Accretion Powered X-Ray Pulsars: Physics of the Accretion Column

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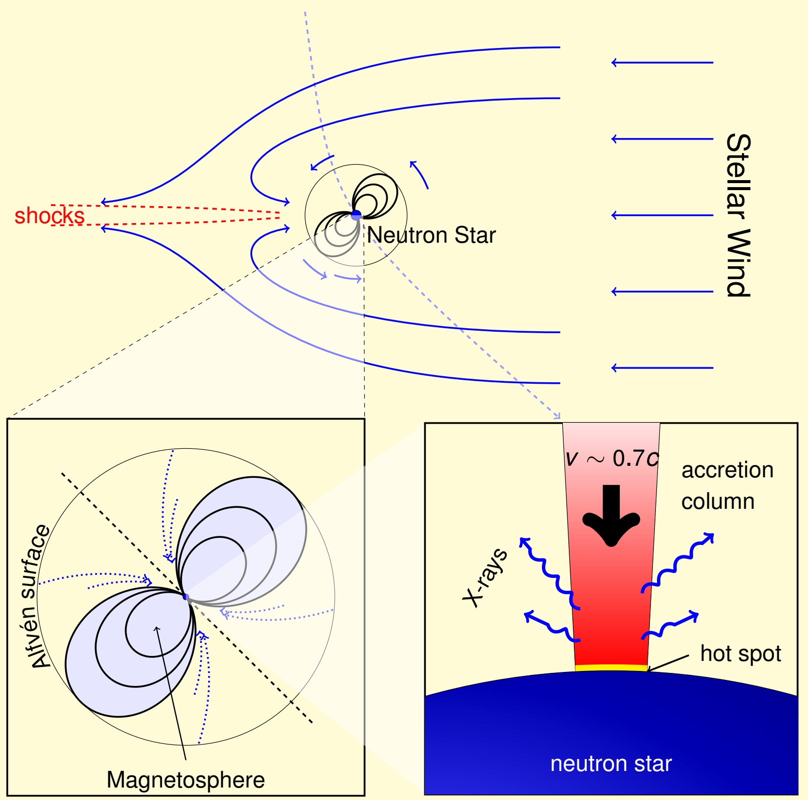
Accretion From Stellar Wind



After Davidson+ (1973)

Accreting plasma couples to magnetic field at Alfven radius

$$r_A = 3.5 \times 10^8\, L_{37}{}^{-2/7}\, \mu_{30}^{4/7} \times (M_{NS}/M_\odot)^{1/7}\, R_6^{-2/7}\,\mathrm{cm}$$

Parameters:

$R_{NS} \sim 10$ km

$B_{NS} \sim$ few $\times\, 10^{12}$ G

$M_{NS} \sim 1.4\, M_\odot$

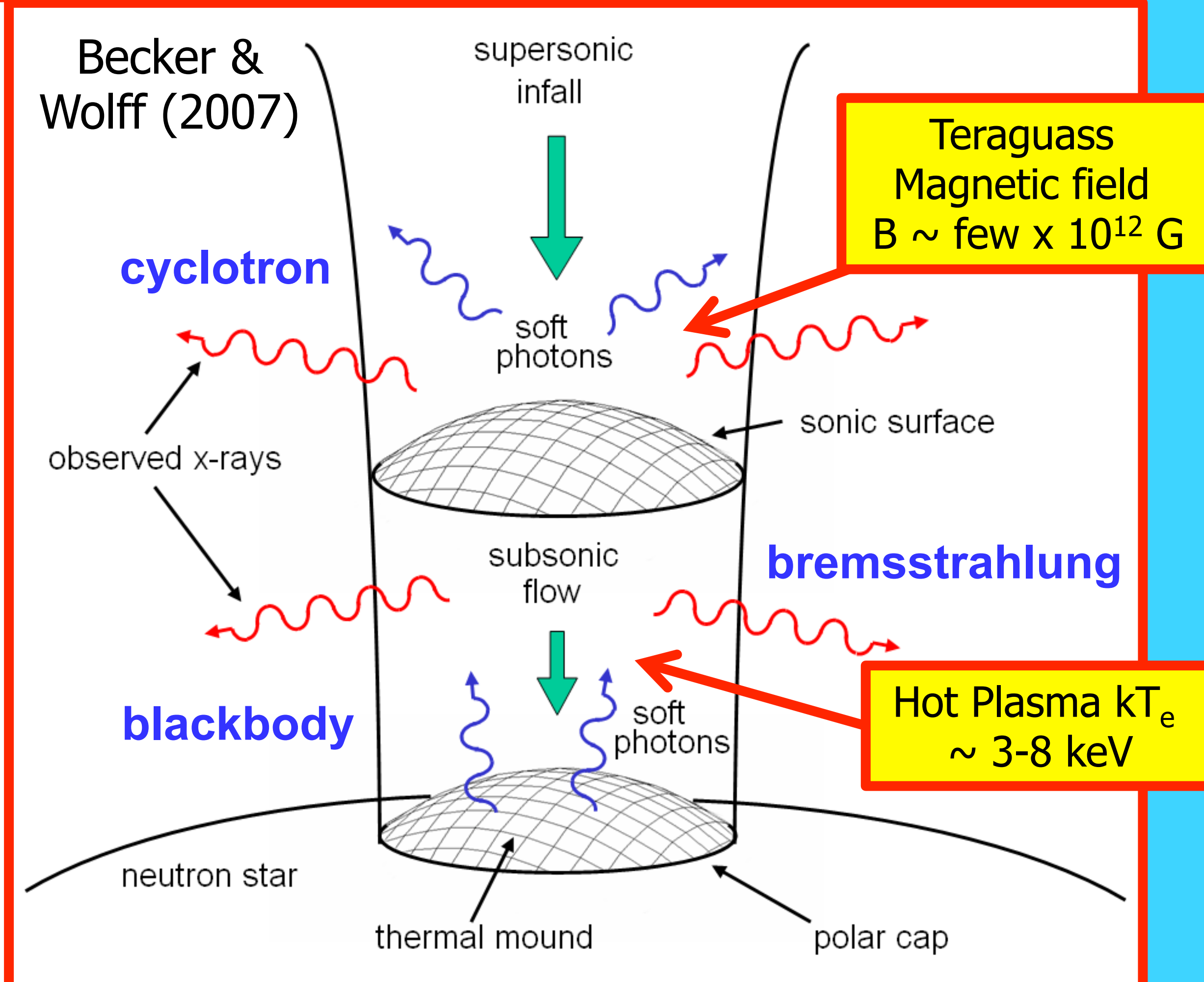
$\dot{M} \sim 10^{-7}\, M_\odot$/yr (~100 GT/s)

$r_A \sim 1800$ km

$v_{ff} \leq 0.7c$

Radiation Processes in Accretion Flows

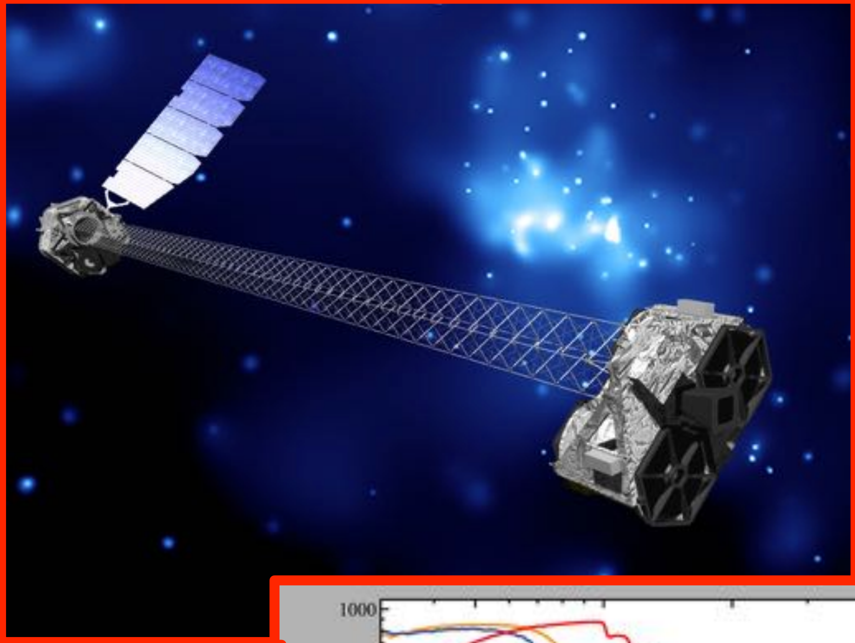
- Supersonic accretion flow passes through a sonic surface.
- Seed photons are produced via bremsstrahlung, cyclotron, and blackbody emission
- Electrons have bulk and stochastic (thermal) motion
- Photons are redistributed in energy via collisions with electrons (Comptonization)



New Era: NuSTAR

NASA: Nuclear Spectroscopic Telescope Array (NuSTAR)

- Large effective area: Up to 6500 cm^2.
- Broad hard X-ray energy coverage: 3-80 keV.
- Good timing resolution: ~2 ms.
- Spectral resolution: ~400 eV.

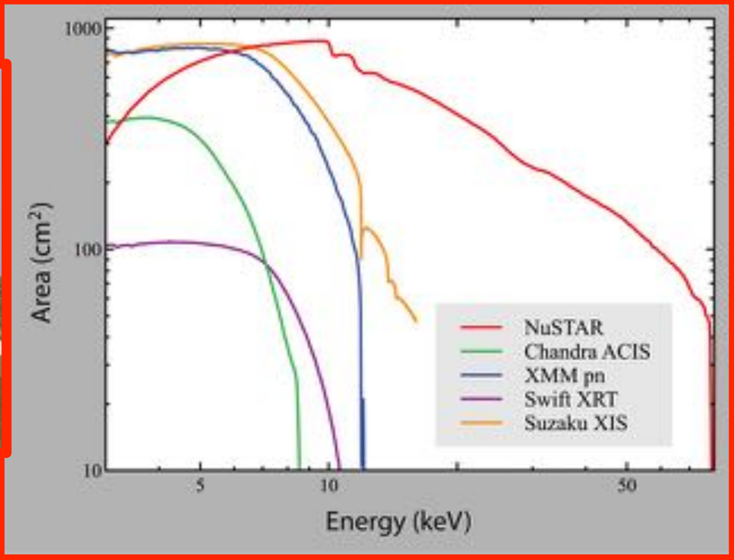


Launched: June 13, 2012

Launch Vehicle: Pegasus

Orbit: Low Earth

NuSTAR results: Furst later in this session. See Posters 120.03 (Bodaghee) & 120.06 (Brumback)

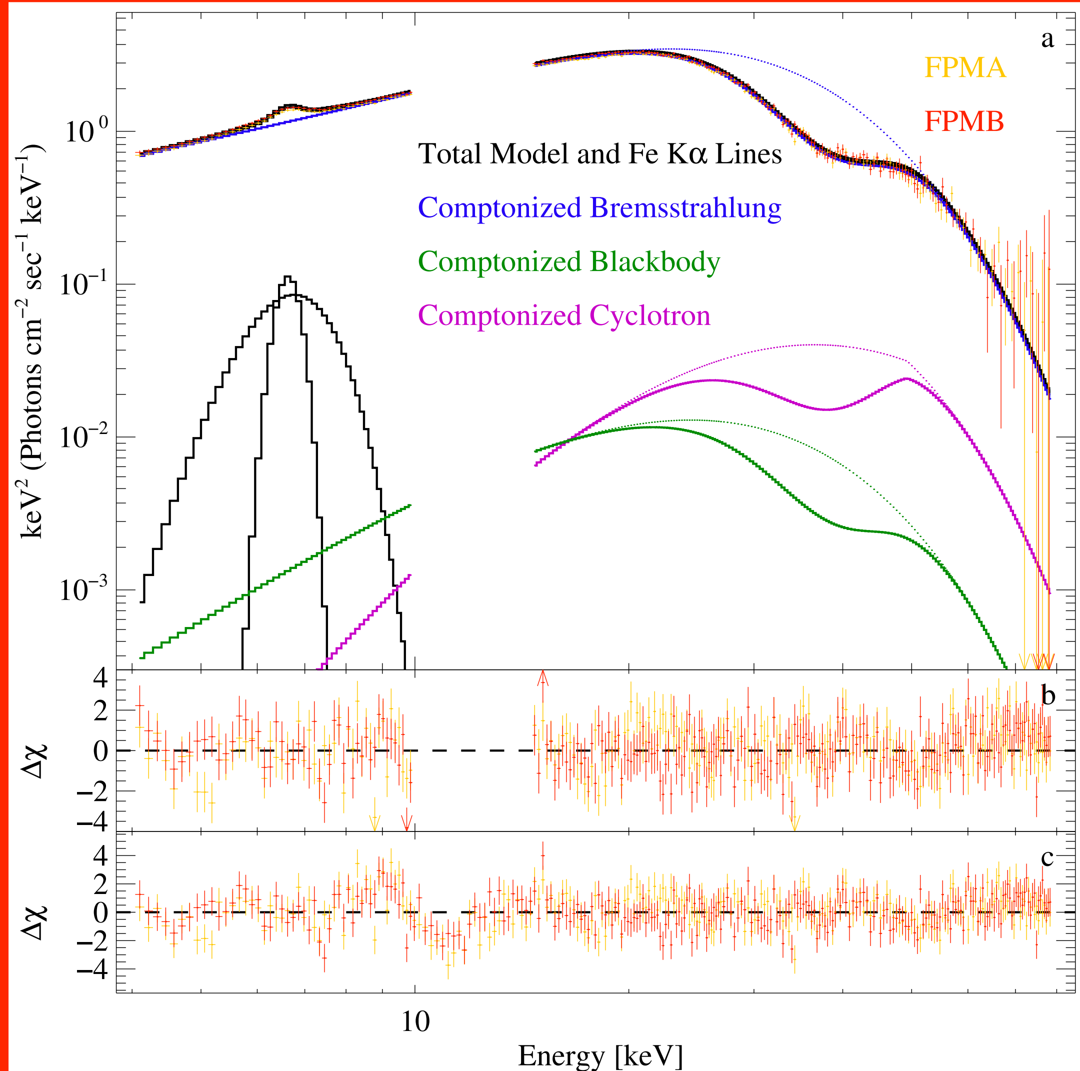


Her X-1: NuSTAR + Becker & Wolff

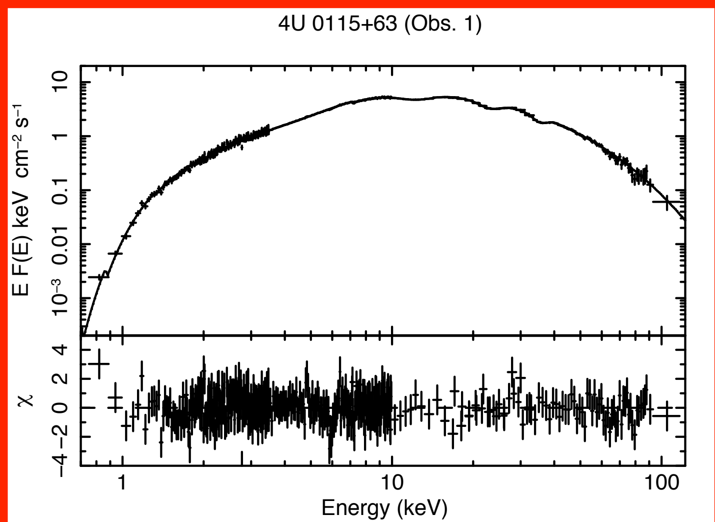
Her X-1 NuSTAR yields broad 3-79 keV high S/N spectra with good energy resolution.

New spectral analysis tool based on Becker & Wolff (2007) allows for multiple component spectrum and constraining parameter space.

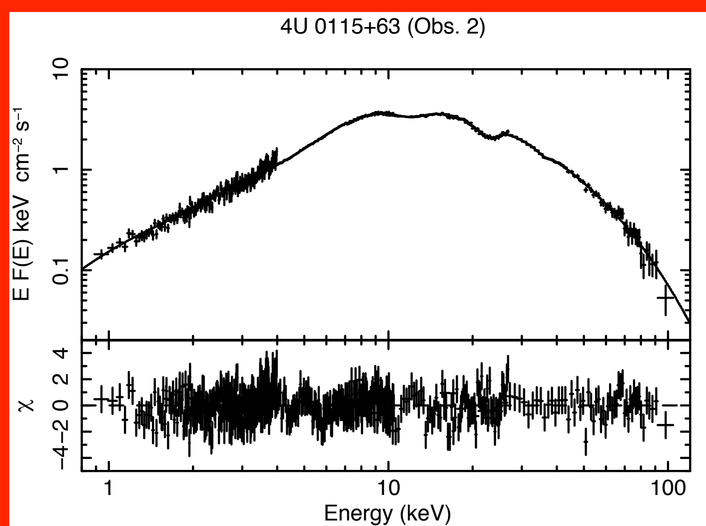
Her X-1: High luminosity source ($L > 10^{37}$ ergs/s) likely Comptonized bremsstrahlung.

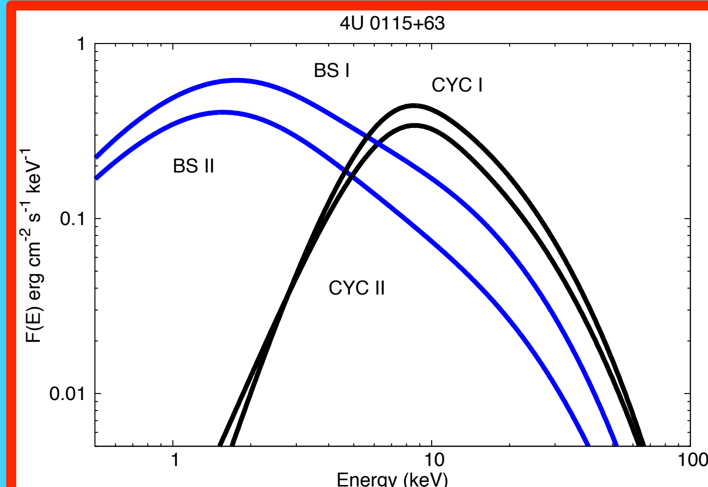


4U 0115+63: Cyclotron Emission



- Real Challenge: 4U 0115+63
- B ~ 10^{12} gauss (3 Harmonics)
- Ferinelli et al. (2016)
- "compmag" model: numerical solution to transfer equation.
- Comptonized cyclotron dominates spectrum above 10 keV.





Accreting X-Ray Pulsars with Observed Cyclotron Lines

28 Cyclotron Resonant Scattering Feature sources and centroid energies

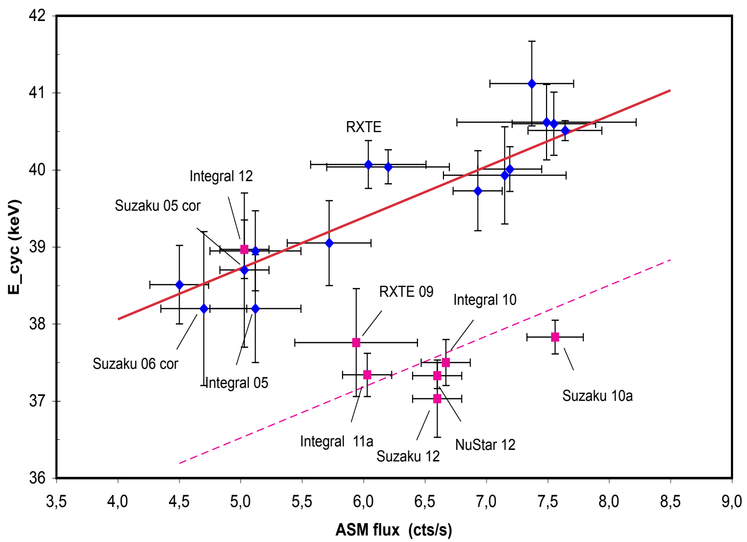
$$E_{cyc} = (1+z)^{-1} 11.57 B_{12} \text{ keV}$$

3A 0114+650	22.0 keV
4U 0115+63	11.5 keV
V0332+53	28.5 keV
X Per	28.6 keV*
RX J0520.5-6932	31.5 keV
X0535+262	47 keV
MX0656-072	36.0 keV
Vela X-1	23.3 keV
GRO J1008-57	78 keV
X1118-616	55 keV
Cen X-3	30.7 keV
GX 301-2	42.4 keV
GX 304-1	54 keV
4U 1538-522	20.7 keV

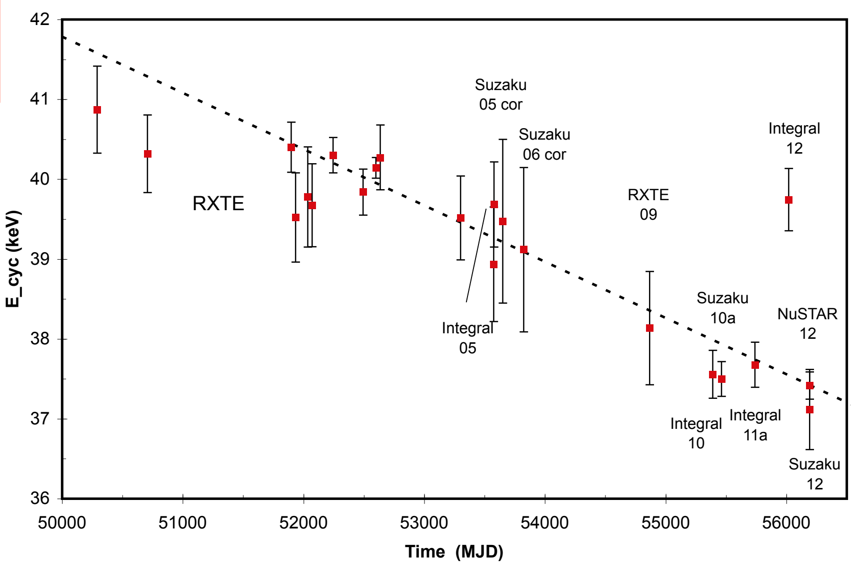
*** - CRSF observation challenged.**

2S 1553-542	27.3 keV
Swift J1626.6-5156	10 keV
4U 1627-673	39 keV
IGR J16393-4643	29.3 keV
Her X-1	40 keV
GRO J1744-28	4.7 keV*
IGR J17544-2619	16.9 keV
4U 1822-371	33.0 keV
4U 1907+09	18.3 keV
XTE J1946+274	34.9 keV
KS 1947+319	12.2 keV
EXO 2030+375	10.5 keV
Cep X-4	30.7 keV
4U 2206+54	32.0 keV

Her X-1: Long Term E_{cyc} Decay



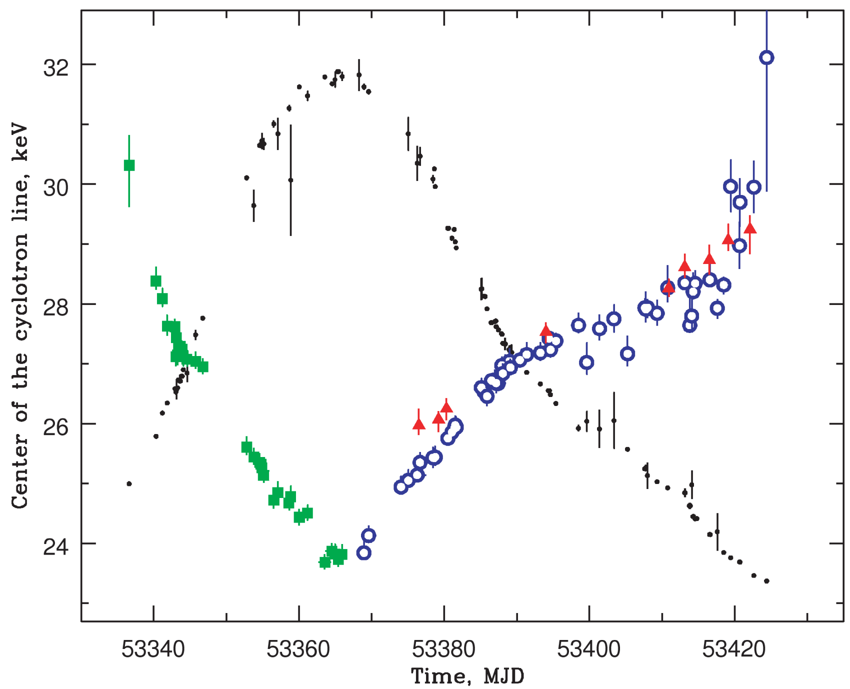
Her X-1: E_{cyc} positive correlation with luminosity

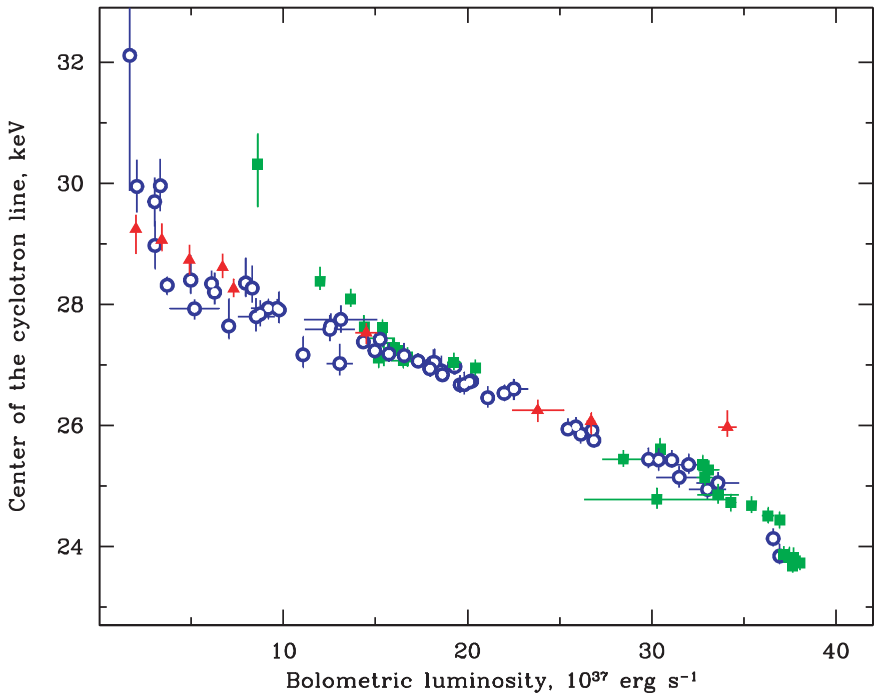


Her X-1: E_{cyc} long-term secular decrease (Staubert et al. later in this session)

V0332+53: E_{cyc} vs. Luminosity

Maximum utilization of broad-band RXTE (PCA + HEXTE) data. Outburst from V0332+53: 2004-2005 Outburst.





Tsygankov et al. 2010

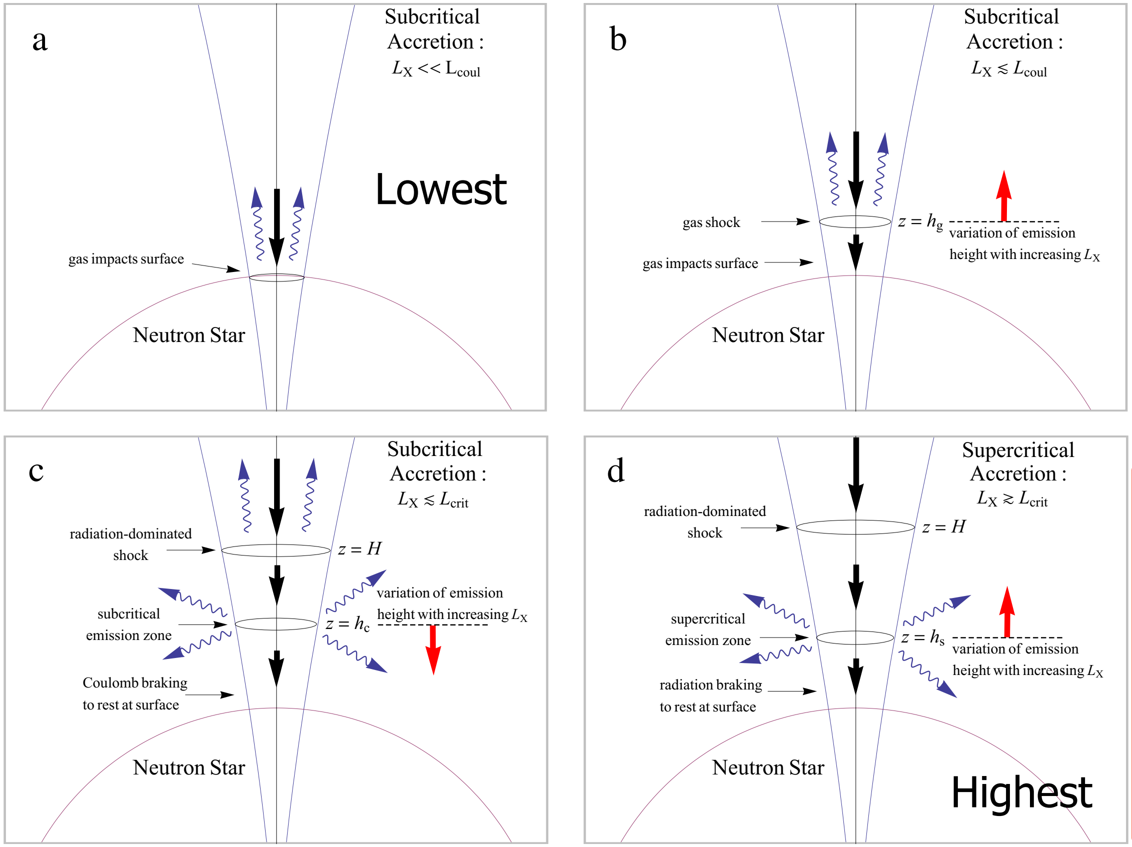
Four Accretion Rate Regimes

Lowest Accretion Rate: Gas Impacts on Surface

Even Lower Accretion Rate: Gas Shock and Coulomb braking

Sub-Critical Accretion: Radiation and Coulomb braking

Above Critical Accretion Rate: Complete Radiation Dominated Shock



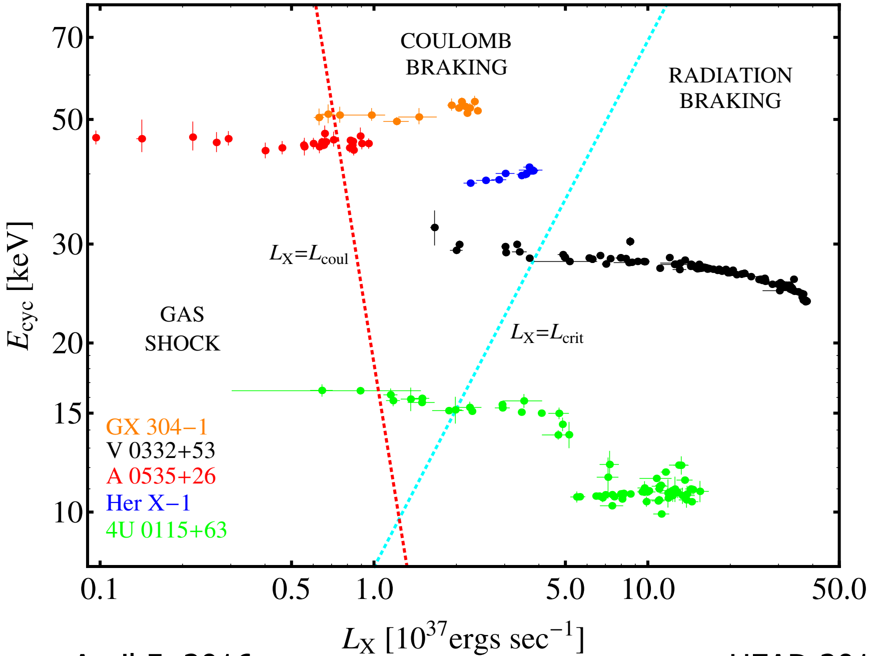
Becker et al. (2012)

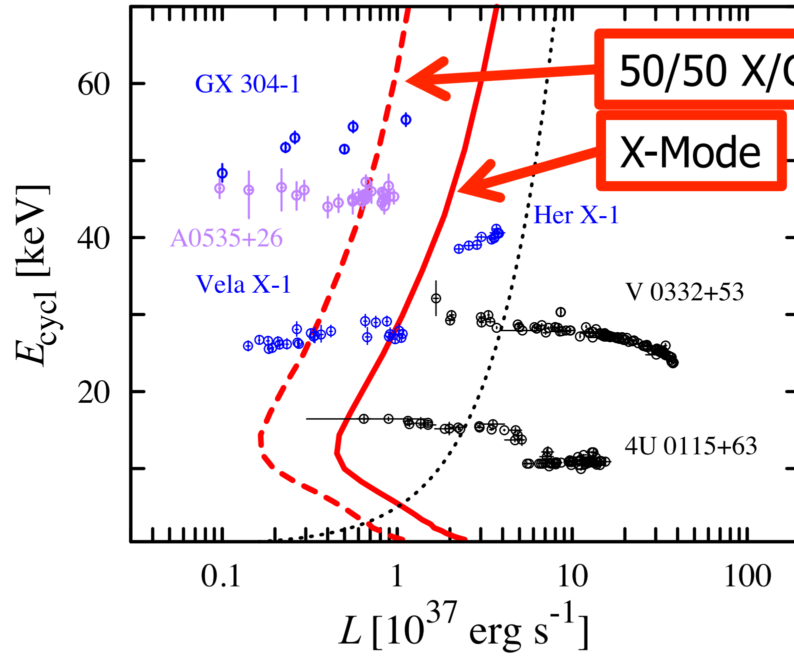
Critical Luminosity: E_{cyc} Behavior

Critical Luminosity: Radiation pressure stops the flow throughout the column

Becker et al. (2012)

$$L_{crit} = 1.28 \times 10^{37} \mathrm{ergs\,s^{-1}} \left(\frac{\Lambda}{0.1}\right)^{-7/5} w^{-28/15} \left(\frac{M_*}{1.4\,M_\odot}\right)^{29/30} \times \left(\frac{R_*}{10\mathrm{km}}\right)^{1/10} \left(\frac{E_*}{10\,\mathrm{keV}}\right)^{16/15}$$

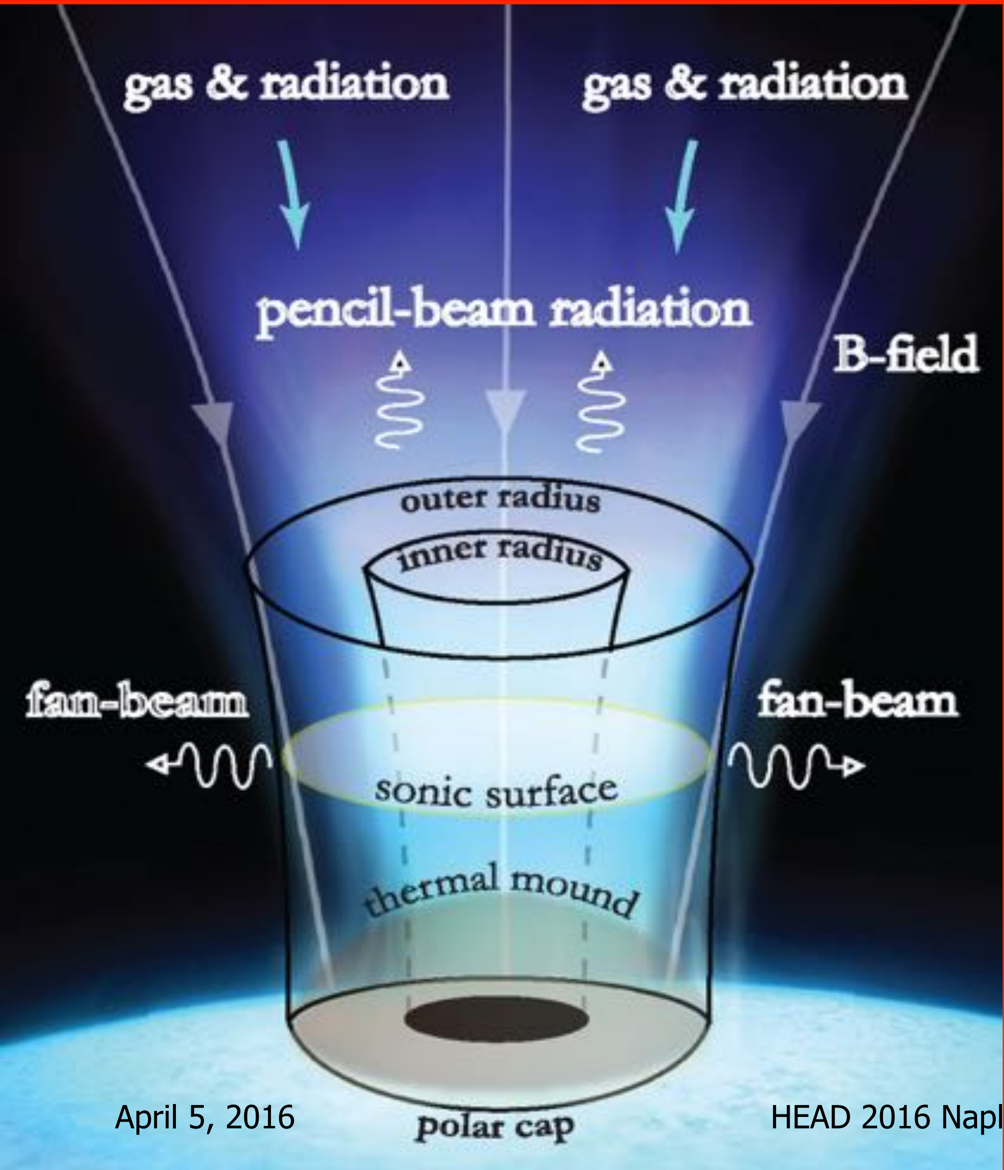




Critical luminosity numerically determined

Mushtukov et al. (2015)

Accretion Dynamics: West, Wolfram & Becker 2016

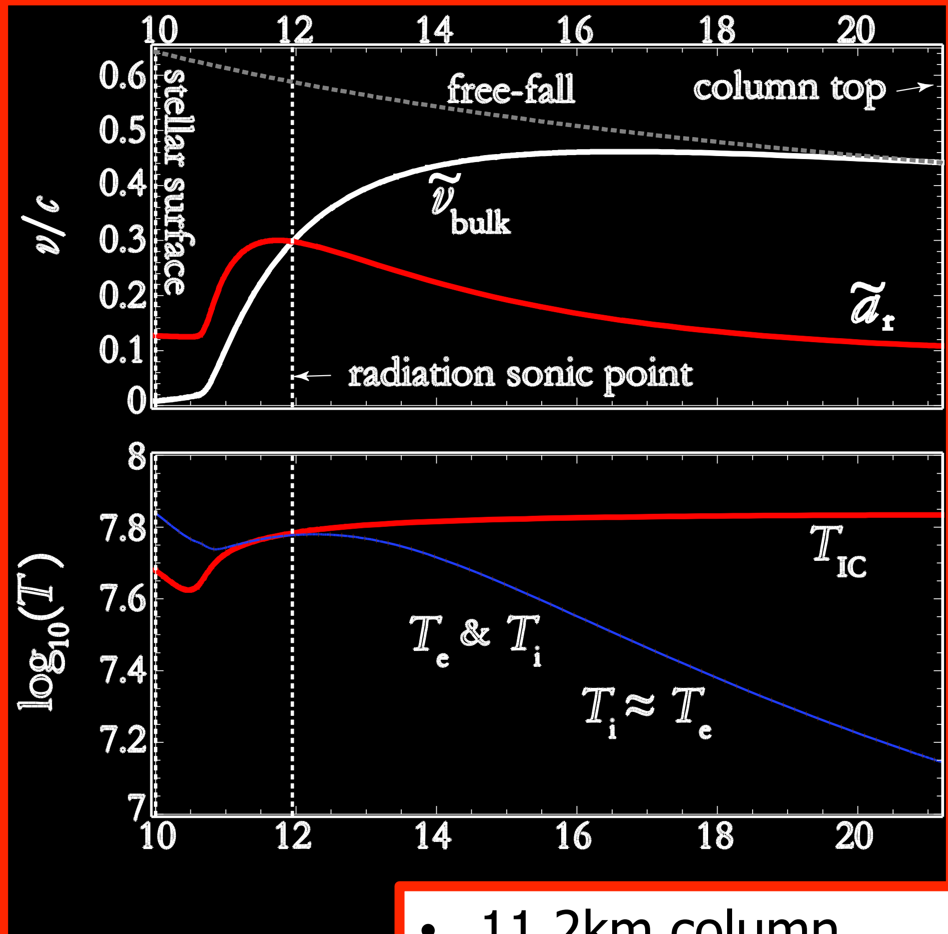


- Full dipole geometry: **interacting ions**, **electrons**, and **photons**.
- **Two-fluid** bulk steady flow: Photons + Plasma Particles. Describes hydrodynamic and thermodynamic **effects of gas** on column structure.
- Includes **bremsstrahlung, cyclotron**, & **blackbody** emission and absorption, and **electron-ion** thermal equilibration processes.
- Full treatment of photon-electron **Comptonization** computed iteratively. Includes bulk compression Comptonization effects.

Her X-1: WWB16 Model

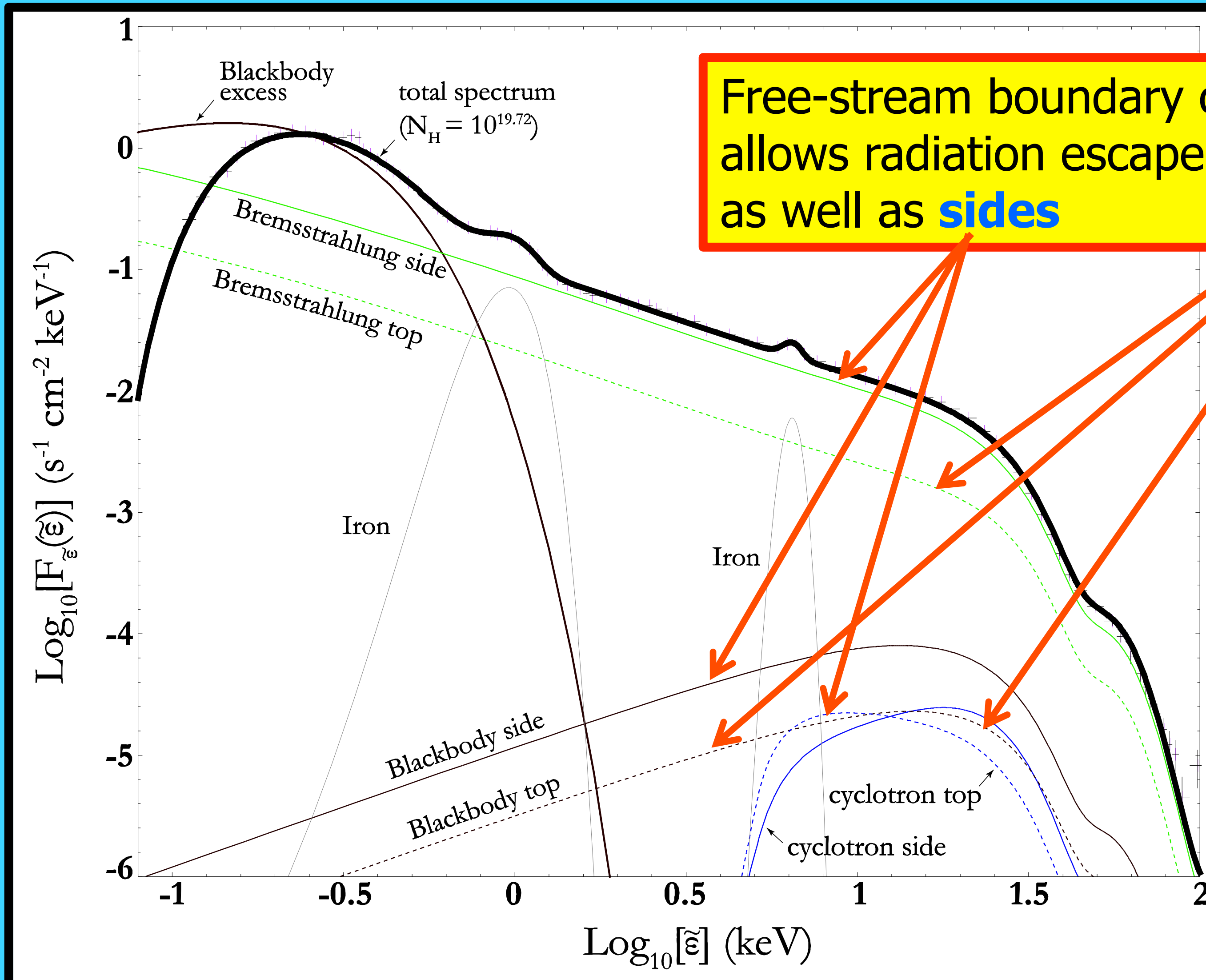
Velocity

Temperature



- 11.2km column
- Free-fall at ~0.44*c
- Stagnation at 0.0084*c
- Sonic surface at 1.95km

Her X-1: WWB16 Spectrum



Summary

- Tremendous progress is being made by multiple groups probing the physics of the accretion flows in accreting X-ray pulsars.
- We are beginning to constrain real flow parameters.
  - Constraints still have built-in model-dependence.
- Real line profiles of Cyclotron Resonance Scattering Features (CRSF) are beginning to emerge (see Talk 201.03 later in this session).
- CRSFs move with accretion luminosity differently depending on X-ray luminosity.
  - Helps probe the physics of plasma deceleration.
  - High luminosity have negative correlations (only one example)?
  - Moderate luminosity have positive correlations?
- Newer, more detailed hydrodynamic models in the pipeline.
  - Radiation and gas effects + self-consistent treatment of the emergent continuum spectrum.
  - CRSF line shapes in hybrid continuum + cyclotron models are in work.
- Need integrated models that incorporate the affects of wind and disk accretion into plasma structures.