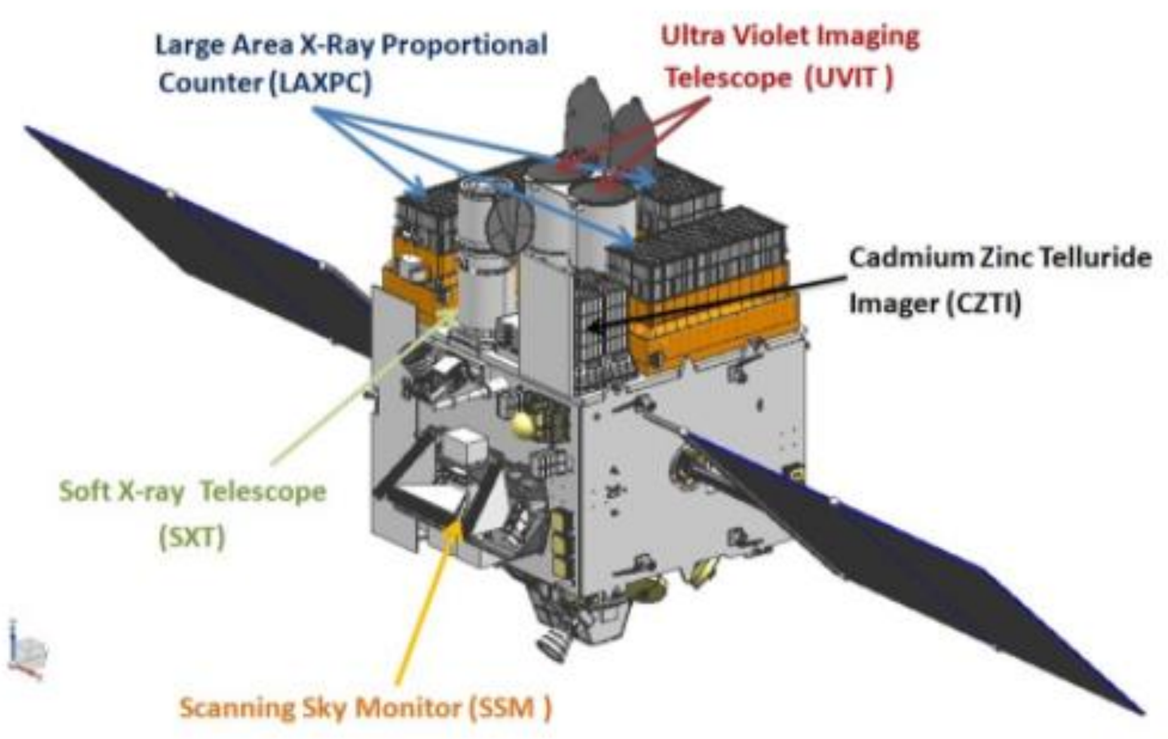
AstroSAT Observations of Hercules X-1.



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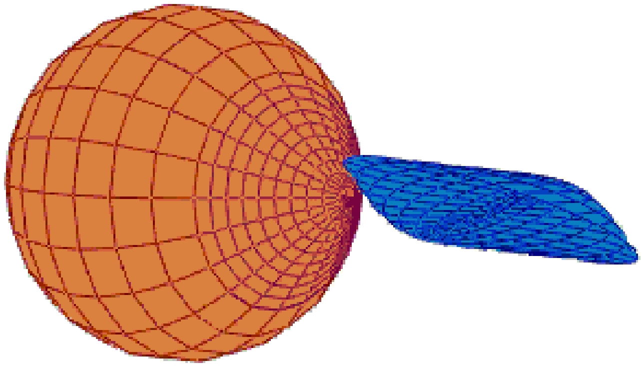
The Hercules X-1 X-ray Binary System

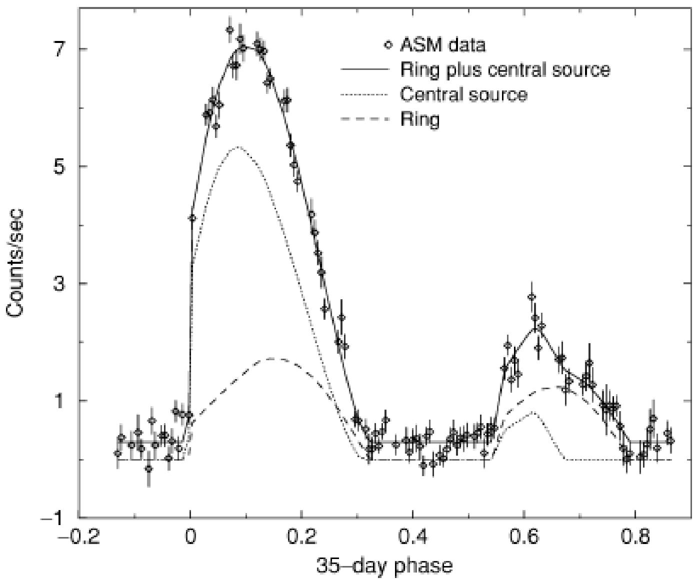
A neutron star (Her X-1) in orbit with an A7 type companion (HZ Her)



- Roche-lobe overflow

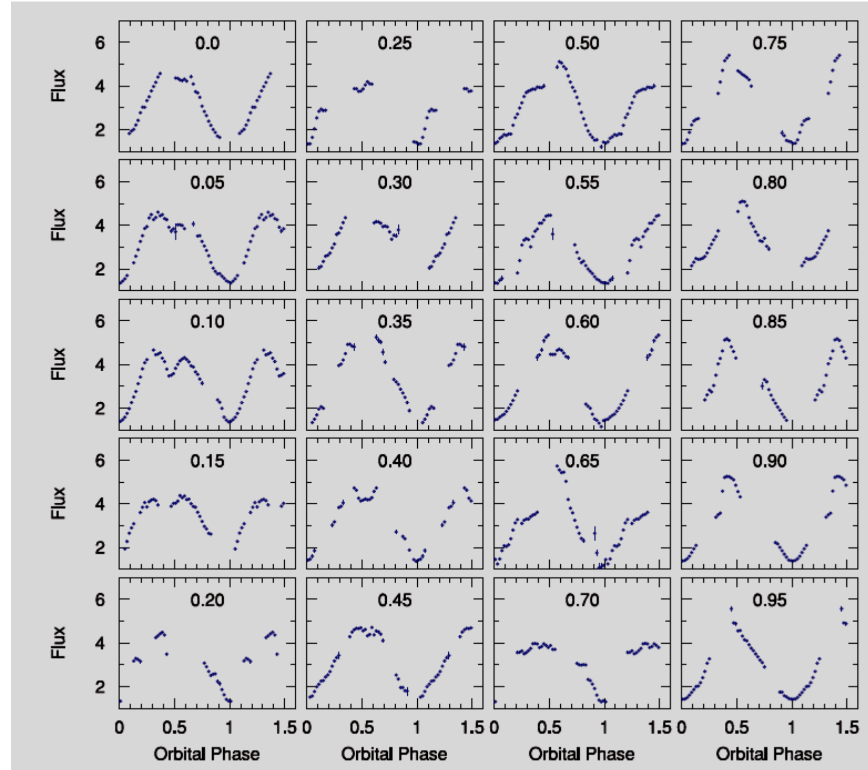
- 1.24-s X-ray pulsations
- 1.7-day orbit with eclipses

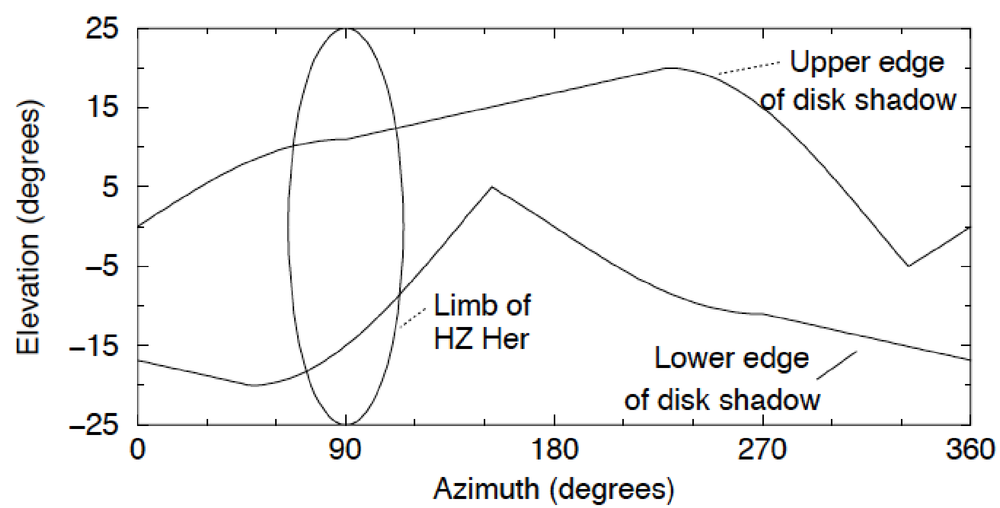
- 35-day X-ray flux cycle and 35-day cycle for systematic pulse shape changes, caused by twisted disk occultation
- X-ray cycle: main high→ low→ short high→low
- Optical cycle caused by X-ray heating of HZ Her

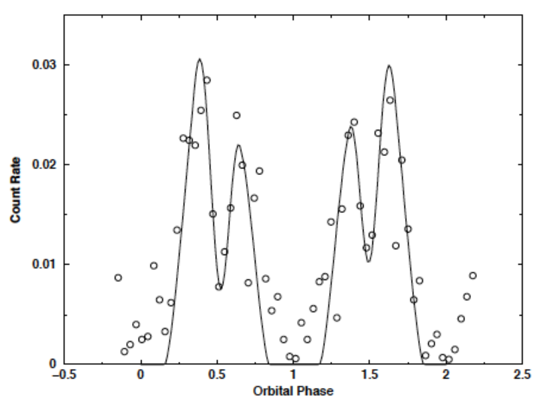


Optical 35-day cycle

- Gerend & Boynton 1976
- Light is mainly from the X-ray heated face of HZ Her: ~16000K vs 7500K unheated
- Optical cycle is caused by the disk shadowing the X-ray illumination of HZ Her
- The shadow varies with orbital and 35-day phase
- Optical data (right, Jurua+ 2011)
- Model (lower right, Leahy+2000)
- EUV data (below, Leahy & Marshall 1999)



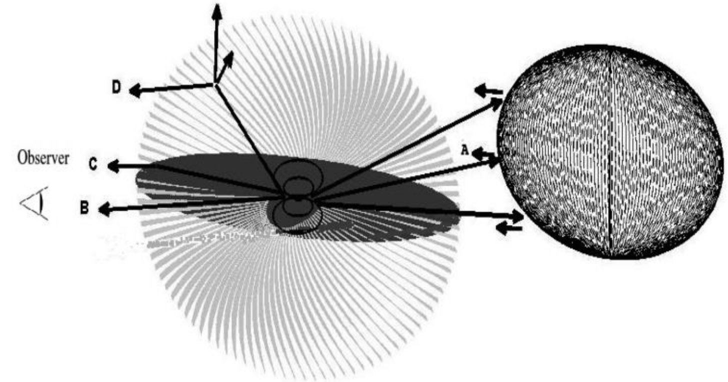




Her X-1 properties

- RXTE spectra and light curves: detection of X-ray reflection of HZ Her (Abdallah & Leahy 2015)

- Recombination lines in high-resolution Chandra X-ray spectrum are from photo-ionized plasma with size 10^{11} cm, electron density 10^{12}-10^{13} cm^{-3} (Jimenez-Garate + 2005, Ji + 2009)
- Extended corona detected during eclipse with RXTE/PCA (Leahy, 2015)
- Ionized disk wind detected in XMM-Newton spectrum (Kosec+2020), velocities 200-1000 km/s, wind mass-loss rate ~70% of accretion rate.



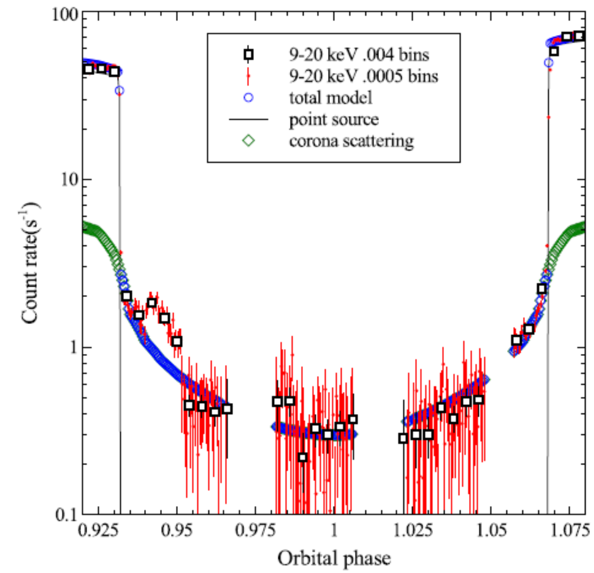


Figure 4. Best fit model corona compared to the 9–20 keV data. The data has been shown, with error bars, for large phase bin size (0.004, black squares) and small phase bin size (0.0005, red dots). The model for point source eclipse by the atmosphere of HZ Her, the model for the corona scattering, and the total model are shown.

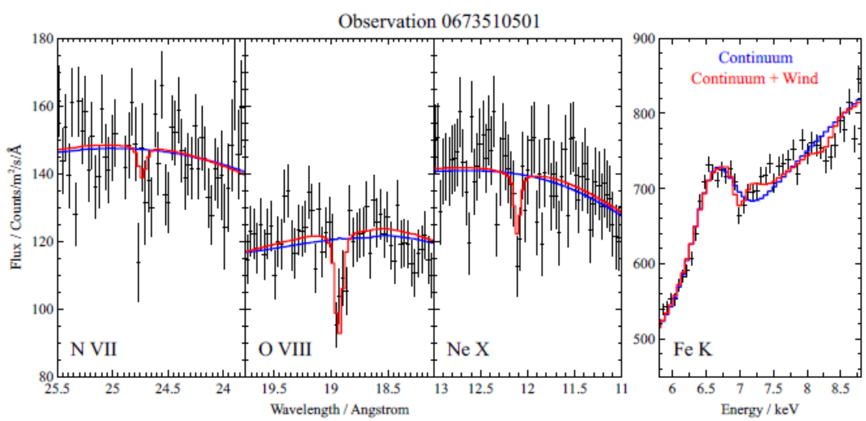


Figure 3. Energy bands around the rest-frame energies of N VII, O VIII, Ne X and Fe XXV/XXVI ions from observation 0673510501. The first three bands only contain RGS1 and RGS2 data, stacked for plotting purposes only, the fourth band only contains EPIC-pn data. The best-fitting baseline continuum is shown in blue, the final wind solution in red.

Her X-1 properties

- Pulse-phase spectroscopy with Suzaku (Kondo + 2021)
- Medium energy component fit either with cutoff power-law or multi-T blackbody
- Consistent with areas of the 3 components changing with phase (caused by viewing angle changing)

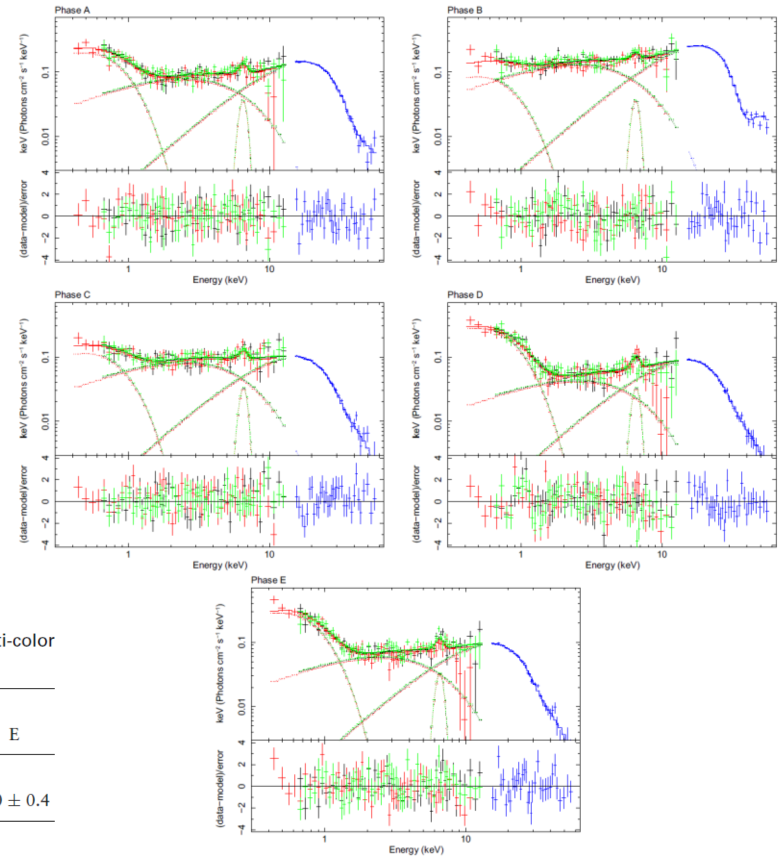


Table 5. Best-fitting parameters of the revised three-continuum component model with the modified multi-color blackbody model.

Component	Parameters	A	B	C	D	E
		Best-fitting values				
Hard bbody	kT_H [keV]	$8.4^{+0.6}_{-0.8}$ (AB)			$6.1^{+0.7}_{-0.5}$ (CDE)	
	S'/D_{10}^2 *	$0.7^{+0.3}_{-0.2}$	$1.1^{+0.4}_{-0.3}$	$1.0^{+0.4}_{-0.5}$	0.9 ± 0.4	1.0 ± 0.4
Multi-color BB	T_{out} [keV]			0.34 ± 0.02 (ABCDE)		
	T_{in} [keV]			$2.4^{+0.1}_{-0.2}$ (ABCDE)		
	p			0.73 ± 0.04 (ABCDE)		
	S'_C/D_{10}^2 †	3.8 ± 0.7	$6.4^{+1.4}_{-1.2}$	$4.1^{+1.1}_{-0.7}$	$2.1^{+0.7}_{-0.5}$	$2.9^{+0.6}_{-0.5}$
Soft bbody	kT_S [keV]			0.17 ± 0.01 (ABCDE)		
	S'/D_{10}^2 * [$\times 10^4$]	9.7 ± 1.3	5.0 ± 0.9	5.8 ± 0.9	13.1 ± 1.6	13.5 ± 1.6
Cyclabs	Depth, $D0$	2.1 ± 0.2	2.2 ± 0.2		$1.1^{+0.3}_{-0.2}$ (CDE)	
	$E0$ [keV]	$37.5^{+1.0}_{-0.8}$	36.9 ± 0.3		32.0 ± 0.9 (CDE)	
	Width, $W0$ [keV]	19 ± 3	12 ± 2		15 ± 4 (CDE)	
Gauss	E_{Fe} [keV]			6.50 ± 0.07 (ABCDE)		
	σ_{Fe} [keV]			0.4 ± 0.1 (ABCDE)		
	N_{Fe} [$\times 10^{-3}$]			$5.5^{+1.5}_{-1.1}$ (ABCDE)		
	Reduced χ^2/d.o.f.			1.22/1059 (ABCDE)		

*S' is the projected area in km^2 and D_{10} is the distance to the source in units of 10 kpc.
†S'_C is defined as $2d_{*,km}R_{km}\cos\theta$. See text for the definition of the symbols.

Her X-1 properties

- XMM-Newton and Chandra grating spectra (Kosec + 2022)
- The narrow emission lines Fe I, O VII(i), and N VI(i) from the atmosphere (ADC) above the outer parts of the accretion disk
- The medium-width emission lines Fe XXV, O VIII, N VII from the boundary between accretion disk and magnetosphere
- The broad emission lines Fe K and Fe L are reprocessing of the primary continuum by the accretion curtain of the neutron star.

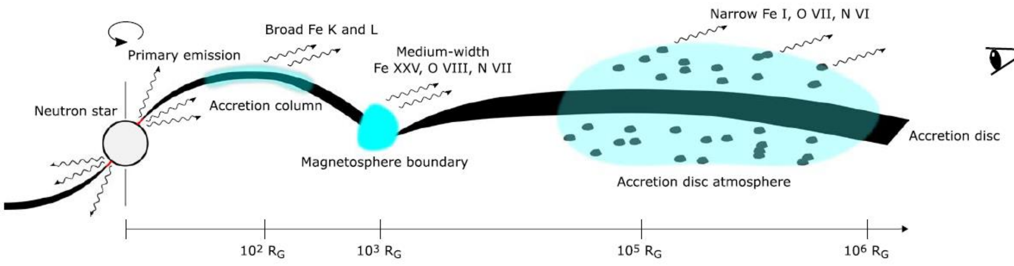


Figure 1. A schematic of the Her X-1 system, showing the different regions producing emission lines of various velocity widths. The *x*-axis of the schematic is in logarithmic scale. For simplicity, the scheme omits the accretion disk wind (detected through its absorption lines), likely originating from the inner parts of the accretion disk atmosphere.

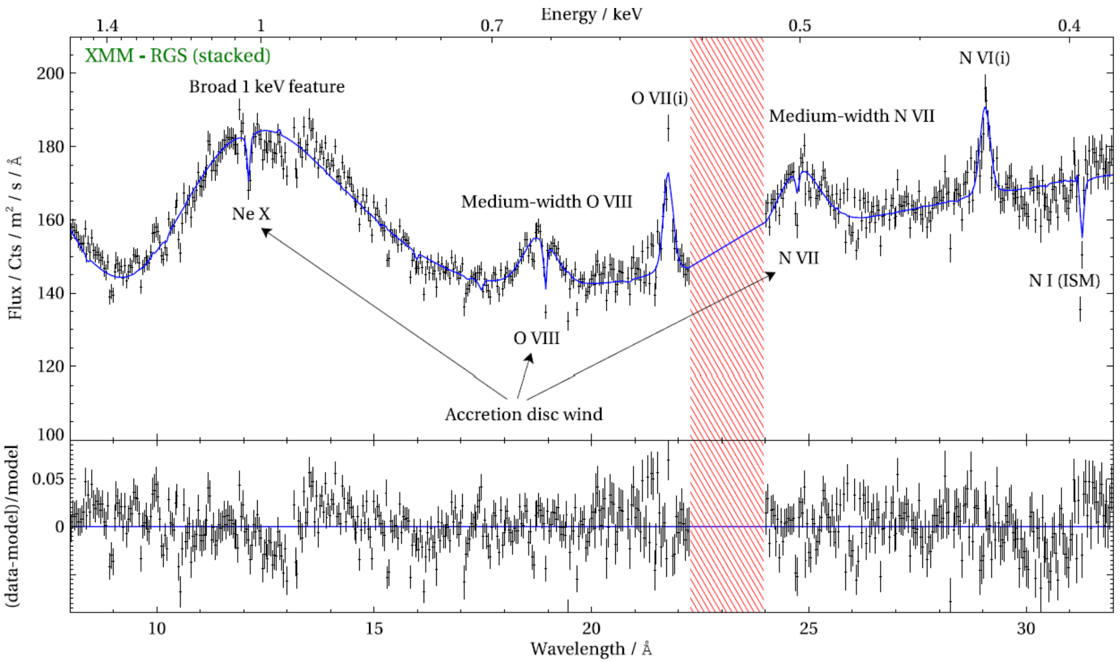
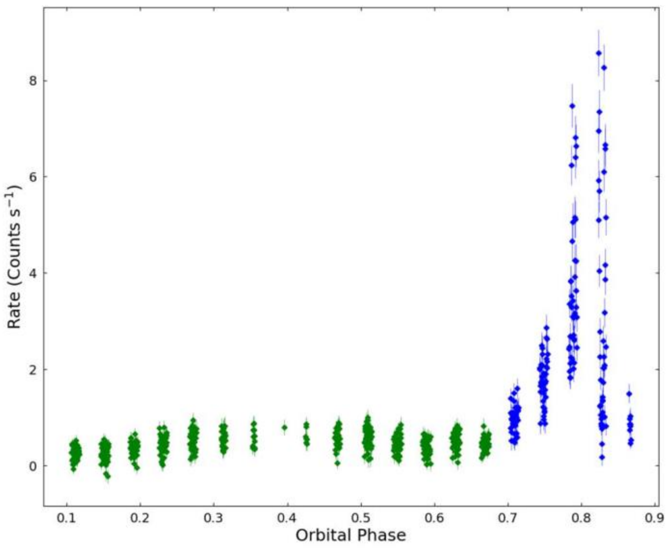


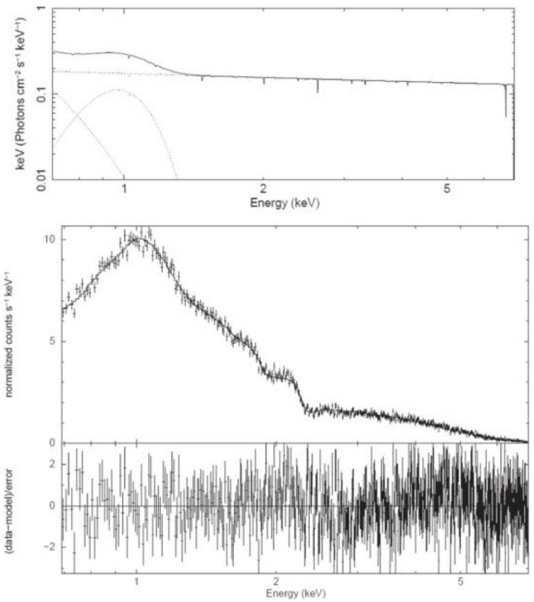
Figure 5. RGS spectrum (RGS 1 and 2 stacked for visual purposes) from the full 100 ks long observation 0865440401 (top panel), fitted with the full spectral model. Notable spectral components and features are described with labels. The red shaded region was ignored in this analysis (Appendix B). The bottom subpanel shows the ratio residuals to the best-fitting model.

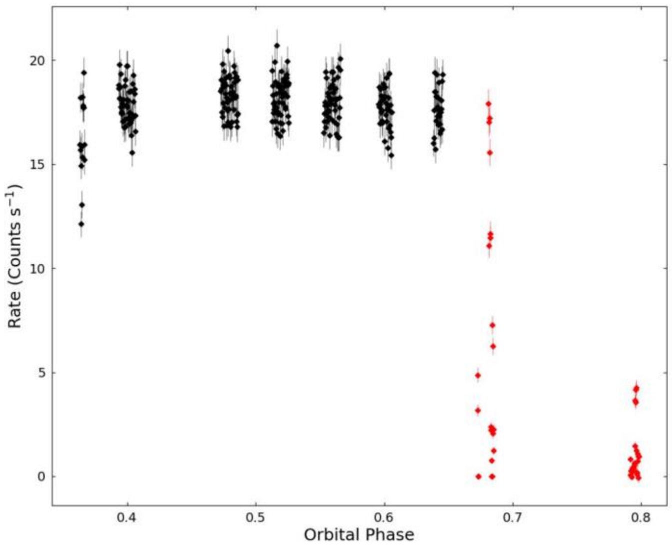
AstroSat SXT observations of Her X-1 (Leahy & Chen 2019)

SXT light curves for low-state, turn-on to Main High (top right); Main High and dip (bottom right)

Main High spectrum, requires an ionized absorber in addition to partially-covered power-law, broad Fe L-line and blackbody (below left)





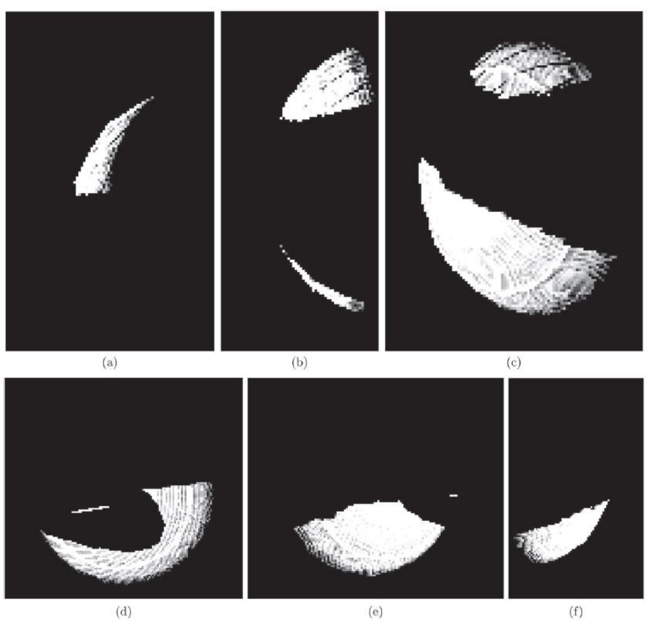


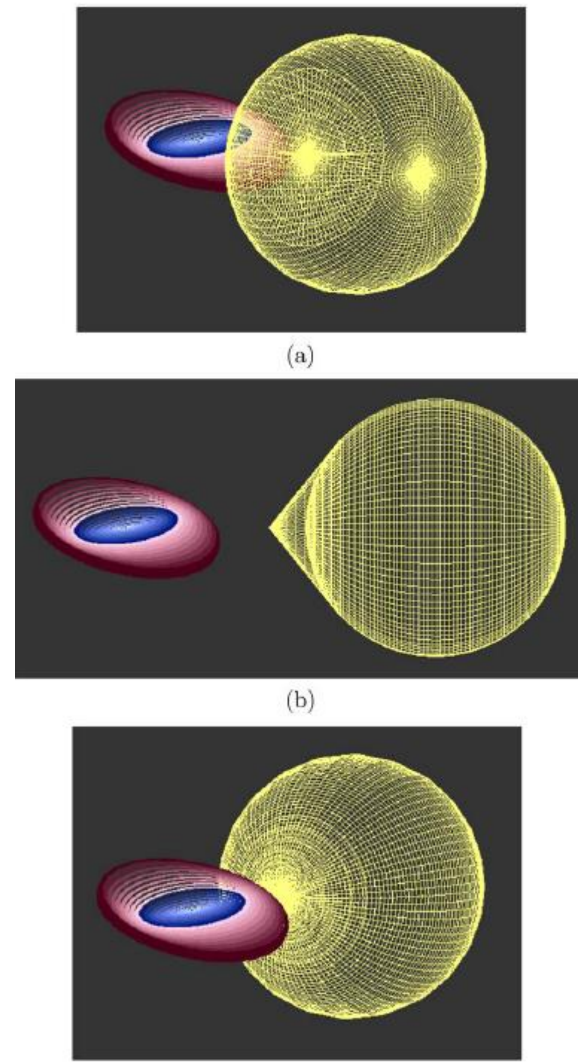
AstroSat UVIT observations of Her X-1 (Leahy+2020)

Binary system model (right)
built using Shape software (Steffan, Koning, +)

Orbital phases a) 0.0833; (b) 0.25; (c) 0.4167.

Calculated FUV emission from heated surface of HZ Her (below) at orbital phases
(a) 0.175, (b) 0.275, (c) 0.375, (d) 0.475, (e) 0.575, (f) 0.675

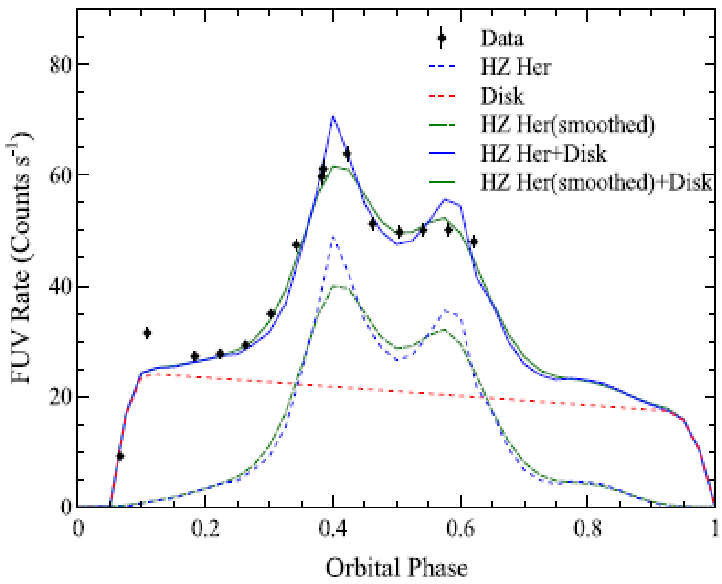


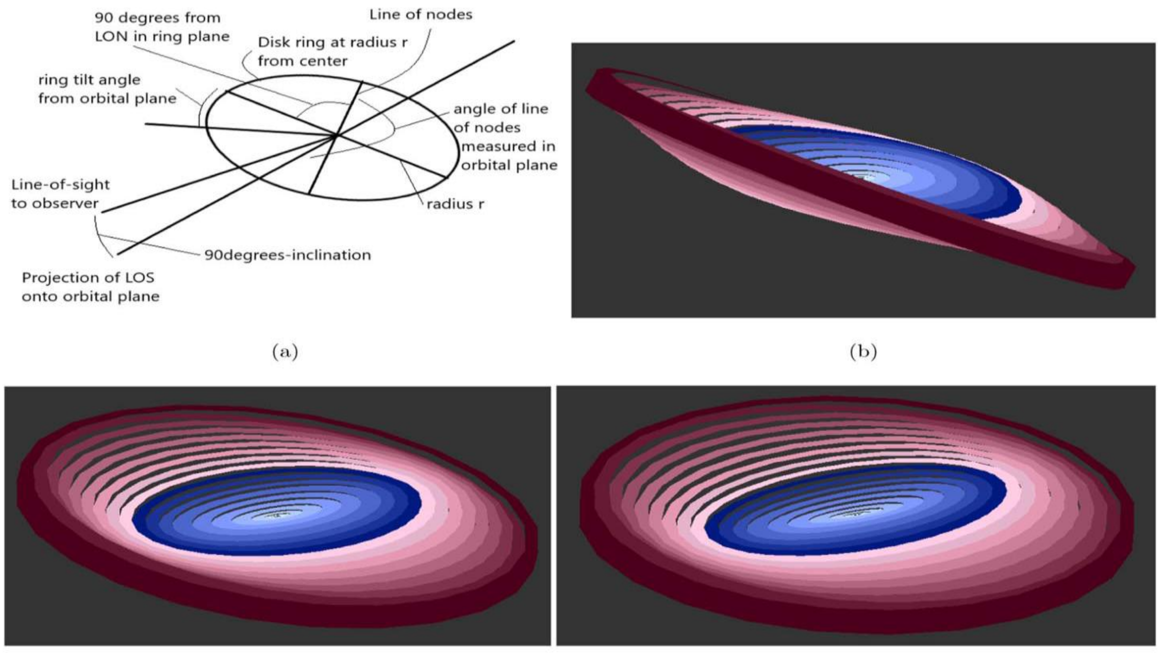


Second FUV component: emission from the disk surface (below left) using alpha-disk temperature profile. Disk rotates with 35 day period.

Adjust disk geometry to fit the UVIT FUV light-curve (inner and outer lines-of-nodes; inner and outer disk tilts)

HZ Her plus disk emission fits the FUV light-curve (right). Fit with smoothing: the disk shadow on HZ Her does not have a sharp edge.





(a) (b)

(c) (d)

Table 2
Parameters of Models for UV Light Curve of Her X-1

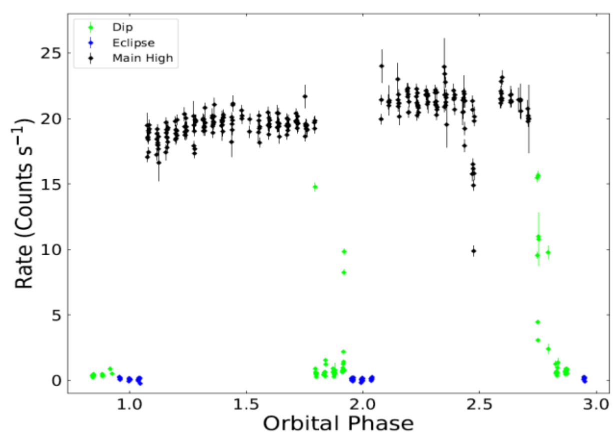
Fixed Parameters[a]:						
M_X	M_c	a	R_c[b]	Disk Radius[c]	Disk h/r[d]	
$1.5M_\odot$	$2.3M_\odot$	$a(i)$	$0.414a(i)$	$0.7d_{L1,X}(i)$	0.11	
Best-fit Parameters:						
Model A[e]						
Inclination(i)	Inner LON[f]	Outer LON	Inner tilt	Outer tilt	χ^2	χ^2_{red}
82°.5 (fixed)	21° (19–24)	132° (129–134)	10° (8–12)	23° (20–25)	203.2	20.3
85° (fixed)	21° (18–23)	131° (128–133)	11° (9.5–12)	24° (22–26)	203.7	20.4
87°.5 (fixed)	19° (17–21)	129° (127–131)	12° (10–14)	26° (24–29)	201.4	20.1
Model B[e]						
Best-fit Parameters:						
Inclination(i)	Inner LON	Outer LON	Inner tilt	Outer tilt	χ^2	χ^2_{red}
85° (fixed)	26°	136°	10° (fixed)	25° (fixed)	89.7	7.5
Model C[e]						
Parameters:						
Inclination(i)	Inner LON	Outer LON	Inner/Outer tilt	FWHM	χ^2	χ^2_{red}
85° (fixed)	26°	136°	10°/25° (fixed)	0.08	46.4	4.2

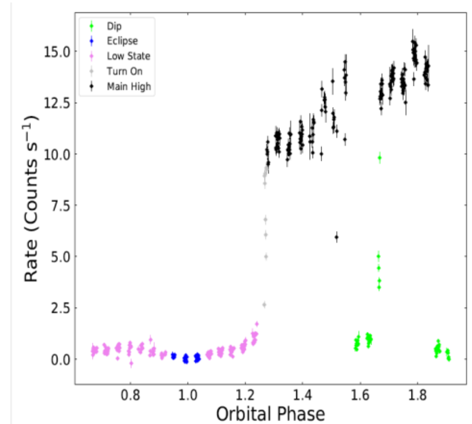
[e] Model A has a non-precessing twisted-tilted disk: a full range of parameters was explored. Model B has a precessing twisted-tilted disk: LON angle parameters were explored. Inclination was fixed at 86°, disk tilt was fixed at 10° (inner), 25° (outer). Model C is the same as Model B but in addition is smoothed with a Gaussian with FWHM in orbital phase to simulate a fuzzy disk shadow on HZ Her.

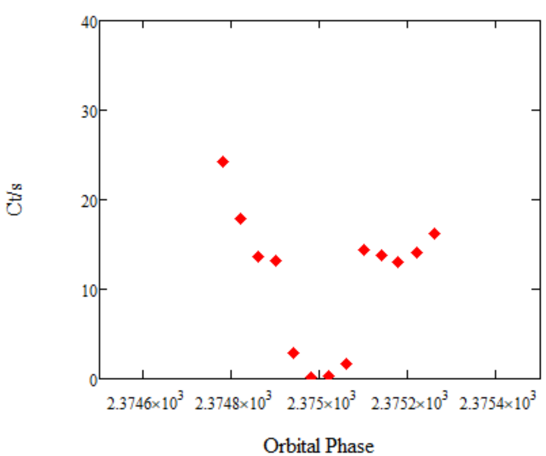
New AstroSAT SXT/LAXPC data (top row), now includes eclipses during Main High and low state

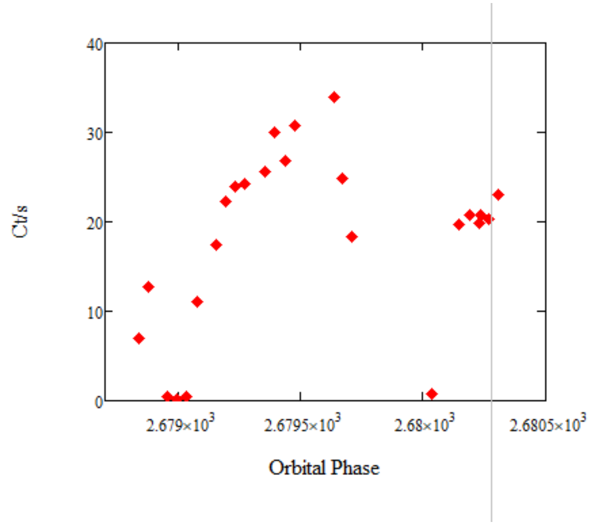
New AstroSAT UVIT FUV data (bottom row), 3 more observations including eclipses

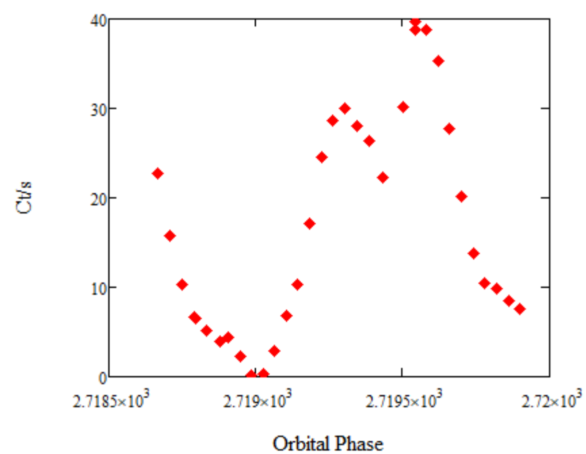
Currently working on modeling this data (X-ray and FUV)







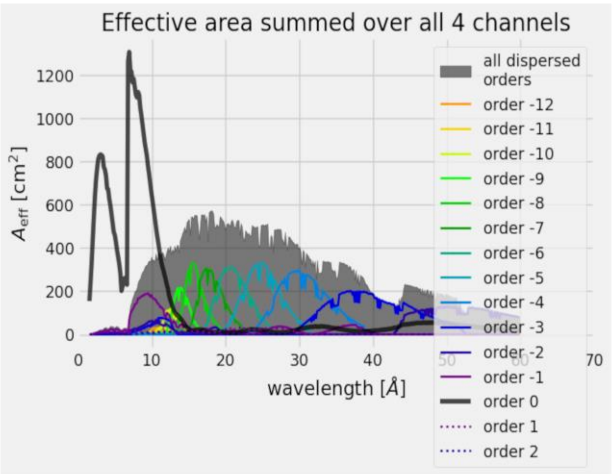


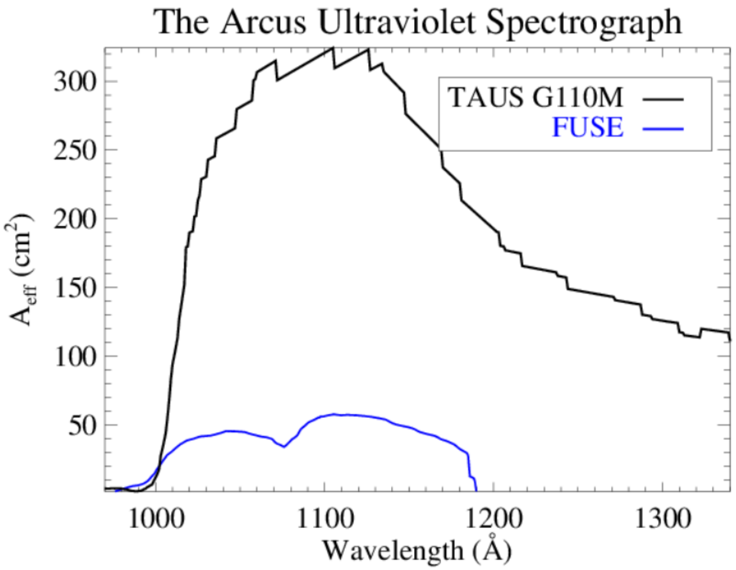


What ARCUS can do for Her X-1

- Spectroscopy in X-ray and in UV to determine the locations of different line emission regions: accretion column reprocessing, illuminated inner disk and warped disk surface, accretion stream, illuminated surface of HZ Her
- E.g. current highest sensitivity for X-ray spectroscopy: XMM Newton RGS peak effective area ~150 cm^2, resolving power 150 to 800 from 5 to 35 Å

Bandpass	**X-ray:** 10-60 Å **FUV:** 970-1,350 Å
Spectral resolution	**X-ray:** R=3,500 (average over band) **FUV:** R=21,000
Effective Area	**X-ray:** 350 cm^2 at 19 Å **FUV:** 330 cm^2 at 1,100 Å
Calibration	**X-ray:** ± 0.4 mÅ (± 5 km/s) **FUV:** ± 0.51 mÅ (± 15 km/s)
X-ray Instrument Technology	Silicon pore optics + critical angle transmission grating + high heritage CCDs
FUV Instrument Technology	Large-format photon-counting detectors + advanced UV mirror coatings
X-ray Background	0.008 cts s^{-1} $Å^{-1}$ at 24 Å
FUV Sensitivity Limit	S/N = 15 in 100 ks with 3e-15 erg/s/cm^2/Å
Target of Opportunity Response Time	24 hours
Continuous Observing	100 ks
Launch Date	December 2031





Summary

- AstroSAT has observed Hercules X-1 with SXT, LAXPC, CZT several times (A02, A03, T02, T03, A07, A10) and with UVIT for a subset of these (T02, T03, A07, A10)

- Orbital light curve model for UVIT data uses disk shadowing to derive disk shape. FUV dominated by HZ Her heated surface. Disk shadow in FUV gives better constraints than previously possible.

- SXT spectra of Main High and Short High turn-ons and declines verify the disk occulation model. Turn-on caused by the outer disk edge moving out of line-of-sight. Main High and Short High declines caused by inner disk edge blockage and scattering of X-rays.

- ARCUS spectra of X-ray emission and absorption lines from the hot gas as a function of orbital and of 35-day phase will resolve the nature of: i) dips; ii) mass outflow physical conditions

- New data and analysis is underway