Broad band continuum spectra of accreting pulsars around and above the critical luminosity

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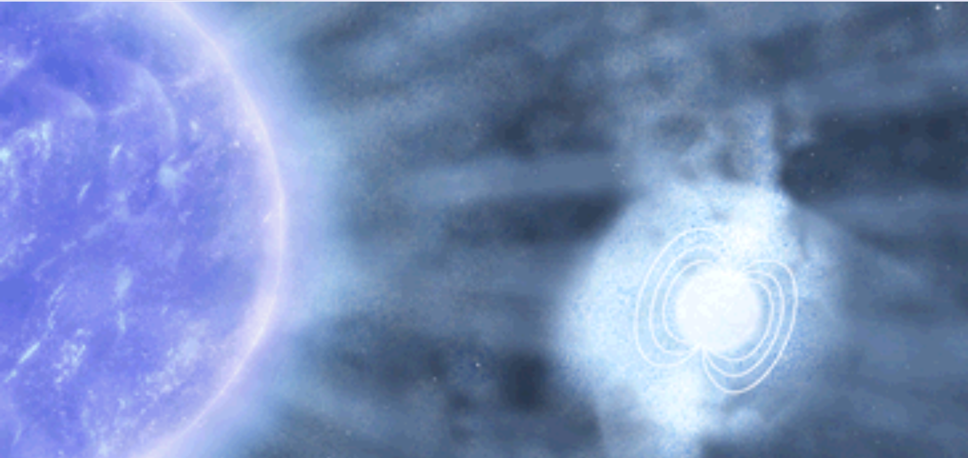
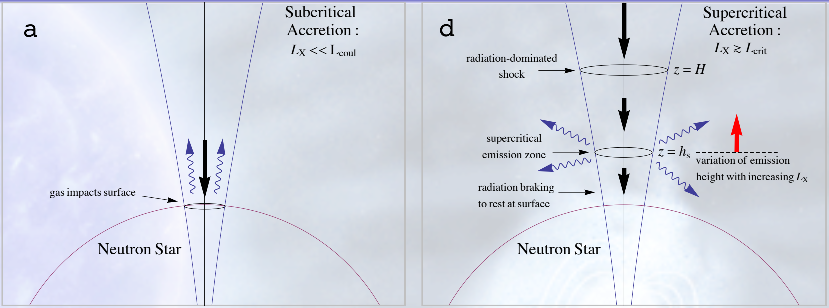
Accreting Pulsars



Credit: ESA/AOES Medialab

- persistent O, B wind accretors or Be transients
- young ($\sim$ 70 MW, 70 SMC, 15 LMC, M82, M31)
- $B_{\mathrm{NS}} \sim$ a few 10^{12} G $r_{\mathrm{Alfvén}} \sim 1800\,\mathrm{km}$ $v_{\mathrm{column}} \sim 0.7\,c$

Changing Deceleration



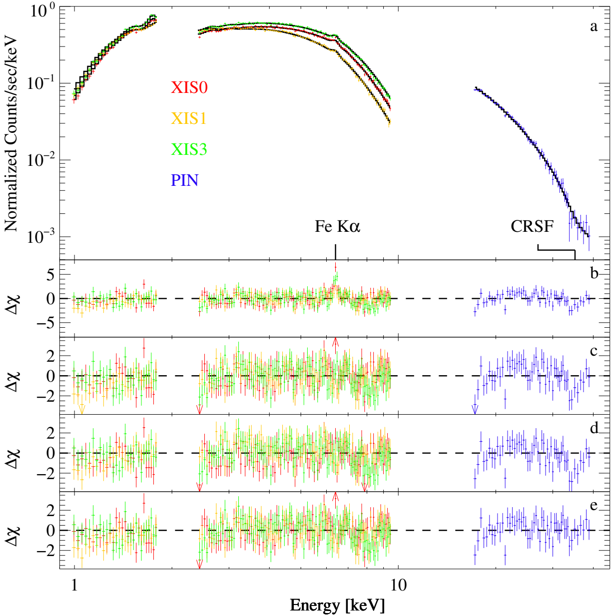
$$L_{crit} = 1.5 \times 10^{37}\,\mathrm{erg/s} \left(\frac{\Lambda}{0.1}\right)^{-7/5} w^{-28/15} \left(\frac{M_{NS}}{1.4\,M_\odot}\right)^{29/30} \left(\frac{R_{NS}}{10\,\mathrm{km}}\right)^{1/10} \left(\frac{B_{NS}}{10^{12}\,\mathrm{G}}\right)^{16/15}$$

Becker+12; alternatives see Mushtukov+15, Postnov+15

$L_X \ll L_{coul}$	$L_{coul} < L_X < L_{crit}$	$L_X \gtrsim L_{crit}$
Free fall, surface impact	Coulomb braking	Radiation braking
Pencil beam (a)	"Fancil" beam	Fan beam (d)
$L_X \uparrow \rightarrow h, B, E_{cyc}$ const.	$L_X \uparrow \rightarrow h \downarrow \rightarrow B, E_{cyc} \uparrow$	$L_X \uparrow \rightarrow h \uparrow \rightarrow B, E_{cyc} \downarrow$

E_{cyc} dependencies on L observed!, e.g., Staubert+07, Mowlavi+06

Typical Spectrum



Hard, cutoff powerlaw:

$$\frac{E^{-\Gamma}}{1 + \exp((E - E_{\mathrm{cut}})/E_{\mathrm{fold}})}$$

Absorption:
$\lesssim$ 3 keV

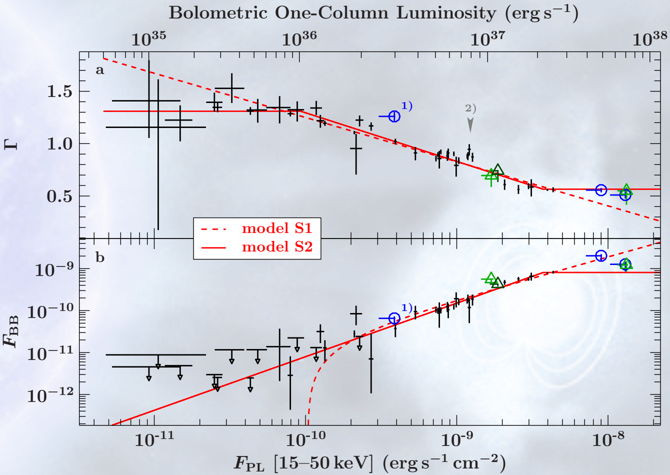
Fe K line(s):
6.4–7.0 keV

Cyclotron line(s):
10–100 keV

Observed spectral changes?

XTE J1946+274, *Suzaku*
Marcu-Cheatham+15

Changing Continuum



GRO J1008−57, *RXTE*, *Suzaku*, *NuSTAR*, Kühnel+16, subm.

- + **hardening/saturation** for 6 pulsars (*RXTE*/ASM, Postnov+15)
- reflection (Postnov+15) or reaching L_{crit}?

Physical Continuum Model

$L_\mathrm{X} \gtrsim L_\mathrm{crit}$: **Radiation dominated radiative shock**
Solve t-indep. cylindrical plane-parallel radiative transport equation

Analytical Solution

Column integrated flux is the sum of three Comptonized seed components:

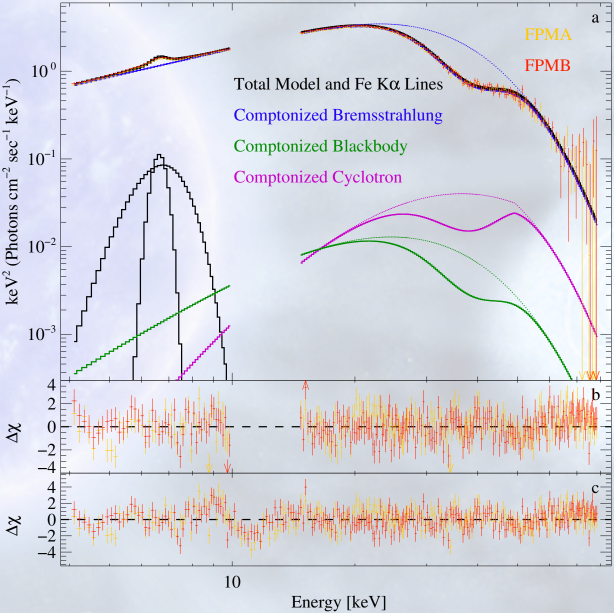
$$F(E) = (4\pi D)^{-1} \left[\Phi^{\mathrm{ff}}(E) + \Phi^{\mathrm{cyc}}(E) + \Phi^{\mathrm{bb}}(E)\right]$$

- Becker & Wolff 05a, 05b, 07, including "spectral fits by eye"
- Ferrigno+09, proof of concept statistical fit
- xspec models: **Wolff+16, Ferrigno ('16, priv. comm.)**

Numerical Solution

- xspec models: Farinelli+12, Farinelli+16

Physical Continuum: Hercules X-1



$L_X = 4.9 \times 10^{37}$ erg/s
$L_{crit} = 7.3 \times 10^{36}$ erg/s

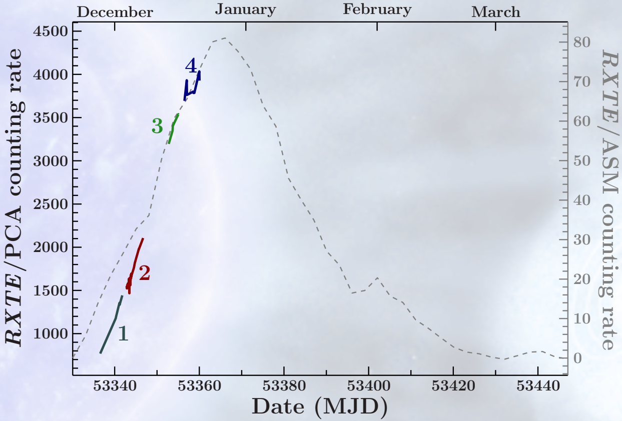
$kT_e = 4.58^{+0.07}_{-0.07}$ keV
$r_{col} = 107.0^{+1.7}_{-1.8}$ m
$\sigma_\parallel/\sigma_T = 5.2(1)\,10^{-5}$
$\bar{\sigma}/\sigma_T = 3.5(2)\,10^{-4}$

(Flux, distance: $\dot{M}$)
(Absorption: N_H)
(2 Fe lines)
(Cyclotron line: B)
($\sigma_\perp = \sigma_T$)

$\chi^2_{red} = 1.2$ **similar to empirical description** by Fürst+13.

Her X-1, *NuSTAR*
Wolff+16

Physical Continuum: V 0332−53



V 0332+53 in 2005, *RXTE*, Hemphill+16, to be subm.

$L_X = 15.5 - 41.2 \times 10^{37}$ erg/s

The brightest Galactic accreting pulsar transient.

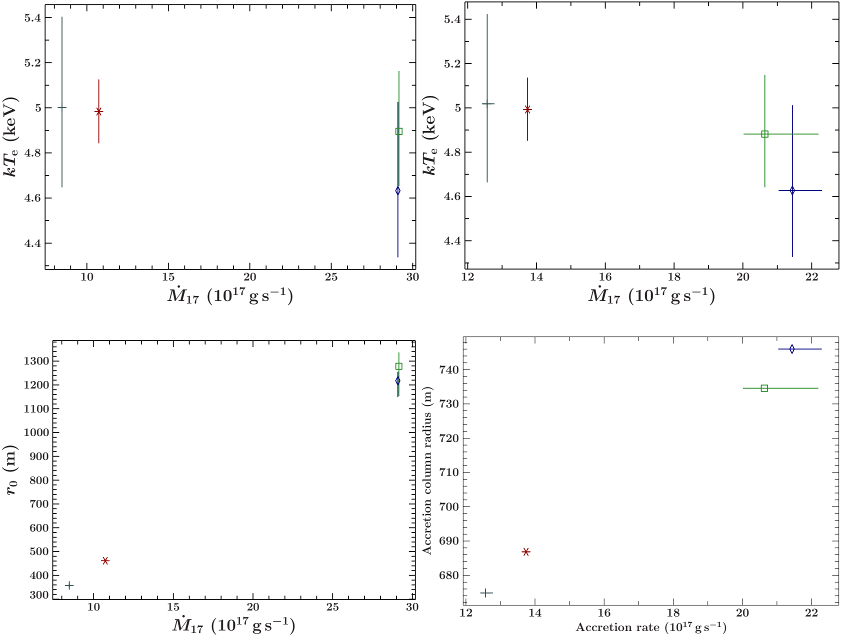
The fun begins:

- fit 2× 1-column
- derive h, redshift continuum & E_{cyc}
- replace the σs:

  $\xi \sim 4.1\, t_{sh}/t_{esc} =$ 1.15 fixed

  $\delta = y_{bulk}/y_{therm}$
- $\dot{M}$ fixed – *or* – $\dot{M}$ tied to r_{col}

⇒ **Free parameters kT_e, $\dot{M}$, and δ.**



$\dot{M}$ fixed

$\dot{M}$ tied

$kT_e \sim 5\,\mathrm{keV}$, $\delta \sim 1.5$ (not shown), r_{col} method dependent.

Work in Progress

L_X (0.1–100 keV) 10^{37} erg s^{-1}		kT_e keV	r_{col} m	$\sigma_\parallel$ $10^{-5}\sigma_T$	$\bar{\sigma}$ 10^{-4} σ_T	
Cen X-3	4	$3.1^{+0.4}_{-0.1}$	65^{+12}_{-4}	$2.8^{+0.2}_{-0.2}$	$1.6^{+0.6}_{-0.3}$	*S*, Gottlieb/KP
Her X-1	5	$4.6^{+0.1}_{-0.1}$	107^{+2}_{-2}	$5.2^{+0.1}_{-0.1}$	$3.5^{+0.2}_{-0.2}$	*N*, **Wolff+16**
V 0332+53	2×20	$4.6^{+0.4}_{-0.3}$	746	5.1	3.8	*R*, Hemphill
LMC X-4	35	$5.6^{+0.1}_{-0.5}$	1218^{+21}_{-14}	5.4	$16.2^{+0.3}_{-0.3}$	*S*, Marcu/KP
SMC X-1	105	6.0	3500	0.5	4.6	*N*, KP/Wolff

S, *N*, *R*: *Suzaku*, *NuSTAR*, *RXTE*

V 0332: r_{col}, σs derived, errors of fit parameters well behaved
LMC X-4: within 10% of superorbital peak
SMC X-1: within 40% of superorbital peak (T-scattering?), **very preliminary**
Farinelli+16: Her X-1, Cen X-3, 4U 0115+63

Good fits, comparable to empirical continua.

Outlook

More Applications

Sources/code comparisons, treatment of superorbital periods, mapping to empirical parameters, . . .

New Observations

E.g., recent NuSTAR ToO of SMC X-3 at $L_{\mathrm{X}} = 84 \times 10^{37}$ erg/s (ATel 9404).

Model Development

Include resonant scattering, add light bending, allow for pencil beam, . . .

Additioal Reading

Contributions to 2016 HEAD Special Session:
`http://www.sternwarte.uni-erlangen.de/wiki/doku.php?id=head16:start`