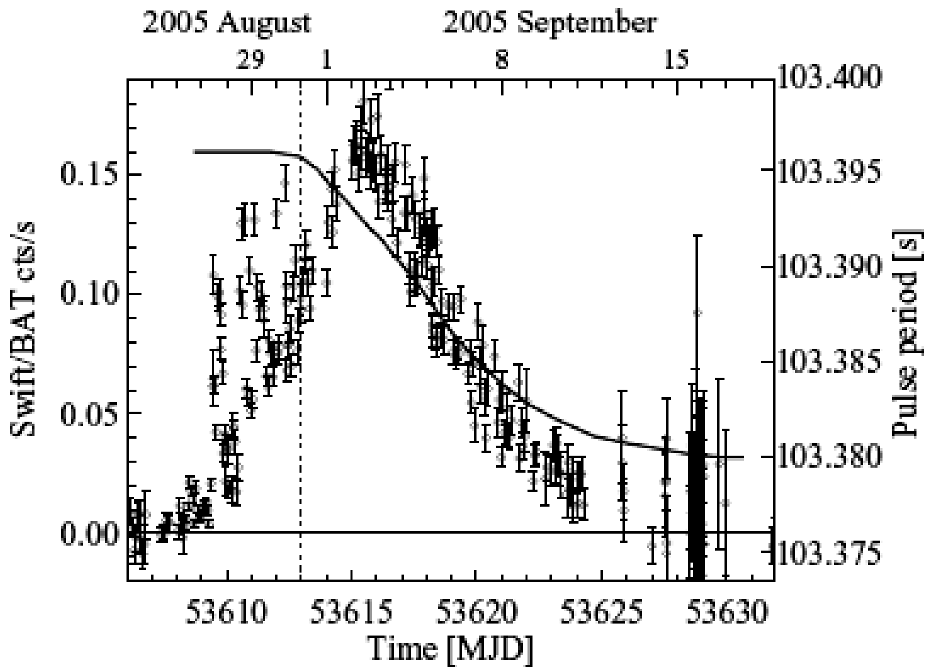
$$\sigma_\perp \approx \sigma_T \left[\sin^2\theta + \cos^2\theta (E/E_c)^2\right] (o)$$

$$\Rightarrow \quad \sigma_P = \sigma_\perp \quad @ \quad \theta \sim \pi/2$$

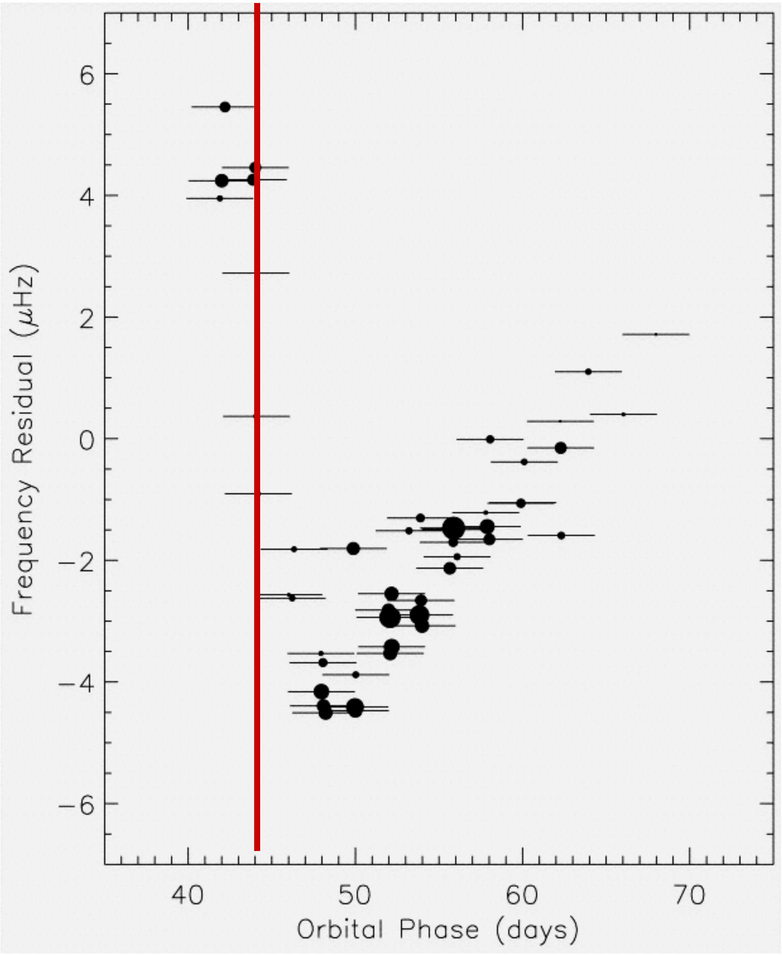
$$E \neq E_c : \ \sigma_\perp \sim \sigma_P @ \ \theta \sim \pi/2$$

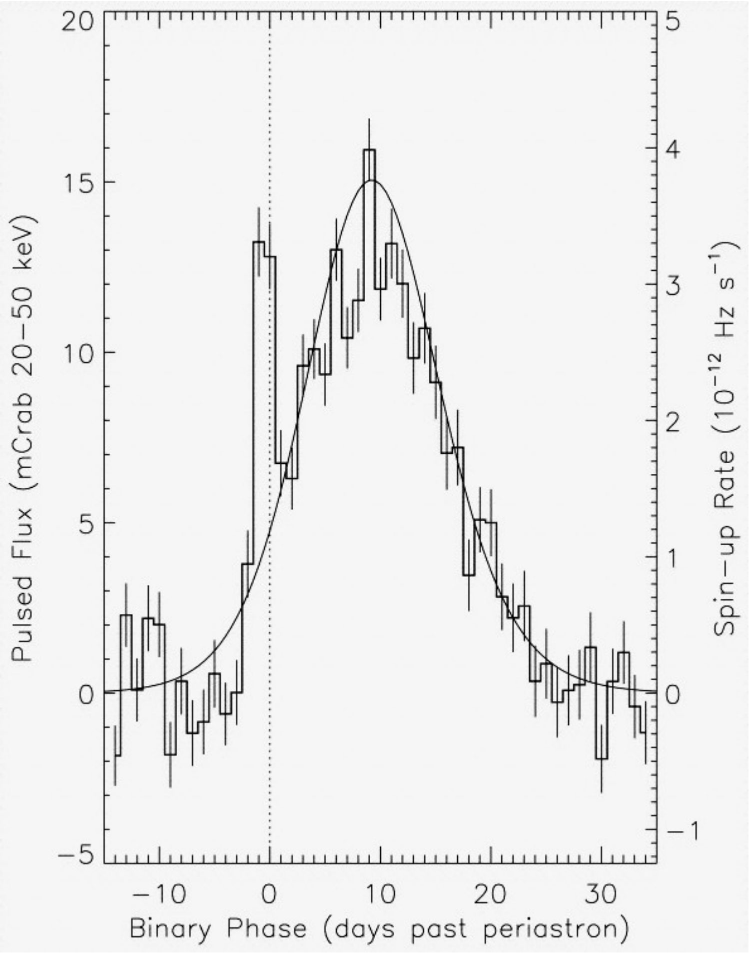

Pencil-beam
Flares
Pencil-beam
B
Fan beam
Main outburst

6. The amplitude of X-ray flares are strongly reduced when the NS spin-up starts, because then $\xi = j/j_{in} \to 1$ and the mass in the boundary layer decreases ($\Delta M \sim (1-\xi)^{3/5}$). When spin-up stops, flaring activity appears again (after Sep. 14, see the BAT light curve)



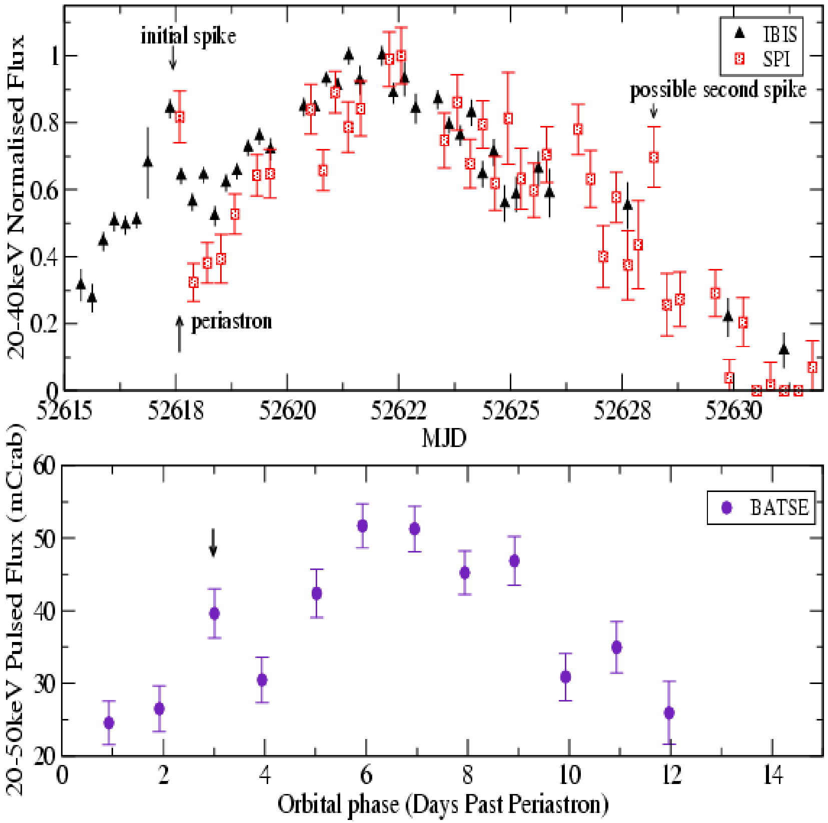
Other X-ray transients:
1) 2S 1845-024

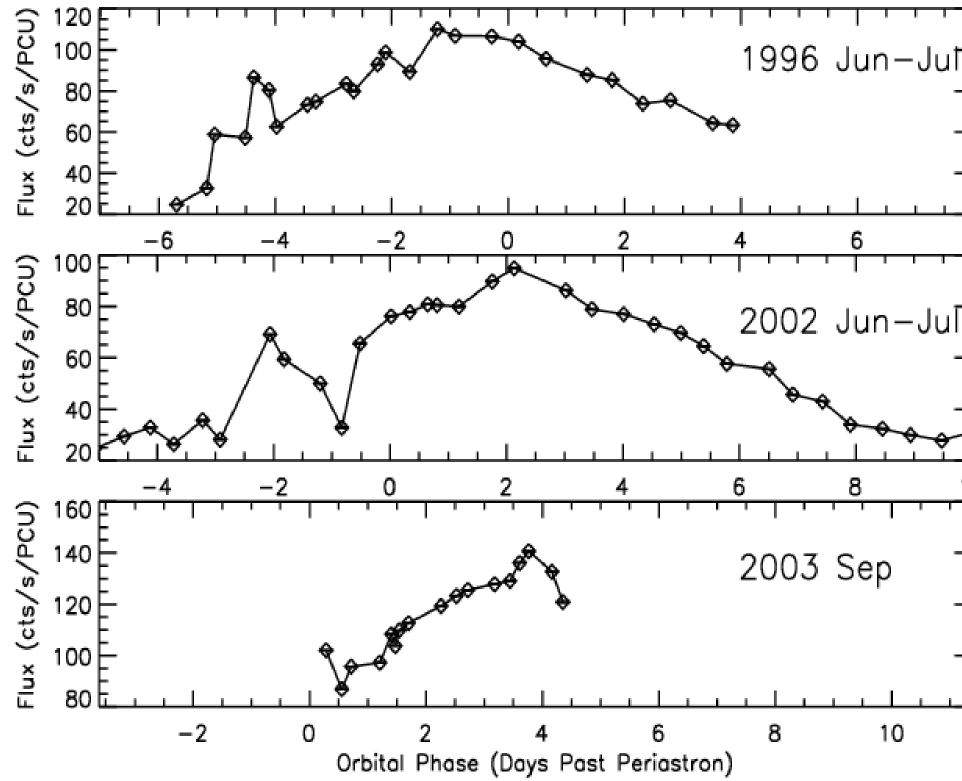




Finger et al. 1999

2)EXO 2030+375





Camero Arranz et al 2005

Conclusions

- *X-ray flares at the beginning of X-ray outbursts in A0535+26 can be due to low-m mode magnetospheric instability*
- *Spasmodic accretion on top of quasi-stationarily increasing accretion rate explains all features observed in Aug/Sep 2005 outburst of A0535+26*
- *Such behavior is expected at some critical accretion rate and is observed in other sources (e.g. 2S 1845-024 (Finger et al. 1999), EXO 2030+375 (Camero et al. 2005)).*
- *Further studies are underway searching for cyclotron line energy in other flares of A0535+26 and in other sources*