Cyclotron Line Sources with *RXTE*, *INTEGRAL*, *Suzaku*, *BeppoSAX*

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on behalf of the Magnet collaboration

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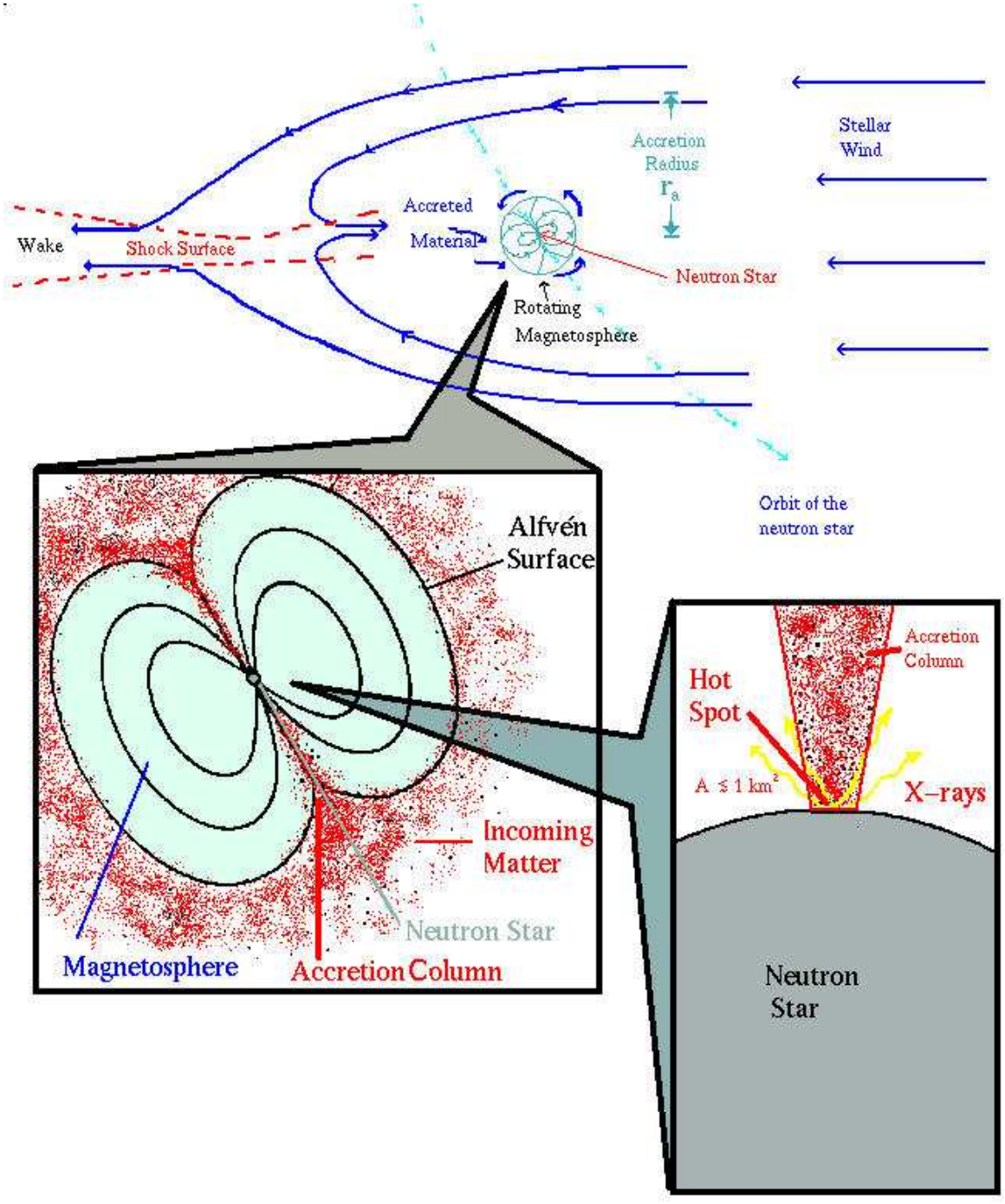


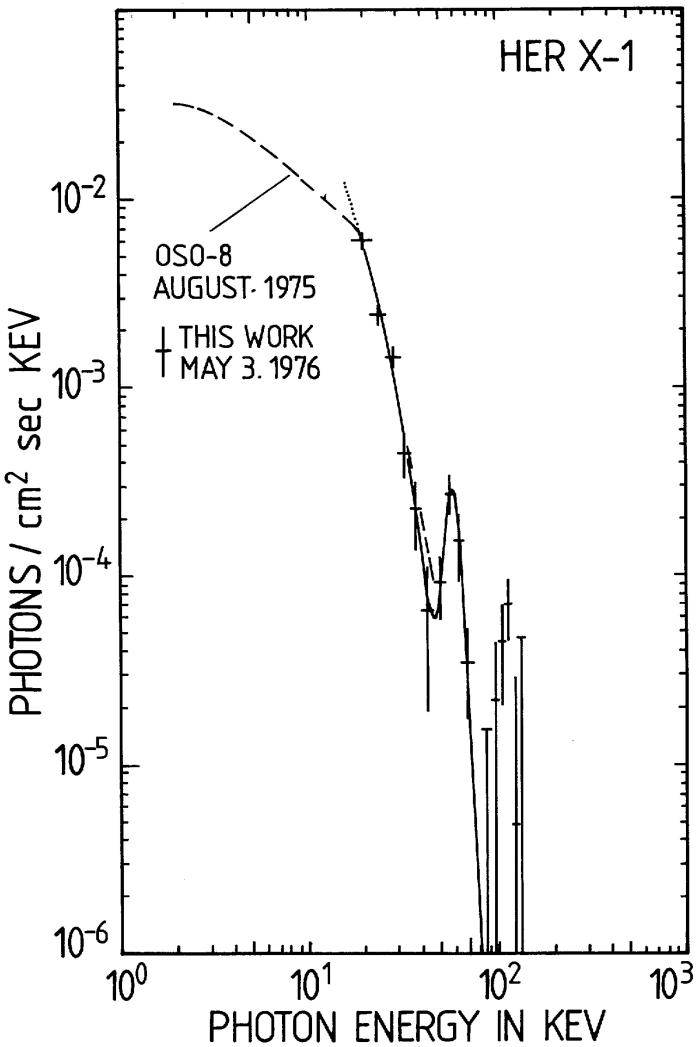
Accreting Pulsars

a few $\times 10^{12}$ G
mainly HMXBs
$\sim$ 17 sources
$\sim$ 50% transient

- wind accretion
  dips & flares
- Be accretion
  normal & giant
  outbursts

Negueruela, based on
Davidson & Ostriker (1973)

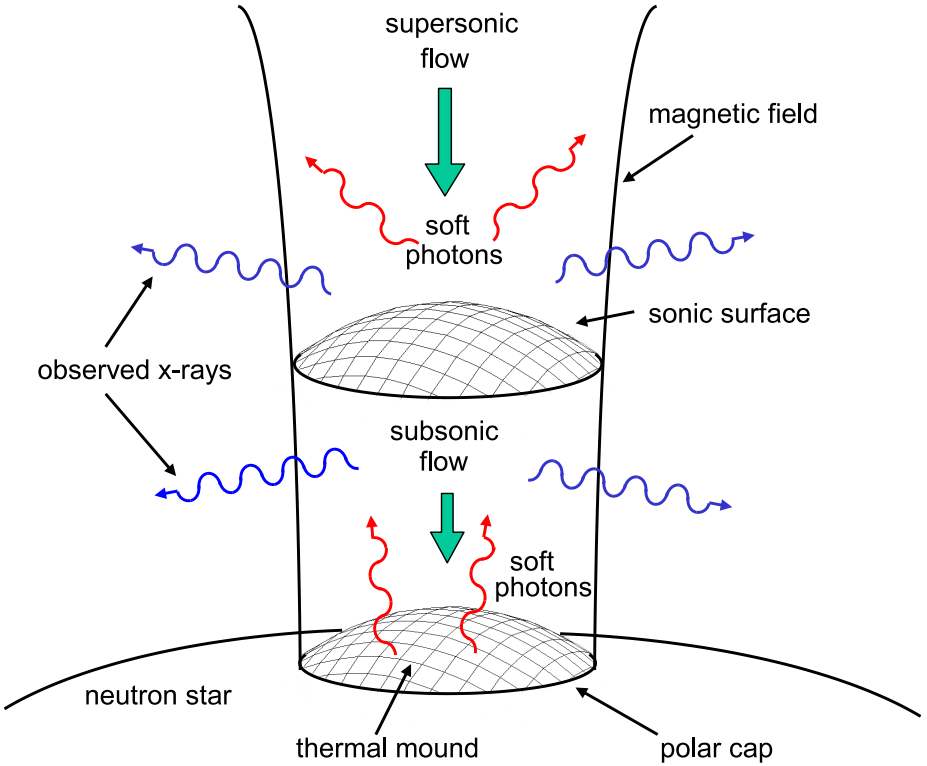
Spectrum



X-Ray Spectral Shape

- power law continuum with exponential cutoff
  Compton scattering
- often strong Fe Kα line at 6.4. . . 6.7 keV
  fluorescence in circumstellar material
- cyclotron line
  strong *B*-field
- luminosity & pulse phase dependence

Trümper et al. (1978a)



Becker & Wolff

Continuum Production

Becker & Wolff (2005a,b, 2007)

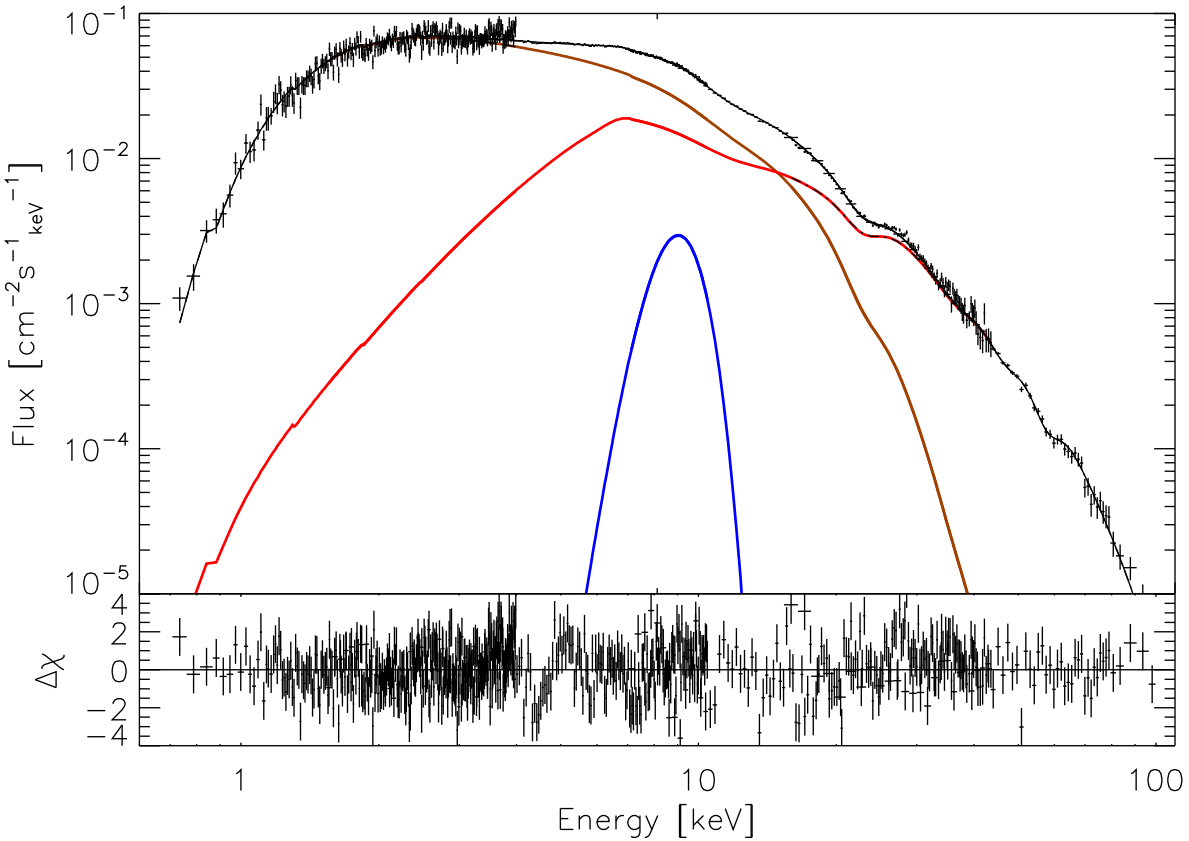
Bulk motion and thermal Comptonization of seed photons:

- accretion mound produces soft X-rays (bremsstrahlung, cyclotron, blackbody)
- X-rays are upscattered in **accretion shock**
- hard X-rays diffuse through walls of accretion column

Continuum Modeling

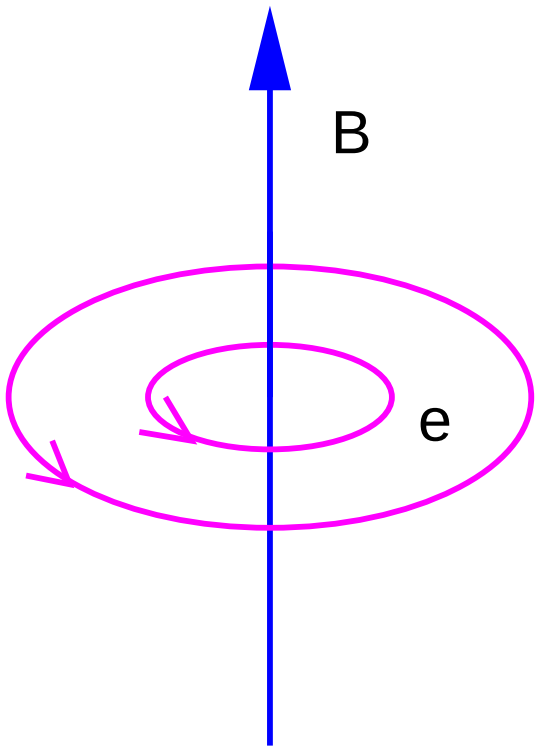
- current – empirical: $E^{-\Gamma}$ with cutoff
- future – physics: see above

Physical Continuum: Example



4U 0115+63, *BeppoSax*, Ferrigno et al., 2009

Becker and Wolff continuum model is now available for spectral fitting.



Work in progess by F. Schwarm.

Line Production

Quantization of electron energies $\perp$ B-field lines, for $B \ll\sim 4.4 \times 10^{13}$ G, distance between Landau levels:

$$E_{\rm cyc} = \frac{\hbar e}{m_{\rm e} c} B = 11.6\,{\rm keV} \left(\frac{B}{10^{12}\,{\rm G}} \right)$$

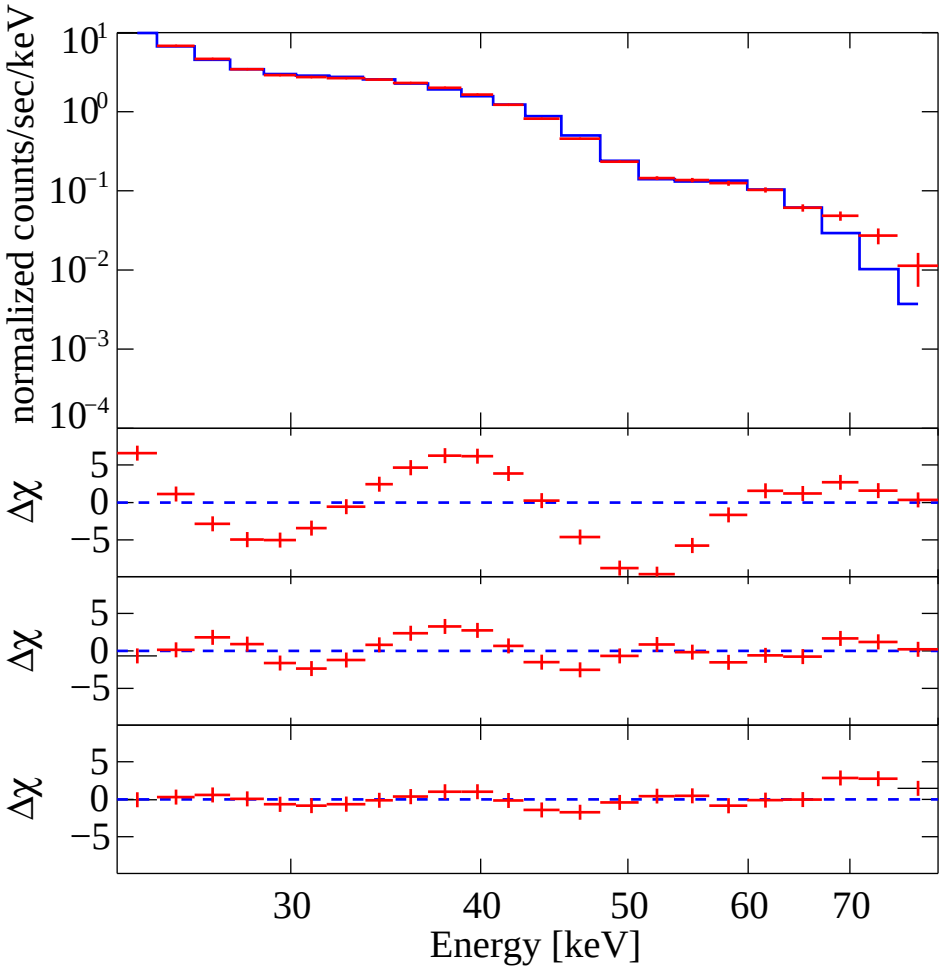
$\Longrightarrow$ Cyclotron Resonance Scattering Features ("cyclotron lines") at

$$E_n = n E_{\rm cyc} = (1+z) E_{n,{\rm obs}}$$

Line Modeling

- current – empirical:
  Gaussian optical depth profile
- future – physics:
  Monte Carlo ($kT_{\rm e}$, $\tau_{\rm es}$, B, μ)
  Schönherr et al. (2007)

Physical Line: Example



V0332+53, *INTEGRAL*, Schönherr et al. (2007)

Line Model – `cyclomc`

$B = 3.05 \times 10^{12}$ G
$kT_e = 10.2$ keV
$\tau_{es} = 0.003$, $\mu = 0.06$

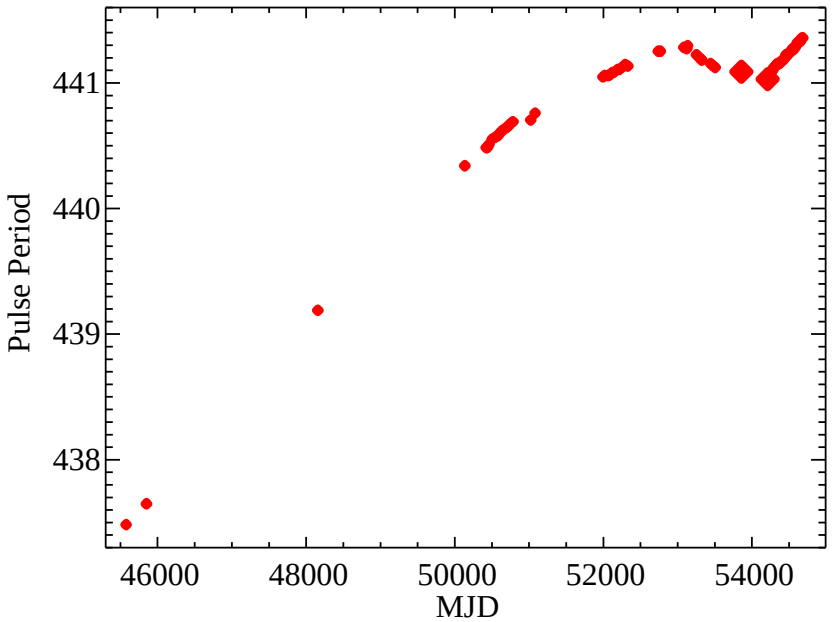
Continuum – `fdcut`

$\Gamma = 0.94$
$E_{cut} = 12.8$ keV
$E_{fold} = 7.5$ keV

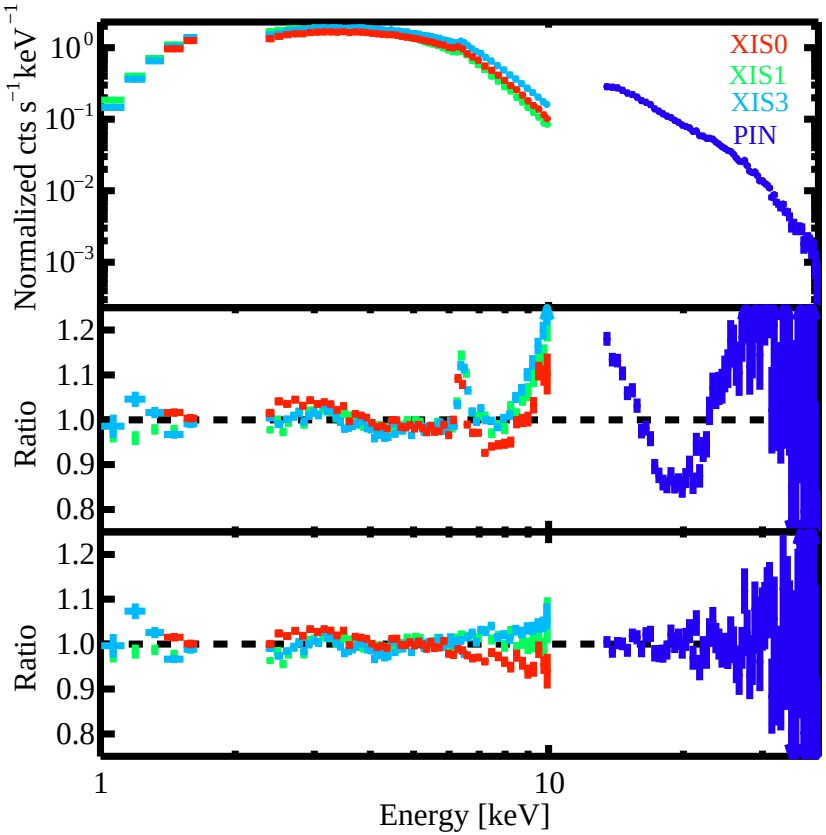
Geometry

accretion column = bottom illuminated slab; partial covering

4U 1907+09 with *INTEGRAL* and *Suzaku*

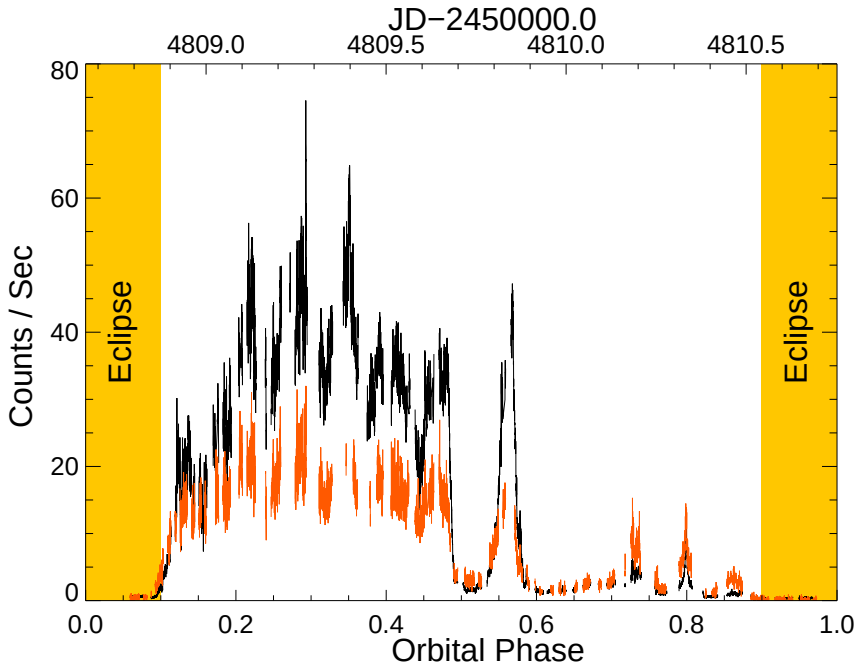


$\dot{P}_{\text{pulse}}$ with *RXTE*, *INTEGRAL*, *Suzaku*
two recent torque reversals
(Baykal et al, 2006, 2009; Fritz et al. 2006; Rivers et al., 2009, submitted)

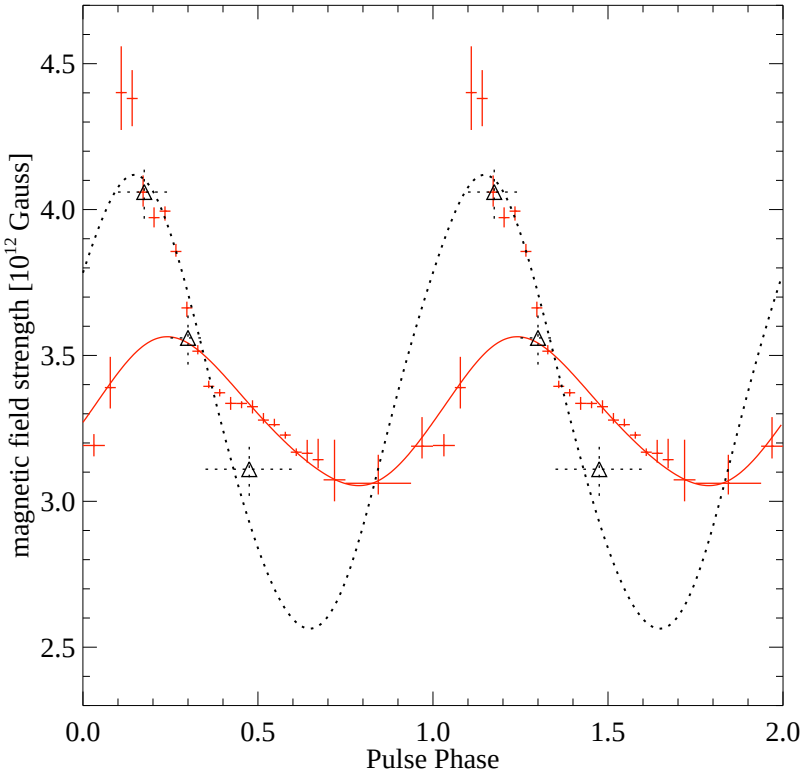


19 keV cyclo & Fe with *Suzaku*
19, 40 keV cyclo with *INTEGRAL*
40 mCrab source

Centaurus X-3 with *Suzaku* and *RXTE*

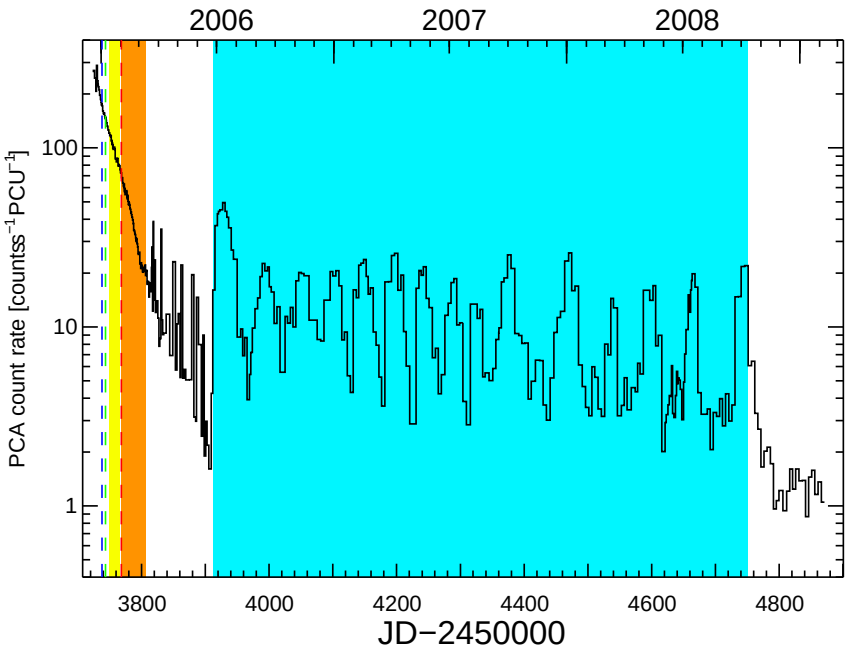


one binary orbit with *Suzaku* in 2008
2nd half supressed
(Suchy et al., 2010, in prep.)



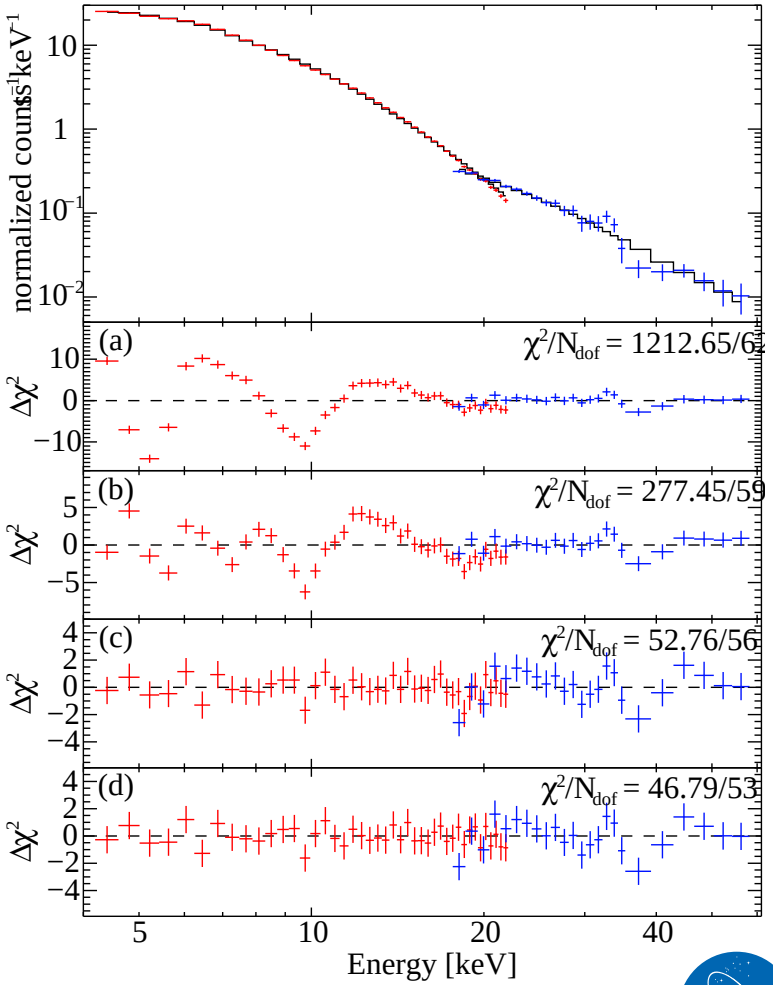
two binary orbits with *RXTE* in 1997
pulse phase dependence of E_{cyc}
not consistent with dipole
(Suchy et al., 2008)

Swift J1626.6−5156 with *RXTE* (& *Swift*)

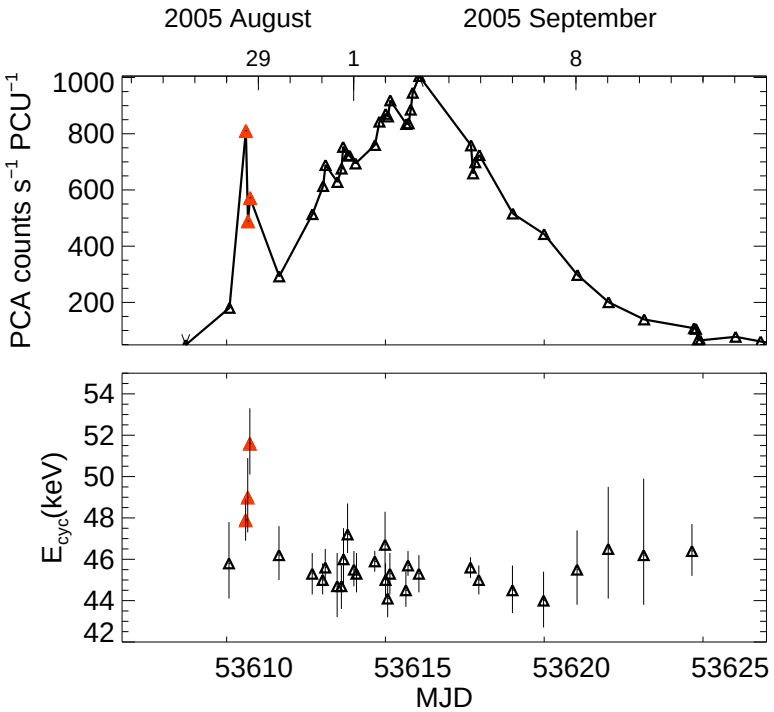


discovered 2005 (Krimm, 2005)
oscillations (Reig et al., 2008)
changing P (DeCesar et al., ATEL #2036)
132.9 d orbit (Baykal, ATEL #2250)

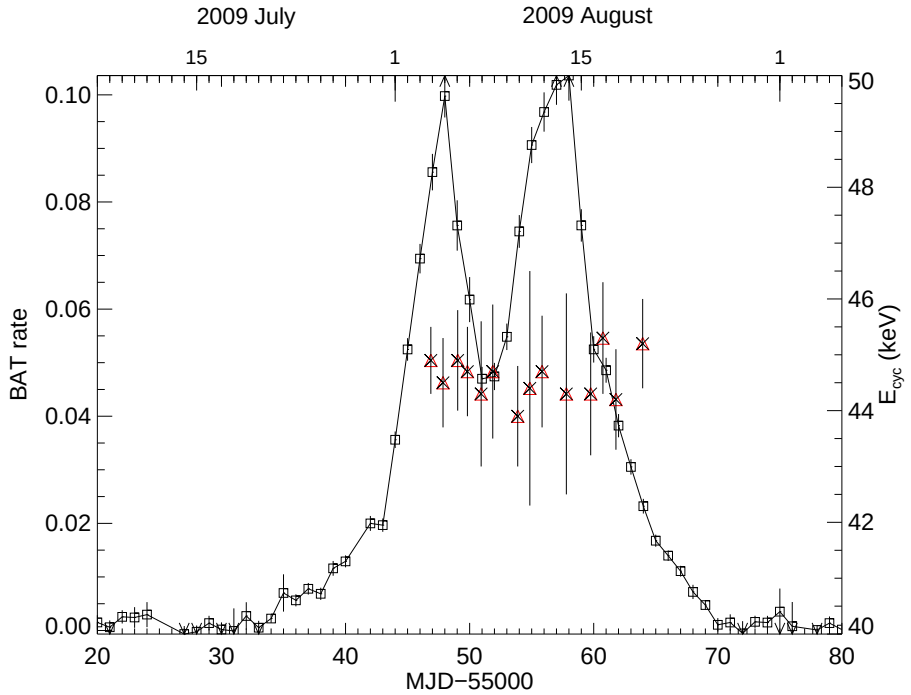
cyclotron lines at ∼10 keV and ∼18 keV
(DeCesar et al., 2009, submitted)



A0535+26 with *RXTE* (& *INTEGRAL*, *Suzaku*)

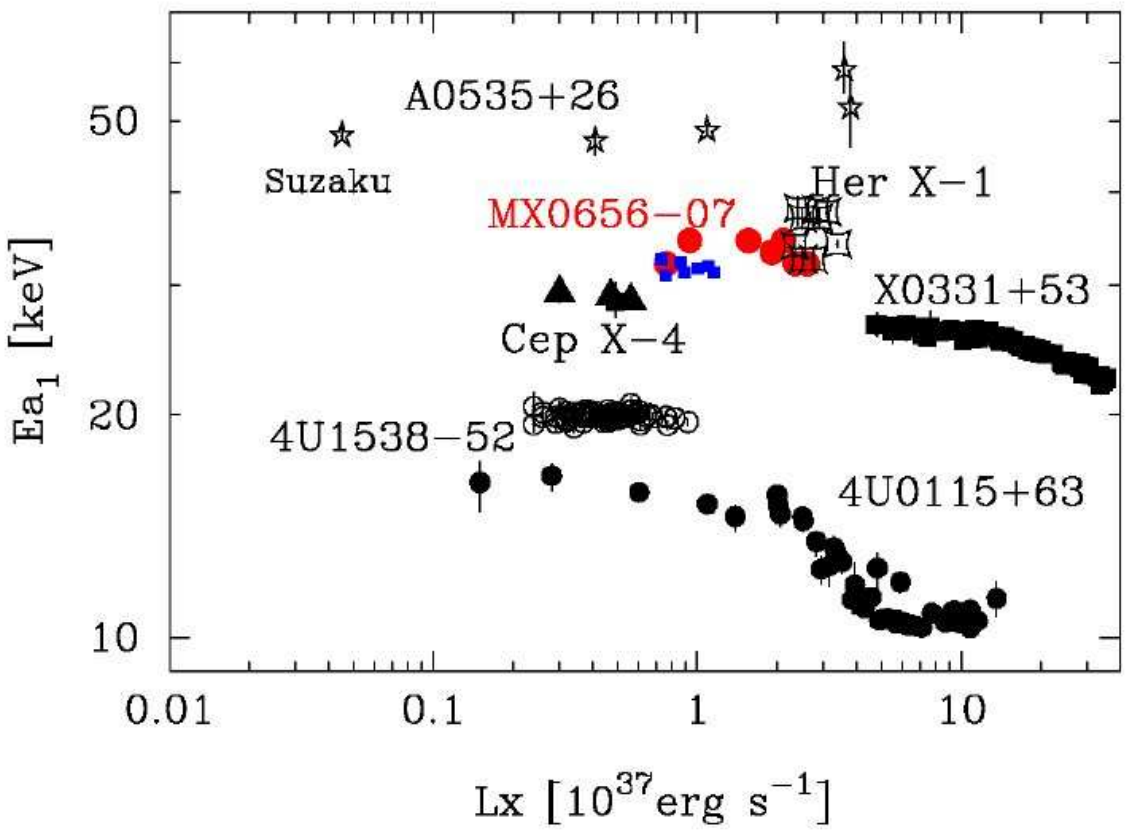


normal outburst in 2005
following giant outburst
E_{cycl} increased during pre-flare
(Caballero et al., 2007, 2008)



normal outburst in 2009
two-peaked, 2nd peak @ periastron
E_{cycl} constant
(Caballero et al., 2009, in prep.)

Luminosity versus E_{cycl}



Height above Magnetic Pole

Ram Pressure (stream) versus Radiation Pressure (mound)

2 Luminosity Regimes

Staubert et al. (2007)

Mihara et al. (2007), Nakajima et al. (2008)
MXB 0656-072 added by Dauser (2008)
work in progress

Summary & Outlook

- Continuum Emission – improve & test physical model
- Cyclotron Lines – improve & test physical model
- Observations – increase coverage of:
  Time, Energy, Luminosity, Phase
- Wind Signatures – observe & model
- Outburst Cycles – observe & model
- Important Diagnostics:
  - spectra (pulse, orbit, time) resolved
  - pulse profiles, lightcurves (energy resolved)
  - luminosity – E_{cycl} relationship
  - E_{cycl} spacing for harmonics
  - "10 keV bump"
  - flare distributions

Source	E_{cyc} [keV]	P_{pulse} [s]	P_{orb} [d]	type
4U 0115+63	14, 24, 36, 48, 62	3.6	24.31	T, Be
V 0332+53	27, 51, 74	4.37	34.25	T, Be
A0535+26	45, 100	105	110.58	T, Be
Vela X-1	25, 53	283	8.96	P, B0.5 Ib
4U 1907+09	19, 40	438	8.38	P, B2 III–IV
Swift 1626.6−5156	10, 18	15.35	132.9	T, Be
4U 1538−52	20	530	3.73	P, B0 I
X Per	29	837	250.3	P, B0 III–Ve
Cen X-3	30	4.8	2.09	P, O6.5 II
OAO 1657−415	36	37.7	10.4	P, B0-B6 Ia-Iab
GX 301−2	37	690	41.5	P, B1.2 Ia
4U 1626−67	37	7.66	0.028	P, WD?
Her X-1	41	1.24	1.7	P, A9-B
EXO 2030+375	11	42	46.0	T, B0 Ve
Cep X-4	28	66.25	>23	T, B1
MXB 0656-072	33	160.4	–	T, O9.7 Ve
XTE J1946+274	36	15.8	169.2	T, B0-1 V-IVe

Candidates: 2S 1417−624 (T), 1A 1111−616 (T), GRO J1008−57 (T), AX J1749.1−2639 (T), XTE J1739−302 (T), GX 1+4 (P), 4U 2206+54 (P), 4U 1909+07 (P), 4U 1700−377 (P), LMC X-4 (P), + ∼ 10 transients