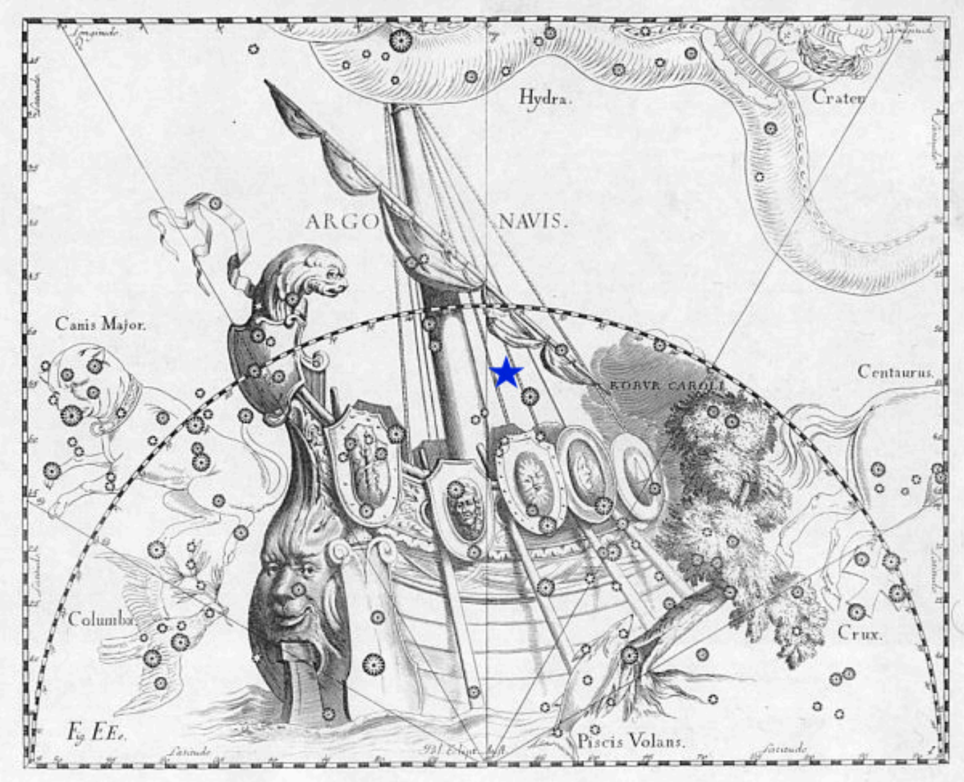
Vela X-1 as a laboratory for accretion in High-Mass X-ray Binaries



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We know this system since 1966 …

ApJ 150, 57

X-RAY INTENSITIES AND SPECTRA FROM SEVERAL COSMIC SOURCES*

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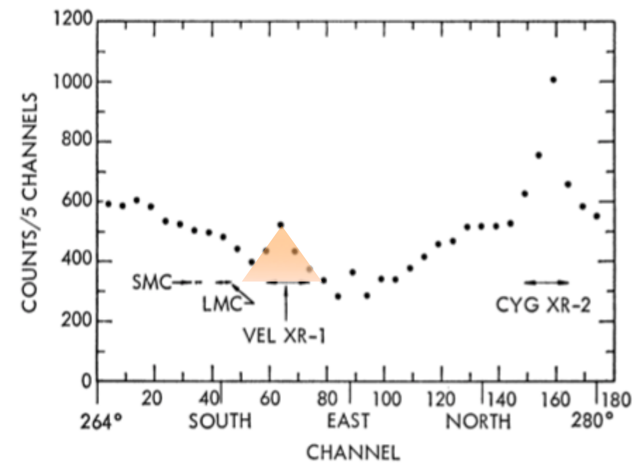
Lawrence Radiation Laboratory, University of California, Livermore

Received March 22, 1967

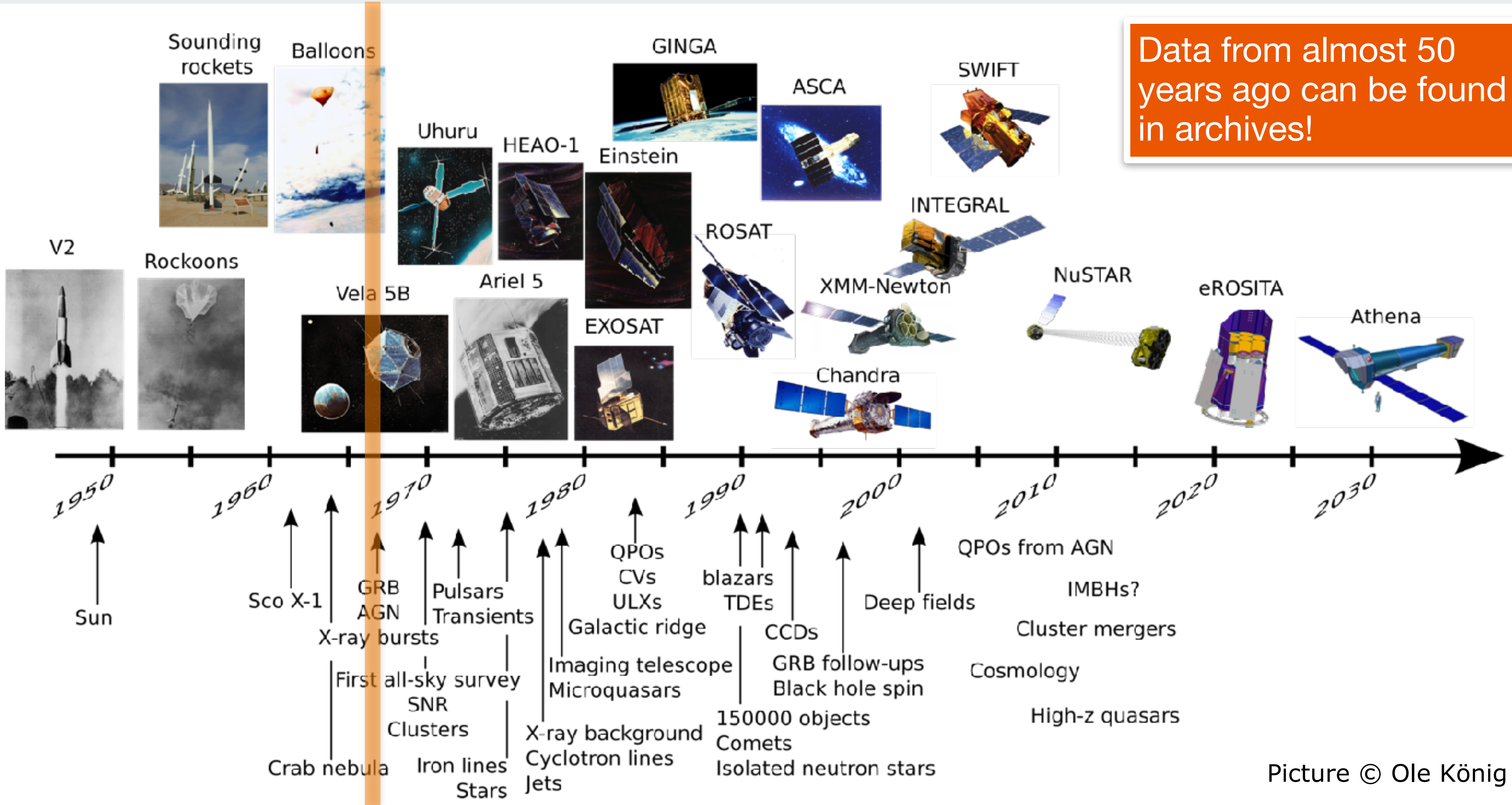
ABSTRACT

This paper reports the results of X-ray spectrum and intensity measurements for several cosmic X-ray sources. Two flights were conducted, one from Kauai, Hawaii on July 28, 1966, and the other from Johnston Atoll on September 20, 1966. Proportional counters with anticoincidence shields to eliminate charged-particle background counts were used to detect the X-rays. Four known sources were observed: Sco XR-1, Tau XR-1, Cyg XR-1, and Cyg XR-2. Total intensity determinations were made for all of these sources, and spectra were obtained for Sco XR-1 and Cyg XR-2. A search was made for X-rays from the Large and Small Magellanic Clouds, but no X-rays above background were found in that region of the sky. An upper limit of the X-ray intensity from the Magellanic Clouds has been determined from these data. A weak X-ray source not previously observed was found in the constellation Vela (Vel XR-1).



In other words, since the early times of X-ray astronomy

Data from almost 50 years ago can be found in archives!

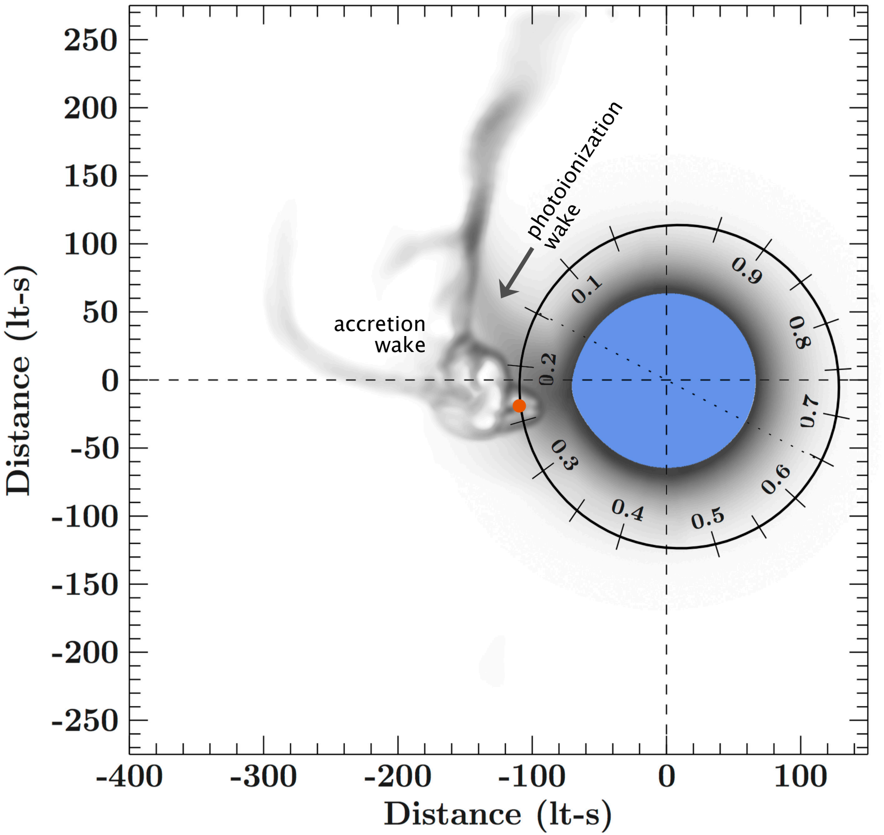


Picture © Ole König

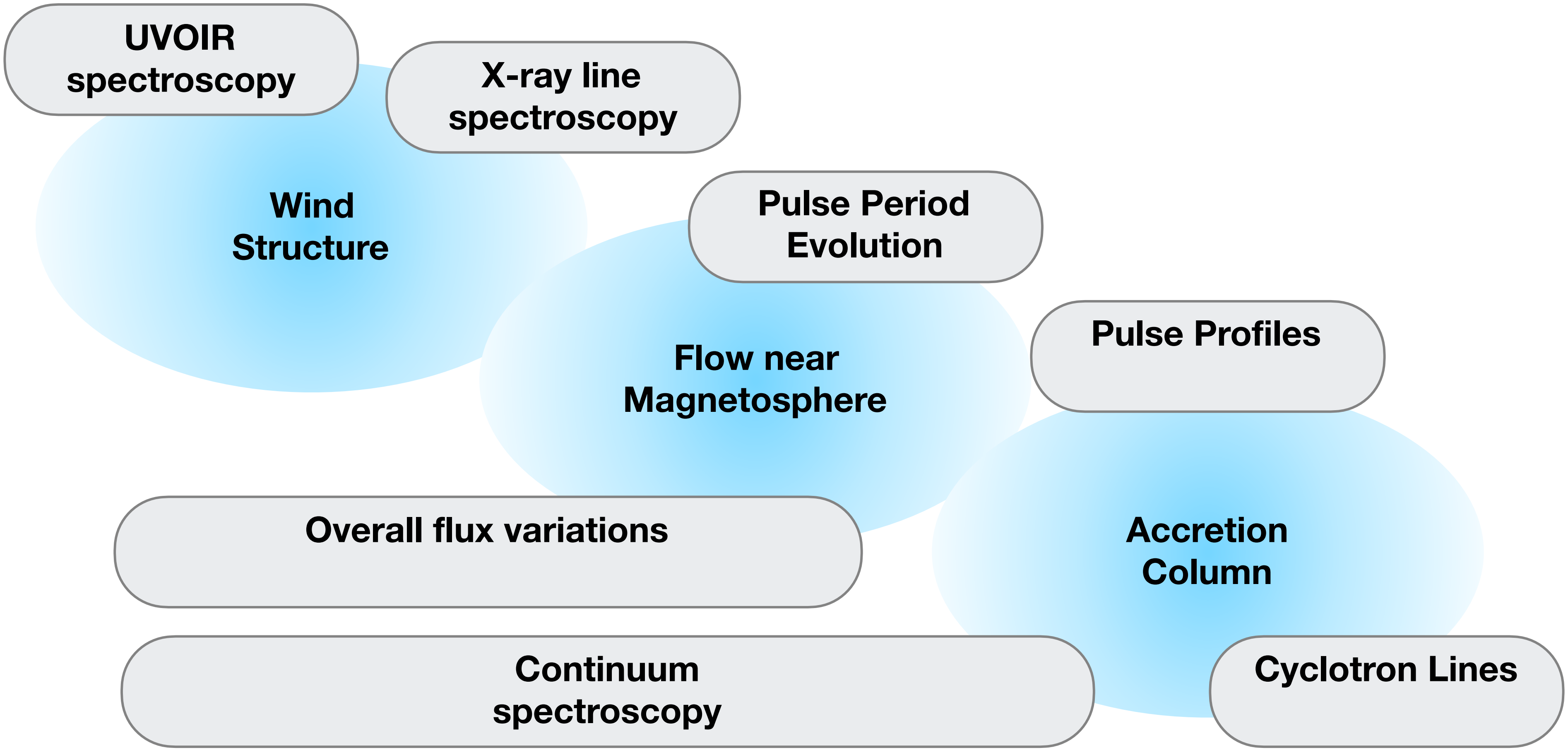
And we know it rather well by now

Distance [1]	2.42 (2.25–2.60) kpc
Mass donor [2]	B0.5Ia, 21.5±4 $M_\odot$
Accretor [2]	neutron star, 1.9+0.7-0.5 $M_\odot$
Orbital period [4]	8.964357±0.000029 d
a sin *i* [2,3]	113.89 lt-sec, *i* > 79 deg
Eccentricity [3]	0.0898±0.0012
Pulse period [4]	~283 s (fluctuating)

[1] Bailer-Jones+ (2018)
[2] Giménez-García+ (2016)
[3] Bildsten+ (1997)
[4] Kreykenbohm+ (2008)



Different diagnostics (obs. & models) covering different scales



Terminal wind speeds are estimated quite differently

Dupree et al. (1980)	v_∞ = **1700** km/s	IUE (selected lines & phases)
Prinja et al. (1990)	v_∞ = **1100** km/s	IUE, P Cyg profiles
van Loon et al. (2001)	v_∞ = **600** km/s	Modelling IUE lines
Watanabe et al. (2006)	v_∞ = **1100** km/s	Modelling Chandra X-ray gratings
Giménez-García et al. (2016)	v_∞ = $\mathbf{700^{+200}_{-100}}$ km/s	IUE + optical + 2MASS, SED fitting & modelling with PoWR code
Sander et al. (2018)	$v_\infty \approx$ **600** km/s	Detailed modelling with PoWR code, including X-ray effects

➟ **Essential system parameter estimate depends significantly on assumptions taken.**

Elaborate modelling indicates slow wind around neutron star

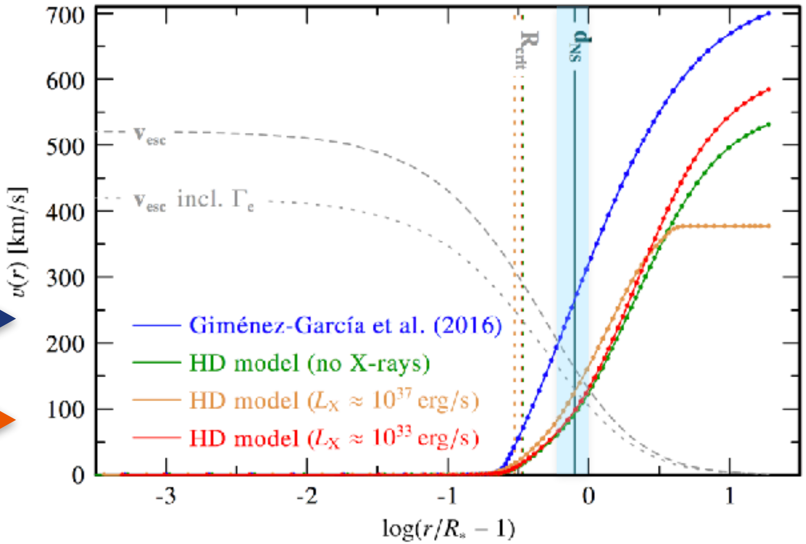
Sander et al. (2018):

- **Hydrodynamically consistent atmosphere model** describing the wind stratification, including effects of X-ray illumination in simplified way.
- Detailed study of contributions of different ions to wind acceleration.
- Velocity field turns out quite different from usually assumed β-law: **wind velocity** at distance of neutron star may be **much lower**.
- Flow of matter may be **very different (see talk by I. El Mellah).**

$$v(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta$$

β-law

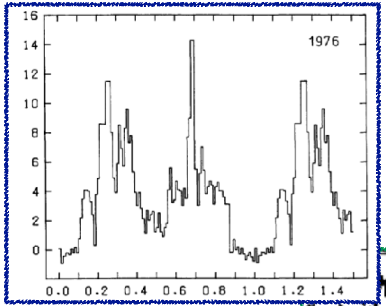
HD Model

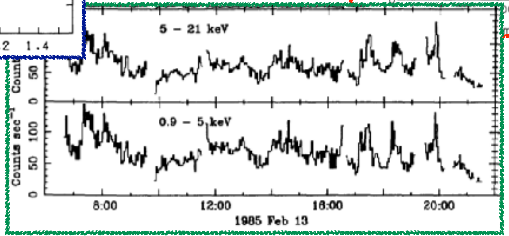


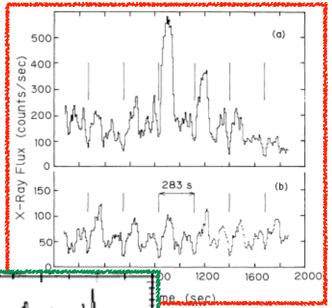
Flux variations are observed on many time scales

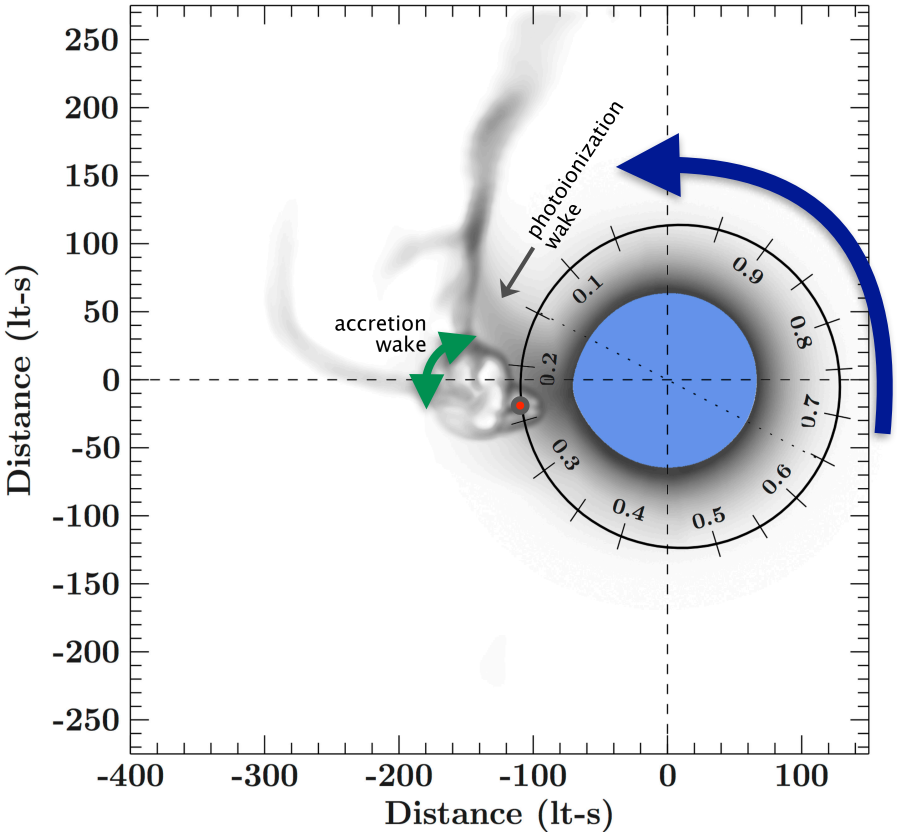
- **Orbital:** ~1–10 d
- **Within orbit:** hours – days
- **Pulse period:** minutes

On longer or shorter time scales no evident variation has been reported.

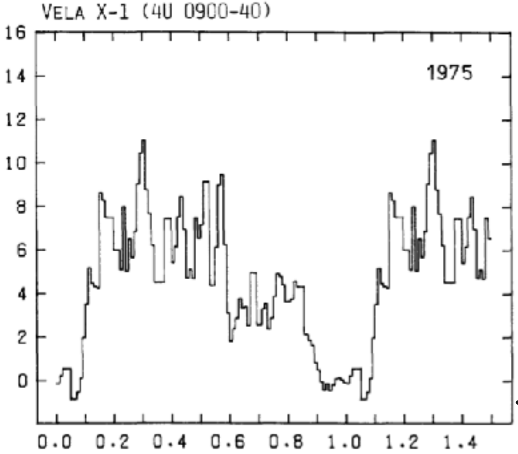


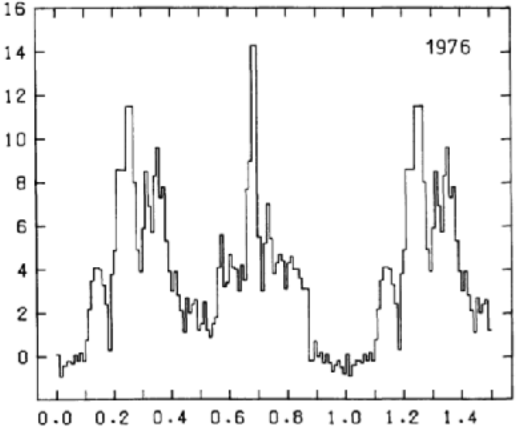






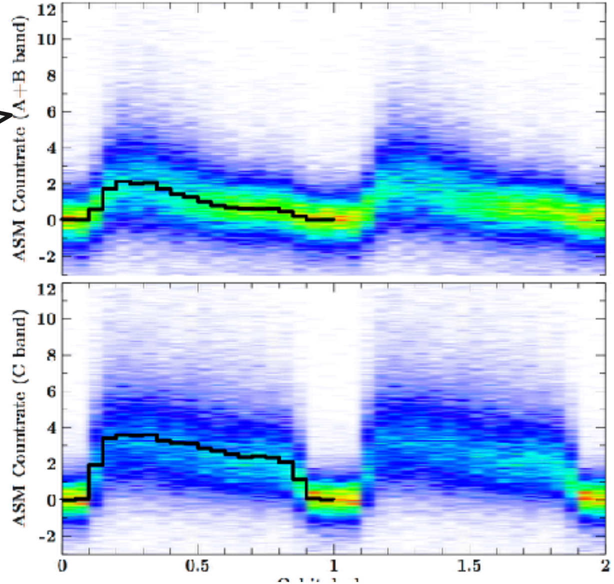
No two orbits are the same, but there are stable mean patterns



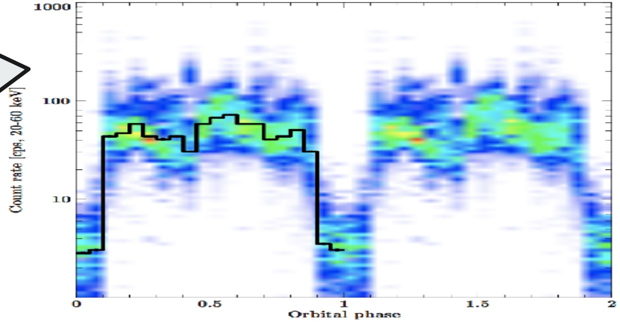


Van der Klis & Bonnet-Bideau (1977)
COS-B X-ray detector
1975 & 1976

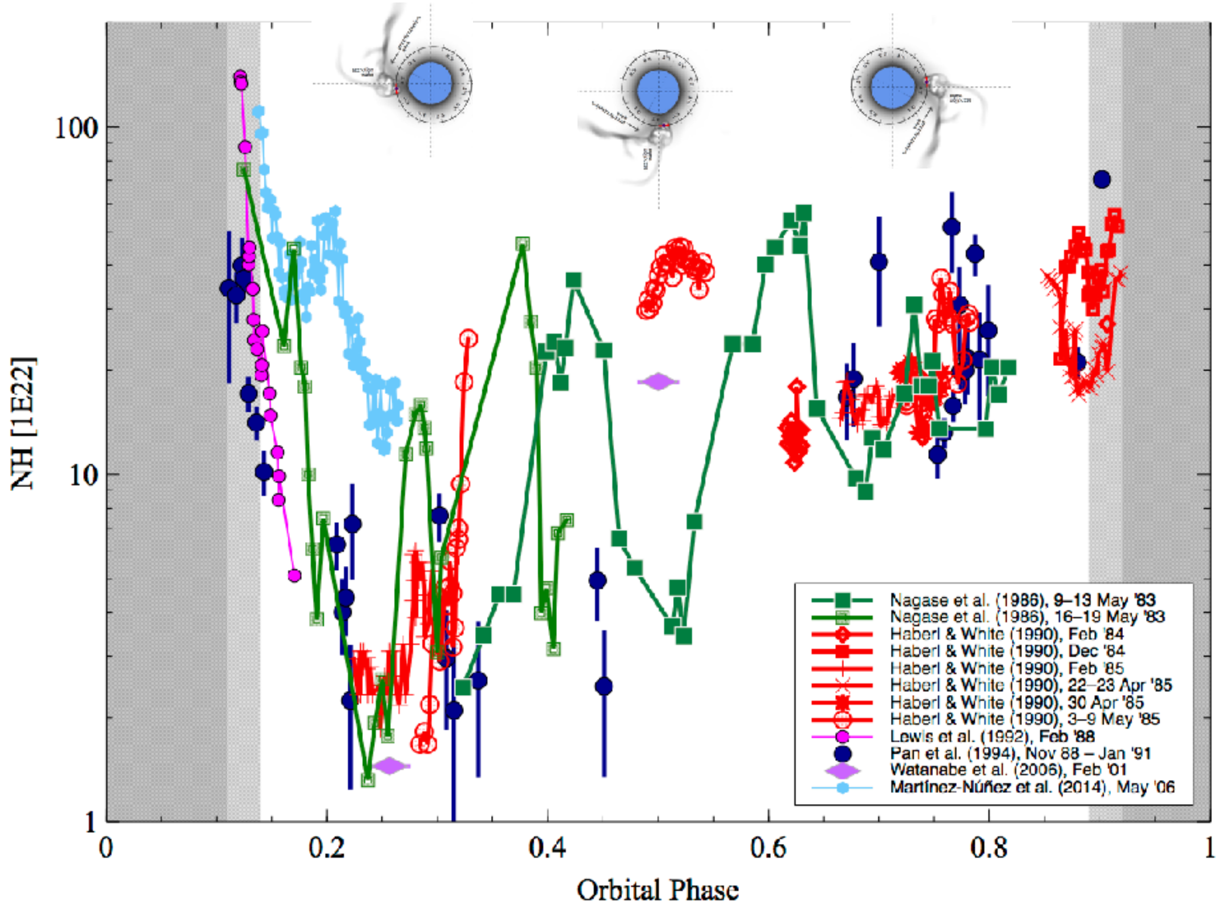
Fürst et al. (2010)
RXTE ASM
1996–2009



Fürst et al. (2010)
INTEGRAL ISGRI
2003/2005/2006



Absorption varies strongly along the orbit

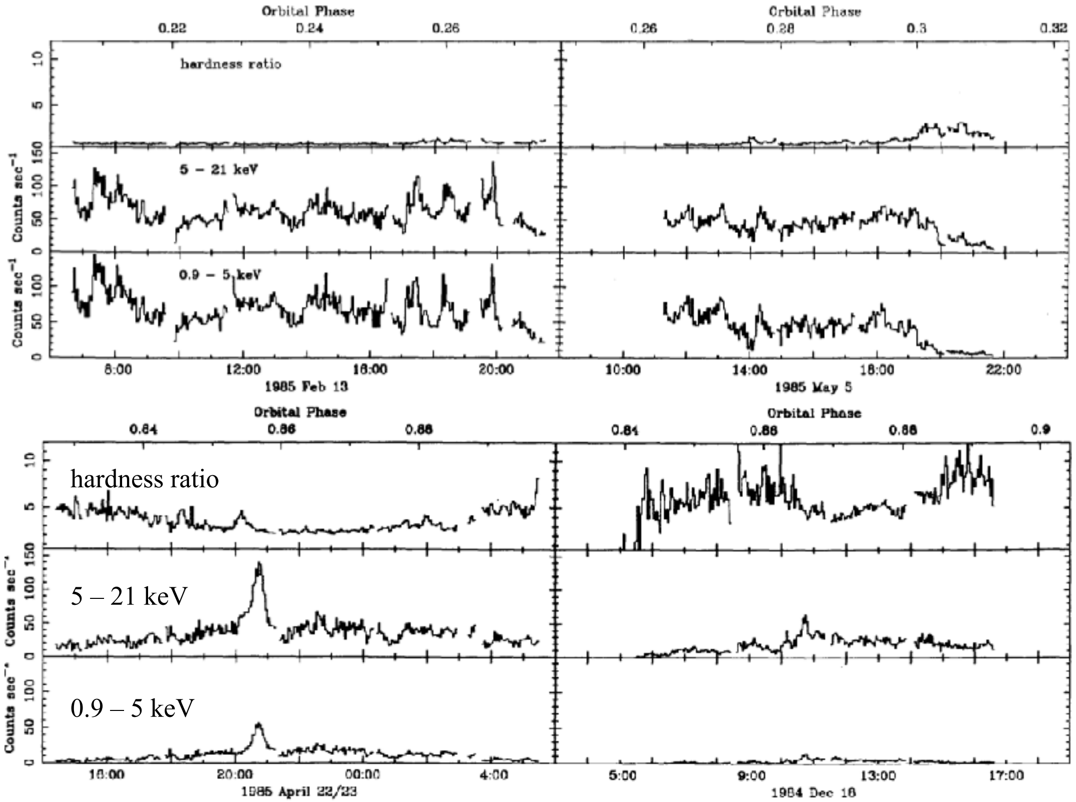


Various satellites find strong N_H variations along orbit as expected from large structures.

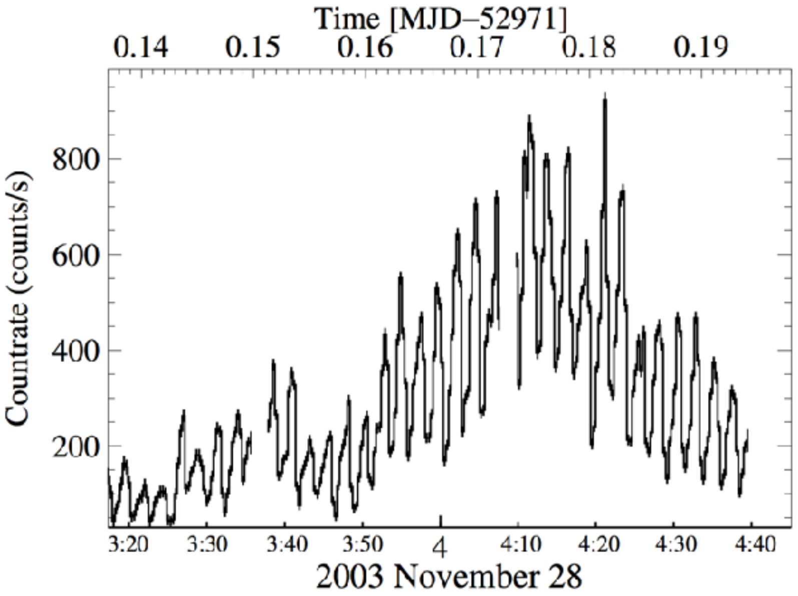
But same phases can look very differently at different times!

Caveat: different spectral models and absorption modelling ➟ absolute values not directly comparable.

Apparently chaotic variability at shorter time scales

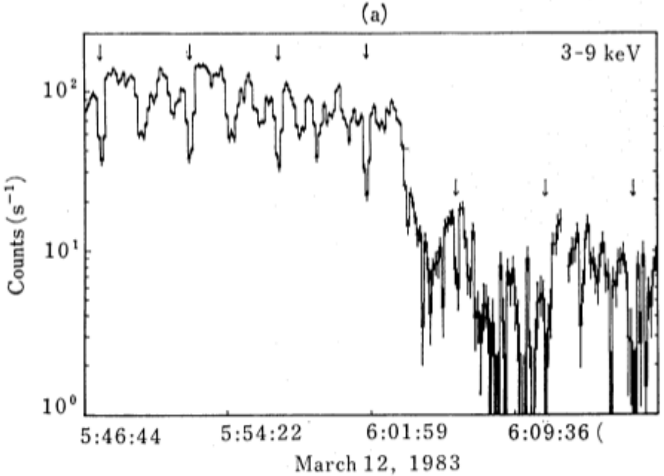


Haberl & White (1990)
EXOSAT
1985



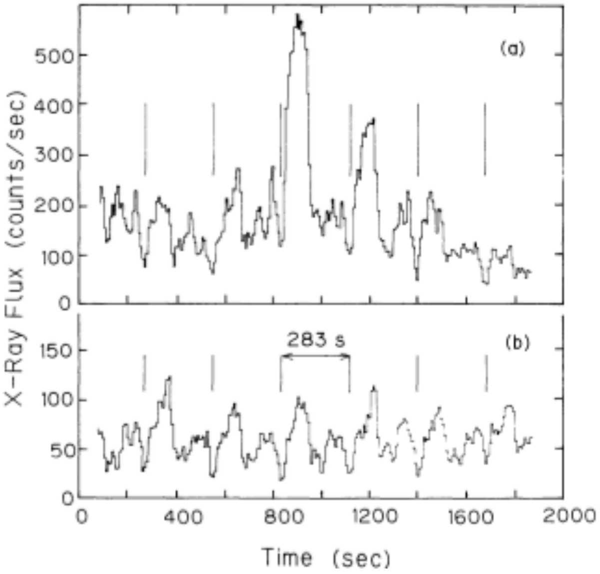
Kreykenbohm et al. (2008)
INTEGRAL ISGRI
2003

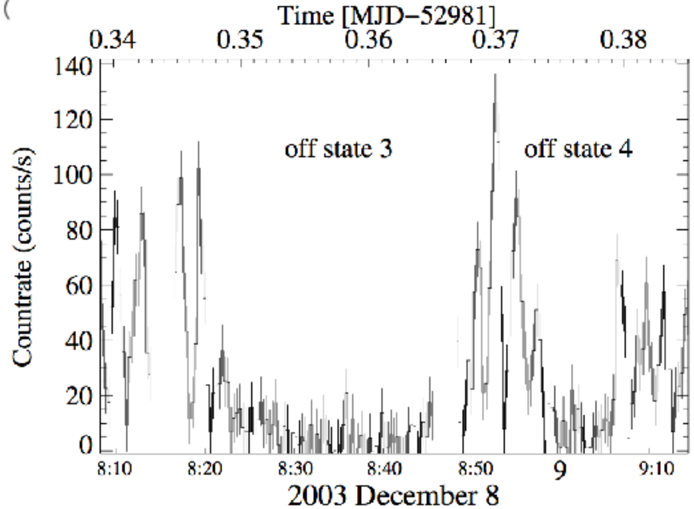
The flux can change from one pulse to next



Inoue et al. (1984)
Tenma
1983

Börner et al. (1984)
Tenma
1983



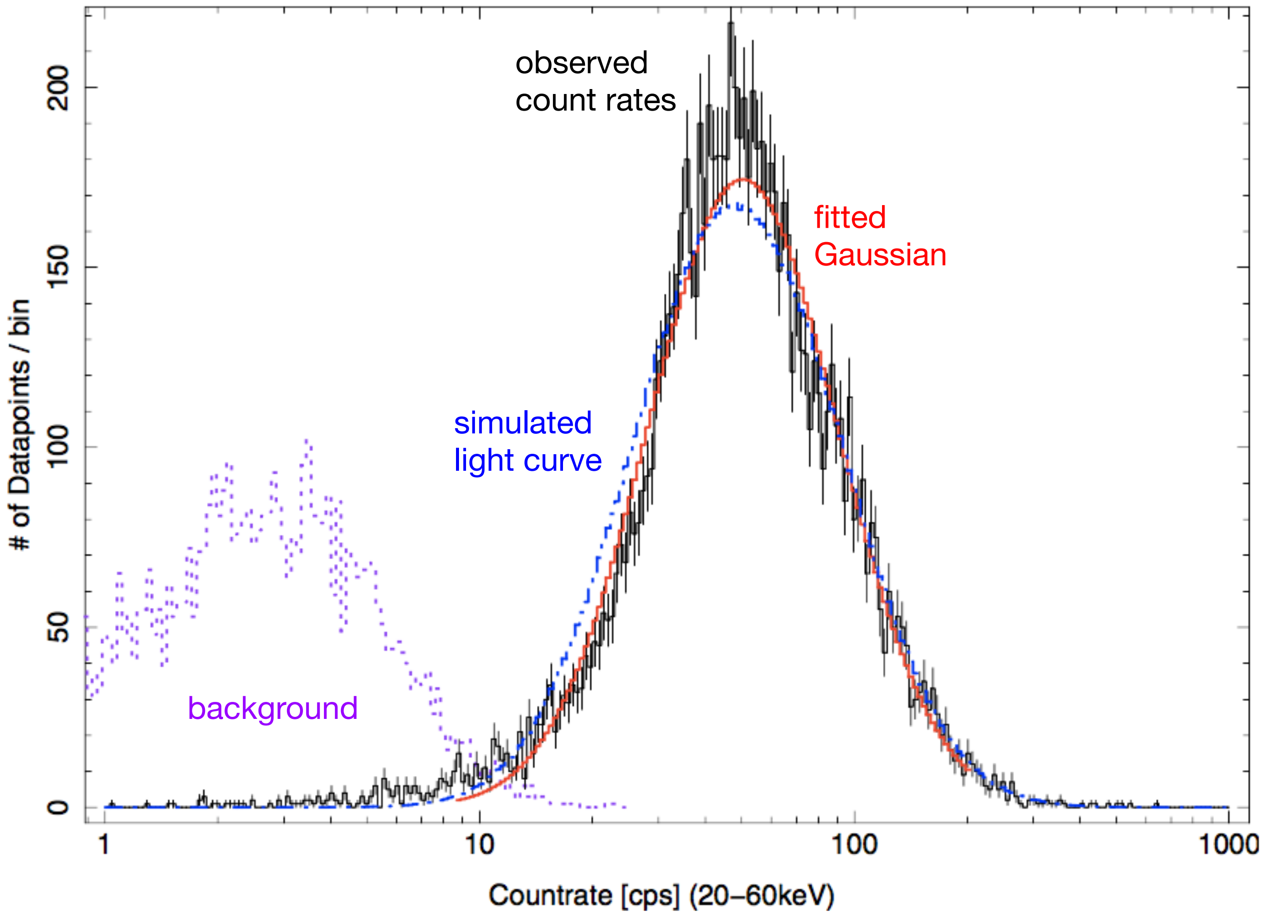


Kreykenbohm et al. (2008)
INTEGRAL ISGRI
2003

Pulse-averaged flux shows log-normal distribution

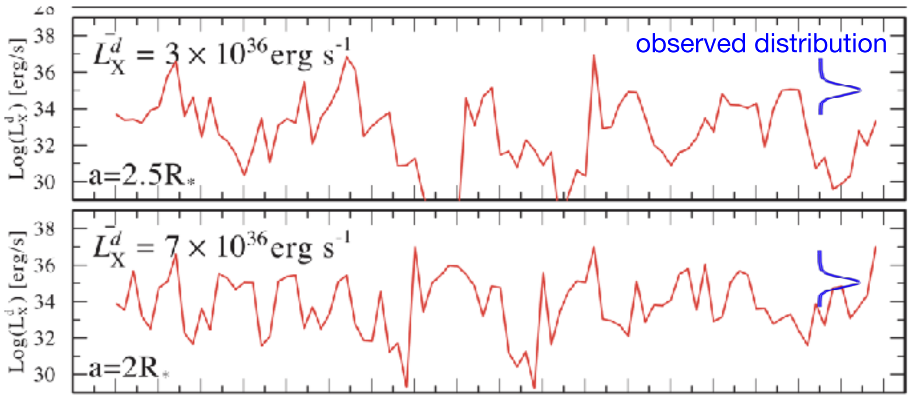
Fürst et al. (2010):
Bins of 283.5 s (~average over pulse), filtered to avoid eclipse.

"Shock fronts and turbulence breaking up clumps can transfer any given distribution into a log-normal like distribution."

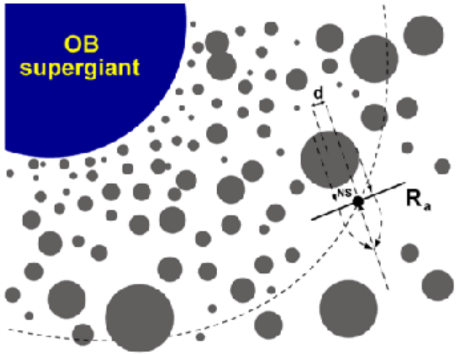


Modelling the *right* amount of variation can be difficult

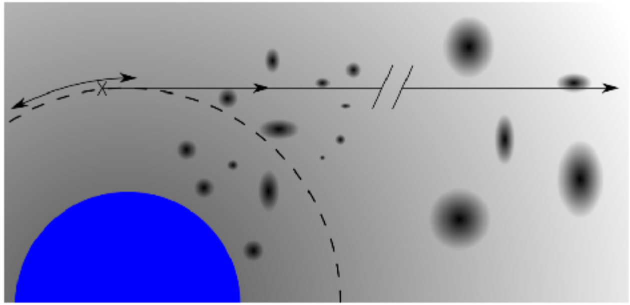
‘Naive’ 1-D modelling of accreting clumps (shells) by BHL accretion over-predicts observed variability strongly.



Simulated clump distribution gives more realistic light curve (Ducci et al. 2009), but clump sizes required uncomfortably large.

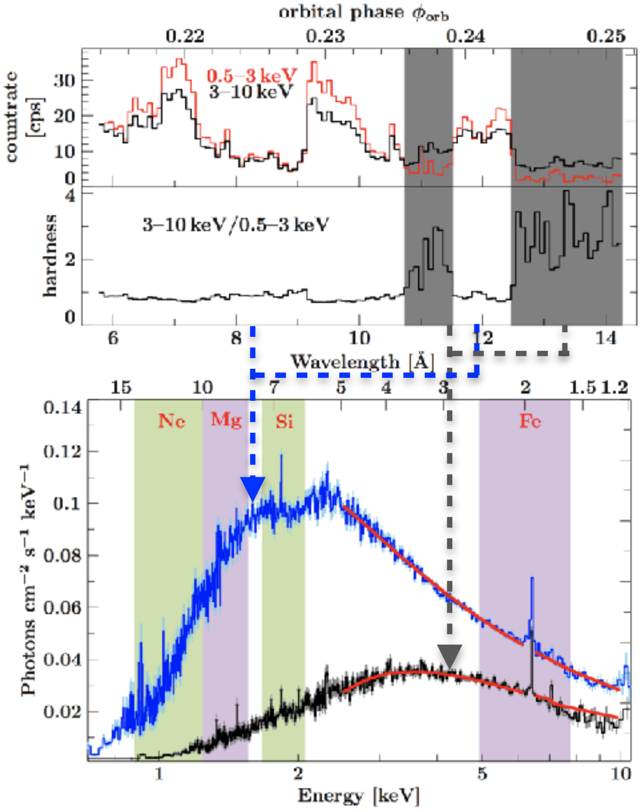


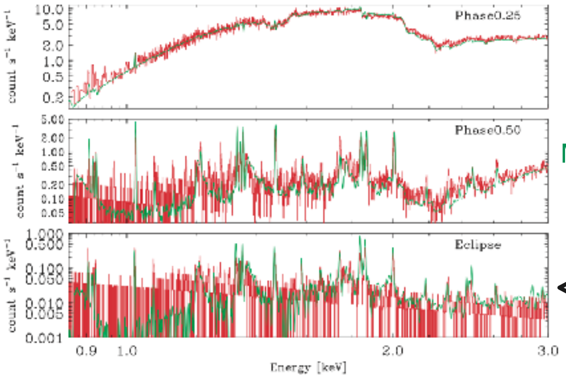
‘Realistic’ clump model for Vela X-1 *under-predicts* observed absorption variations, if assumed to be caused by clumps (Grinberg et al. 2017)



X-ray fluorescence lines yield additional information

- X-ray fluorescence lines can yield additional information about wind structure, velocities and neutron star surroundings.
- Example from Grinberg et al. 2017: Hardness-selected spectra show variable emission and absorption line features from neon, magnesium and silicon. See also Watanabe et al. (2006).





Data

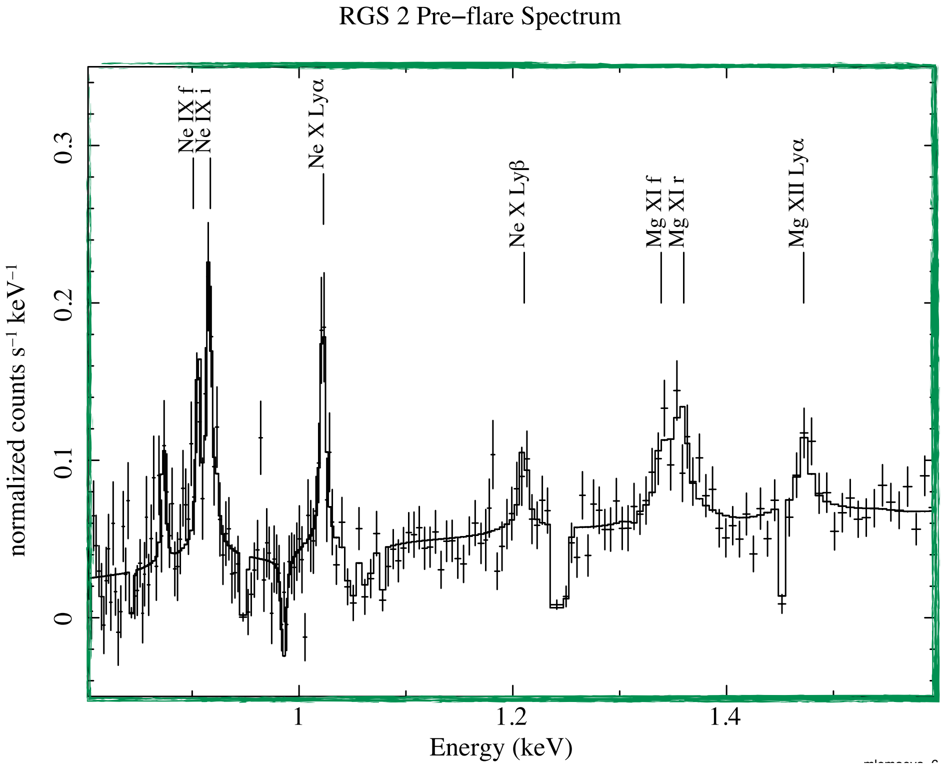
MC model folded

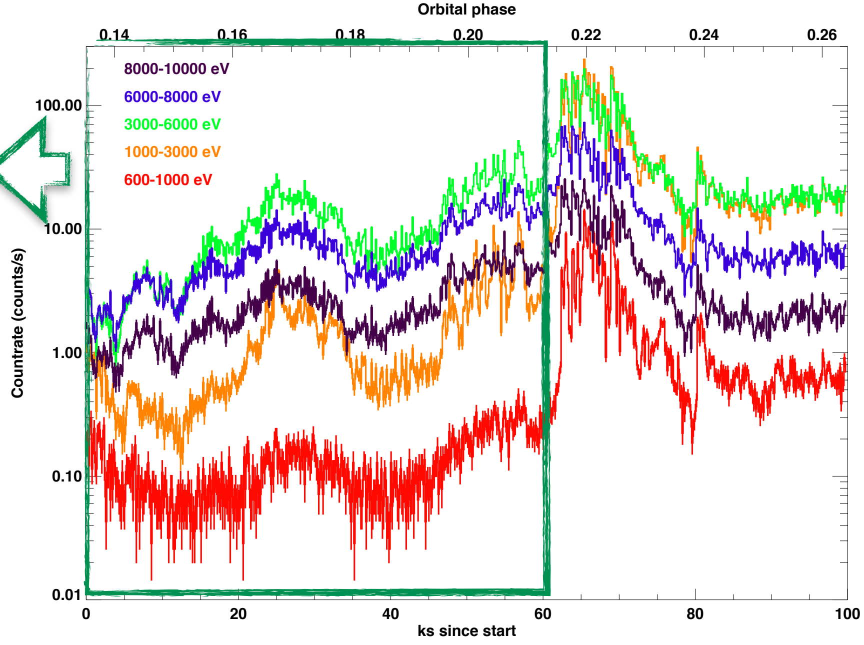
Watanabe et al. (2006)

Grinberg et al. (2017)

X-ray fluorescence lines, more analysis underway

- On-going study by Maria Lomaeva (ESA, ESTEC) on XMM-Newton RGS spectra taken after eclipse egress. Analysis ongoing.





The Vela X-1 system is now also found in the radio!

Very recent result (Degenaar, van den Eijnden, et al.):

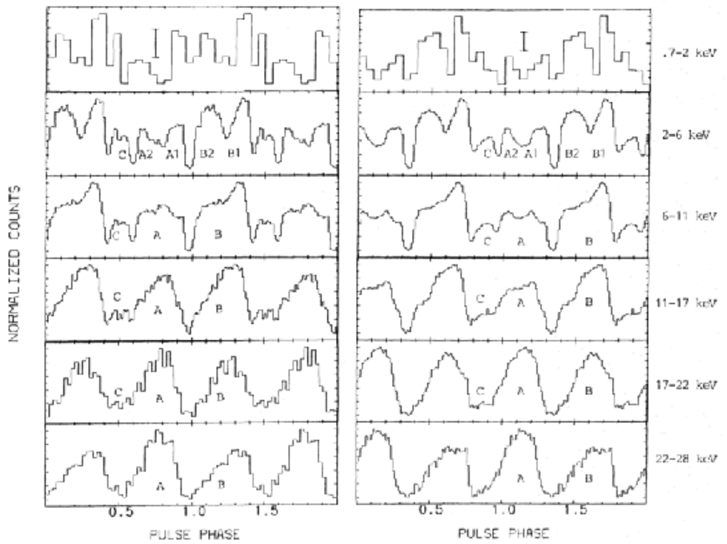
- Highly significant (~100 μJy) radio detection of Vela X-1 with ATCA.
- Observation done by chance at mid eclipse. More foreseen.
- Flat radio spectrum, like for a compact jet.
- Cannot exclude donor star as radio source yet, but this would also be interesting.

Pulse profiles *should* allow to disentangle the emission geometry

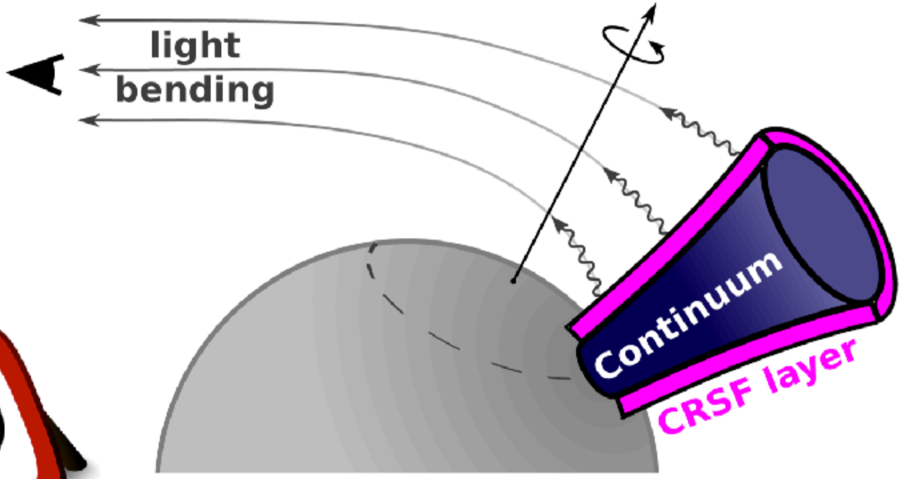
- The pulse profile is complex at lower energies and overall rather stable *usually*.
- Doroshenko et al. (2011) found changed pulse pattern in “off-state”.

➡ *In principle* able to derive information on emission geometry.

- But complicated analysis if general relativity and realistic emission geometries are taken into account! Still quite a bit of work on models and comparison.



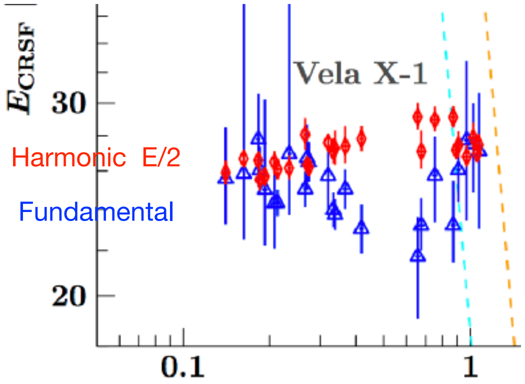
Raubenheimer (1990)



Falkner at al. (2016)

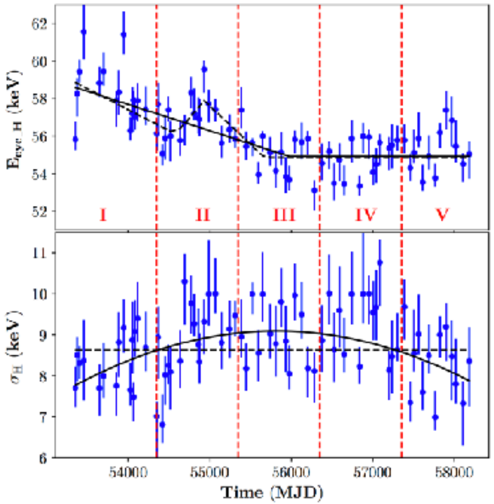
Cyclotron lines maybe more puzzling than enlightening

- Cyclotron Resonant Scattering Features found in 36 sources so far (Staubert et al. 2019).
- Most direct measure of magnetic field strength. Variations in observed centre energy ➟ changes in (height of) emission region.



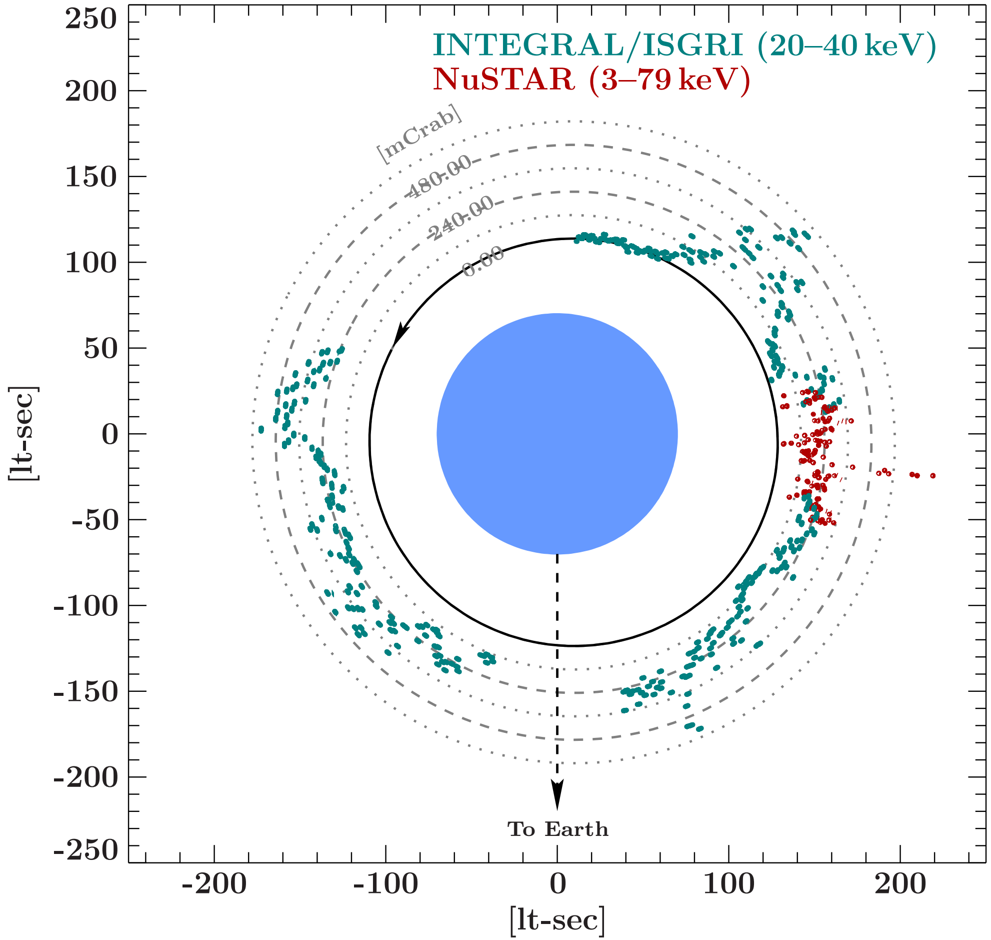
- Fürst et al. (2014): *harmonic* line varies with luminosity. No clear picture for fundamental.
- Ji et al. (2019, submitted): possible long-term trend in energy (Swift BAT).

➡ Will need improved accretion column models to better interpret the data.



More data is coming from large observing campaign in January 2019

- Major observational campaign motivated by planned X-Calibur balloon observations (polarisation).
- Coordinated by H. Krawczynski with involvement by V. Grinberg and F. Fürst.
- Sadly, the balloon deflated prematurely, but INTEGRAL data for one full orbit plus NuSTAR and some Swift & NICER observations.



Working to solve a complex, multi-scale puzzle