

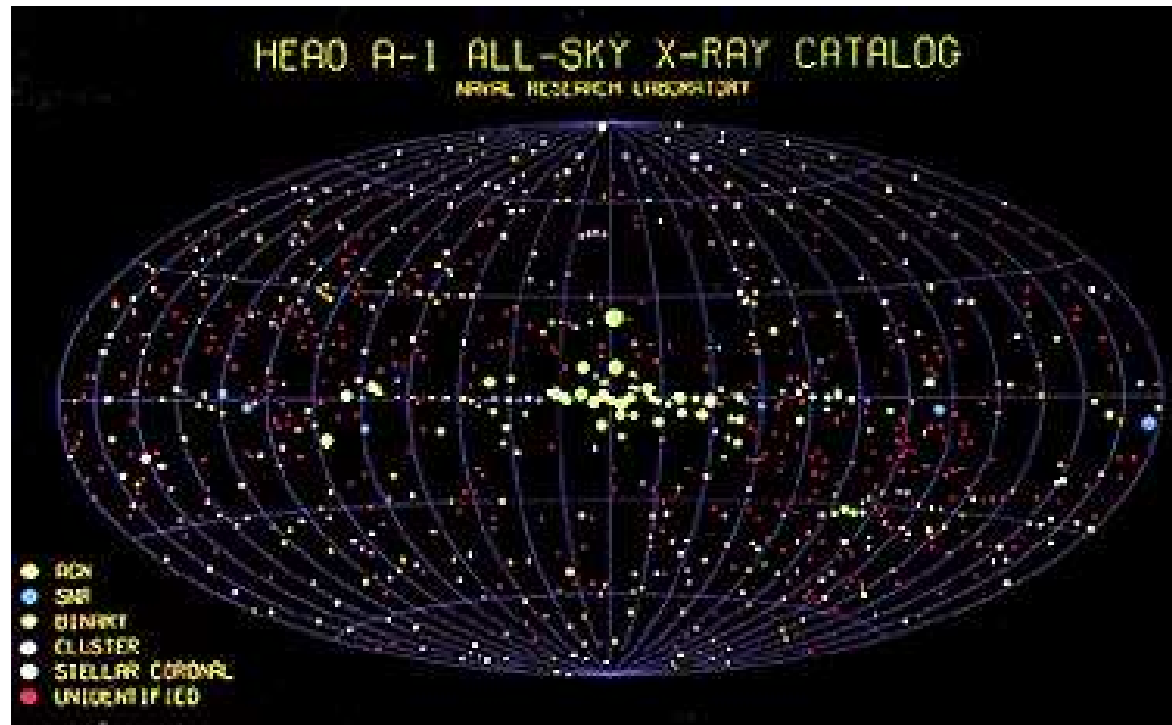


# **Time-Resolved X-ray Spectroscopy of Accreting White Dwarfs**

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# CVs among 2–10 keV Sources



- Of the 660 sources in the HEAO A-3 catalog (a subset of the 842 sources in the A-1 catalog that were localized using the modulation collimator), 42 are classified as CVs.
- CVs are a significant minority population of the X-ray sky.

# Plan of Talk

Cataclysmic variables (CVs) in which a white dwarf accretes from a Roche-lobe filling secondary provide an excellent laboratory to study accretion up close, and in a mostly non-Relativistic (i.e., simple) regime.

This talk includes:

- A note on subtypes, space density, and X-ray luminosity function.
- A side note on classical and recurrent nova outbursts.
- An observer's standard scenario of X-ray emission in non-magnetic CVs.
  - Spectral model and the white dwarf mass
  - Puzzle 1: RS Oph in quiescence
  - Puzzle 2: The outburst cycle of SS Cyg
  - A possible solution?
- The spectra of magnetic CVs.
  - Reflection and complex absorption

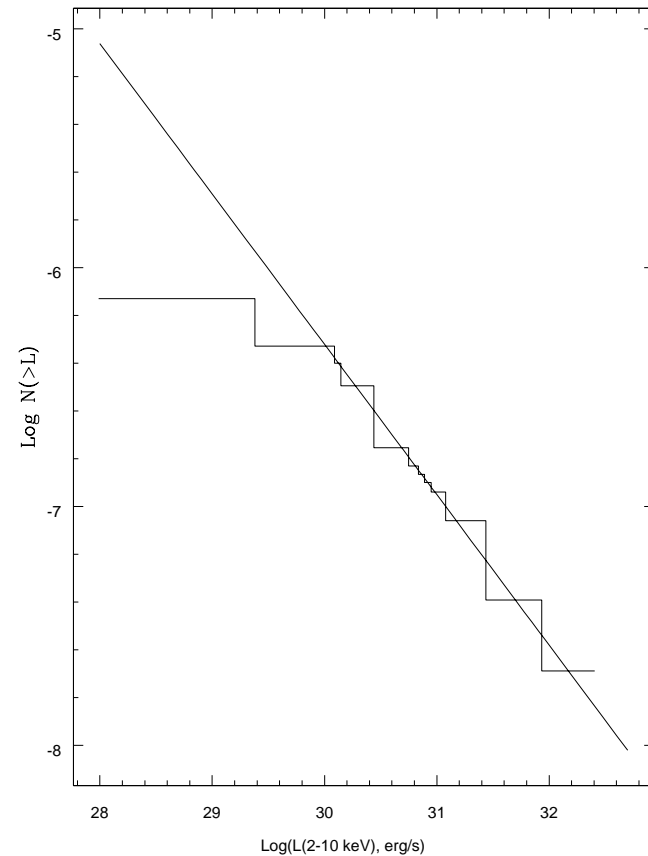
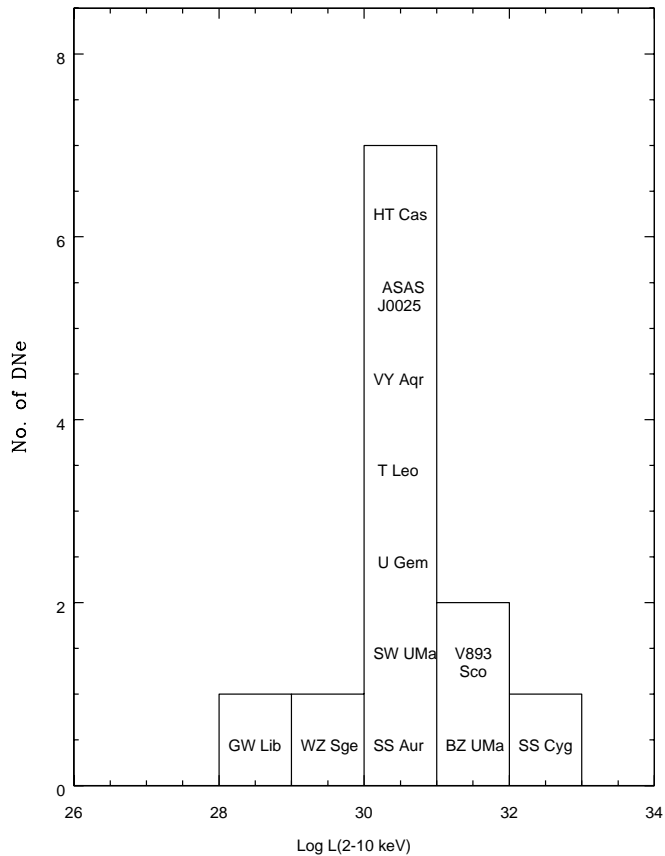
# The Global Population of CVs

- Most common type: dwarf novae (DNe; non-magnetic, unstable disk): estimated local space density  $\sim 5 \times 10^{-6} \text{ pc}^{-3}$
- Intermediate Polars (asynchronously rotating magnetic white dwarf, hard X-ray bright): most known IPs are near  $L_x \sim 10^{33} \text{ ergs s}^{-1}$ ,  $\sim 1 \times 10^{-8} \text{ pc}^{-3}$ 
  - Hard X-ray surveys have efficiently discovered such IPs out to  $\sim 1.5 \text{ kpc}$ .
  - Additional fainter ( $L_x \sim 10^{31}$ ) IP population likely at  $\sim 1 \times 10^{-7} \text{ pc}^{-3}$
- AM Hers (strongly magnetic, synchronized spin, usually soft X-ray and cyclotron dominated):  $\sim 1.2 \times 10^{-6} \text{ pc}^{-3}$ , mostly short orbital period (below the “period gap” of CVs, 2–3 hrs)
- Other non-magnetic CVs: a few  $\times 10^{-6} \text{ pc}^{-3}$ ?
- The Galactic nova rate suggests something like 3–30 million total CVs in the Milky Way Galaxy.
- In addition, the population of symbiotic stars (white dwarf accreting from the wind of a red giant) is poorly known but may be important.

# $T_X$ and $L_X$ of CVs

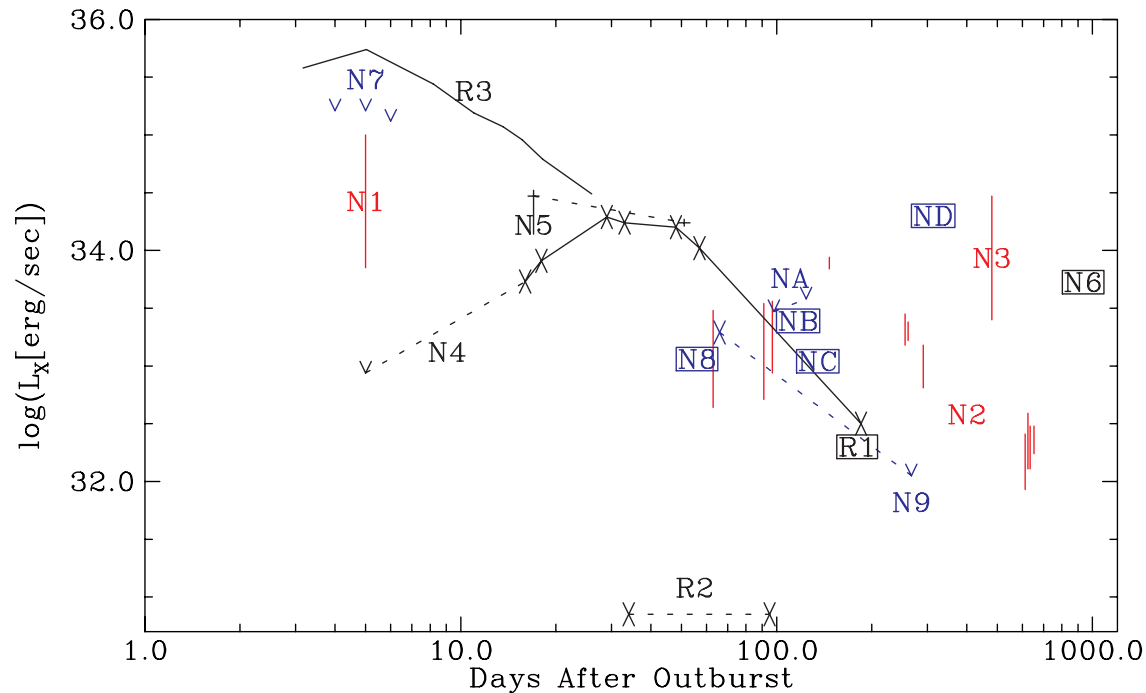
- If accretion onto the white dwarf is optically thin, the plasma temperature is of order 10 keV; if thick, effective temperature is of order 10 eV.
- In magnetic CVs, free-fall is a good approximation, in which case:  $kT_{X,max} \propto (GM_{WD}/R_{WD})$  and  $L_X < (GM_{WD}/R_{WD}) \dot{m}$
- In non-magnetic CVs, Keplerian flow hits the white dwarf surface:  $kT_{X,max} \propto 1/2 (GM_{WD}/R_{WD})$  and  $L_X < 1/2 (GM_{WD}/R_{WD}) \dot{m}$ 
  - $\dot{m}$  depends on the mass transport through the disk; the basic version of the disk instability model predicts extremely low values for  $\dot{m}$ , contradicted by X-ray observations
- Sample numbers for non-magnetic CVs:
  - $M_{WD}=0.6 M_{\odot}$ :  $kT_{X,max}=11$  keV,  $L_X < 2.8 \times 10^{32}$  ergs s<sup>-1</sup> at  $\dot{m} = 1.0 \times 10^{-10} M_{\odot}$  yr<sup>-1</sup>
  - $M_{WD}=1.0 M_{\odot}$ :  $kT_{X,max}=28$  keV,  $L_X < 7.4 \times 10^{32}$  ergs s<sup>-1</sup>
  - $M_{WD}=1.3 M_{\odot}$ :  $kT_{X,max}=63$  keV,  $L_X < 1.7 \times 10^{33}$  ergs s<sup>-1</sup>
- X-ray observations provide lower limits for  $M_{WD}$  and  $\dot{m}$ , or allow measurements of these quantities if we can eliminate other cooling mechanisms.

# X-ray luminosity function of DNe



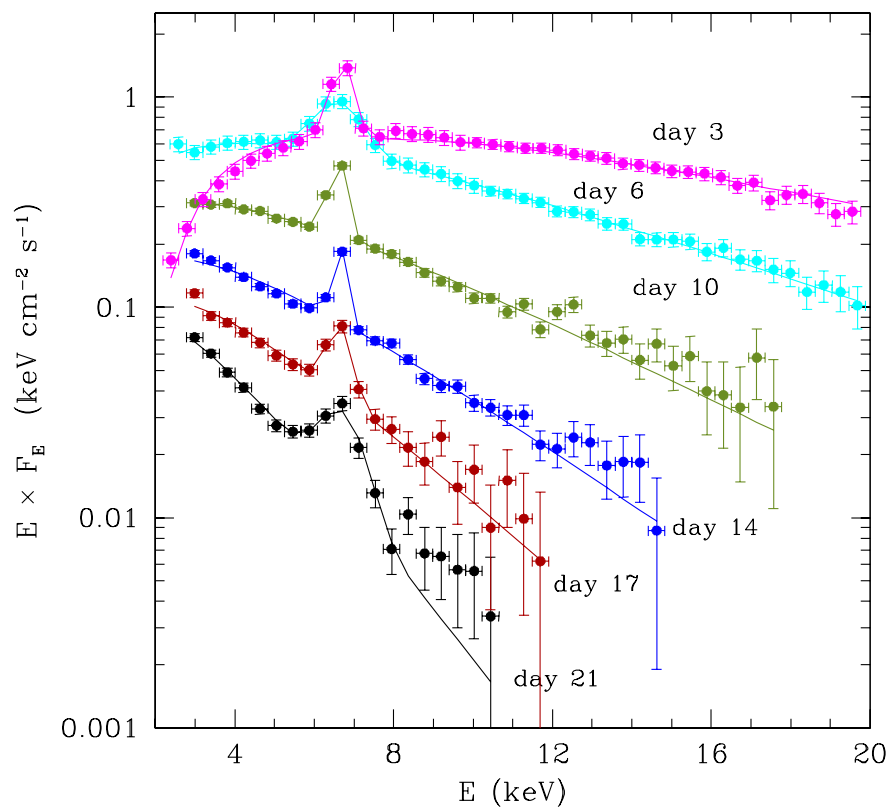
(From Byckling et al. 2010) Cf. the “Galactic ridge.”

# Accretion vs. Nuclear Luminosity



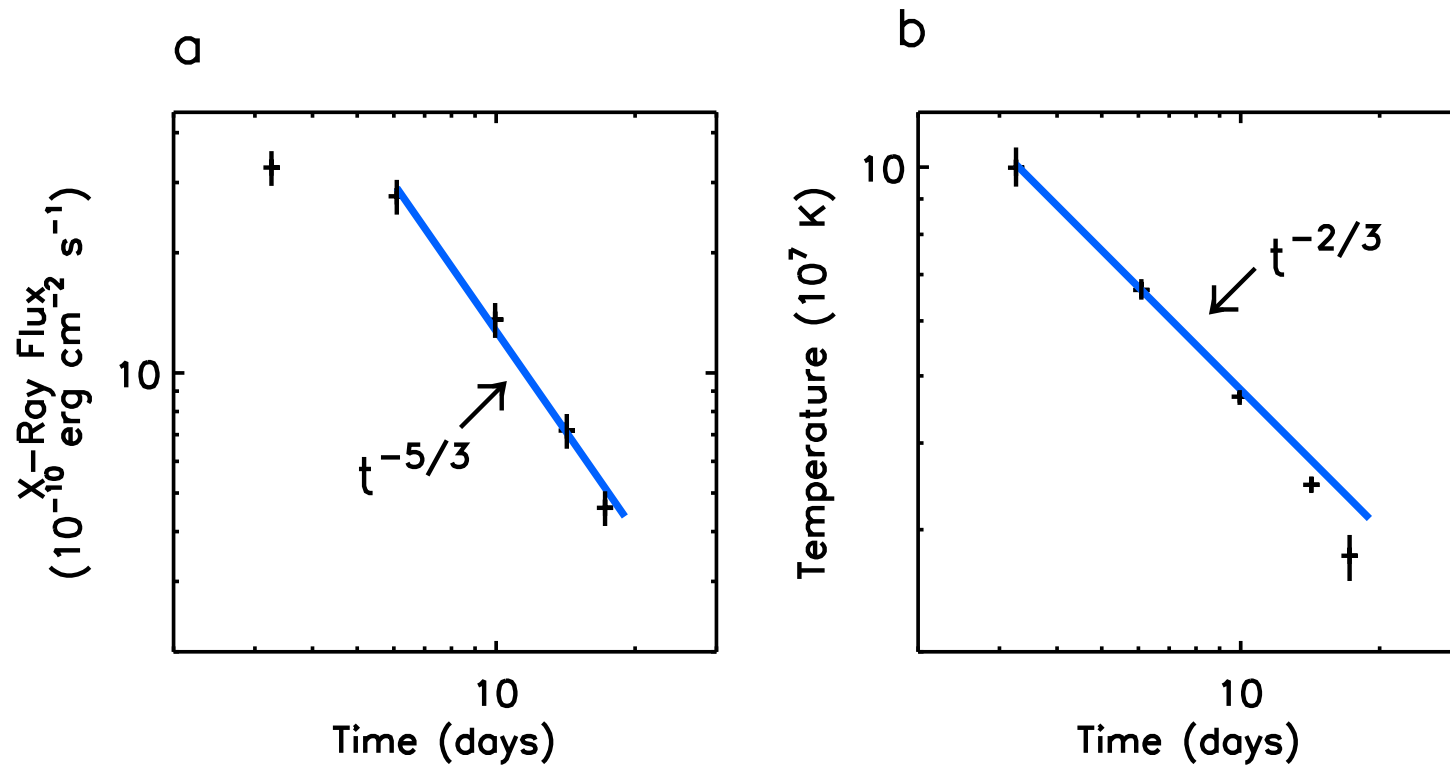
- Nuclear fusion is a more efficient energy source than accretion for white dwarfs.
- White dwarfs can sometimes become luminous supersoft X-ray sources.
- In addition, the ejecta from a classical nova outburst has  $\sim 10^{45}$  ergs of kinetic energy, leading to strong X-rays from the subsequent shocks.

# The 2006 Outburst of RS Ophiuchi



RS Oph was exceptionally luminous, as the nova ejecta immediately ran into the dense wind of the M giant mass donor. The X-ray became softer as both the temperature and the intrinsic  $N_{\text{H}}$  decreased with time.

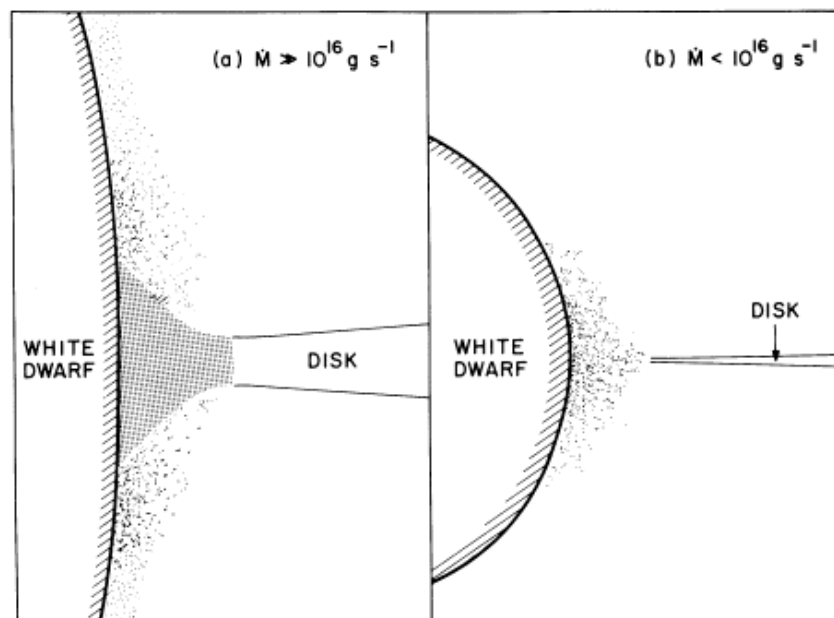
# X-ray Evolution of RS Ophiuchi



(From Sokoloski et al. 2006)

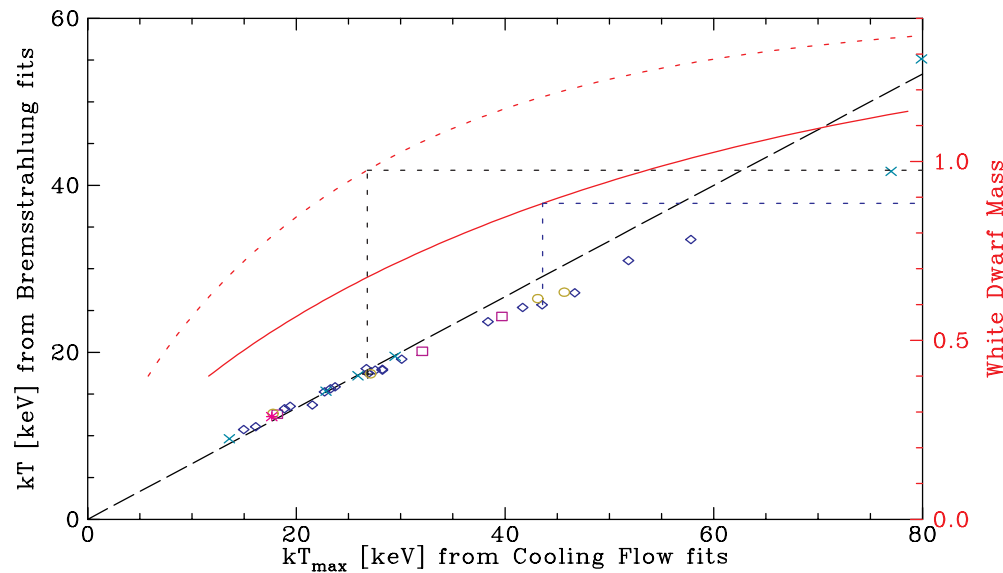
- The evolution of the X-ray luminosity and temperature indicates that RS Oph quickly entered the “Sedov-Taylor” phase; this analysis leads to an estimate of the ejecta mass.

# The Boundary Layer



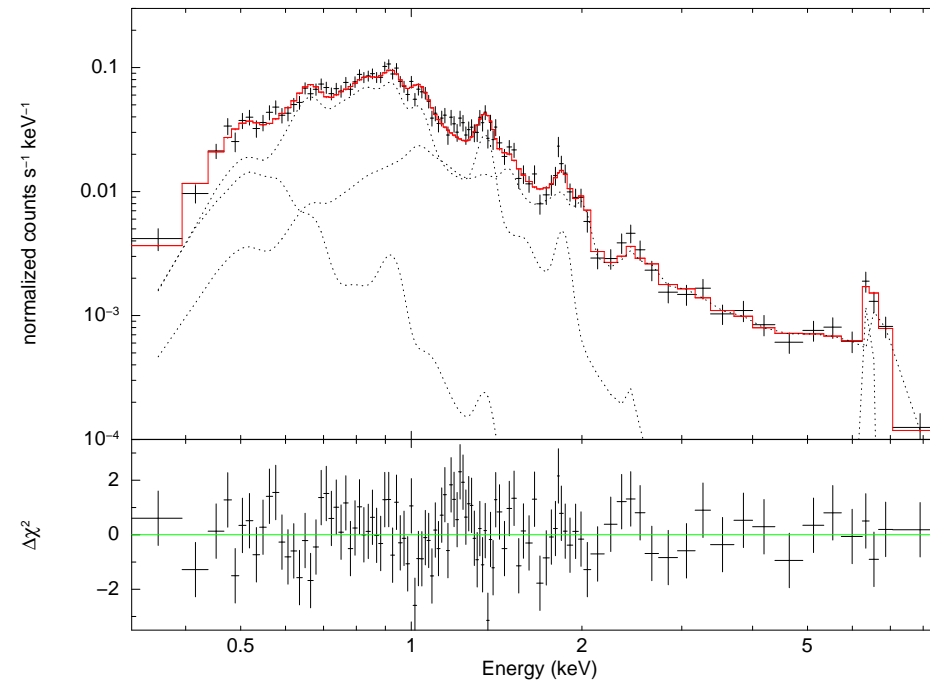
- At low  $\dot{m}$  (DNe in quiescence), the boundary layer between the Keplerian disk and the slowly rotating white dwarf is optically thin. Accreting gas is shock-heated to  $\sim 10$  keV, and radiatively cools before it can settle onto the surface.
- At high  $\dot{m}$  (DNe in outburst, nova-like systems), the bulk of the boundary layer is optically thick, emitting soft X-ray/EUV photons. There is an optically thin skin that emits 2–10 keV X-rays.

# The Shock Temperature



- The same spectrum can often be fit with single-T and multi-T models.
- For a given instrument, the  $kT$  from the 1T fit and the  $kT_{max}$  from the multi-T fit are simply related.
- In either case, the measurements probably arrange these systems in  $M_{WD}$  order.

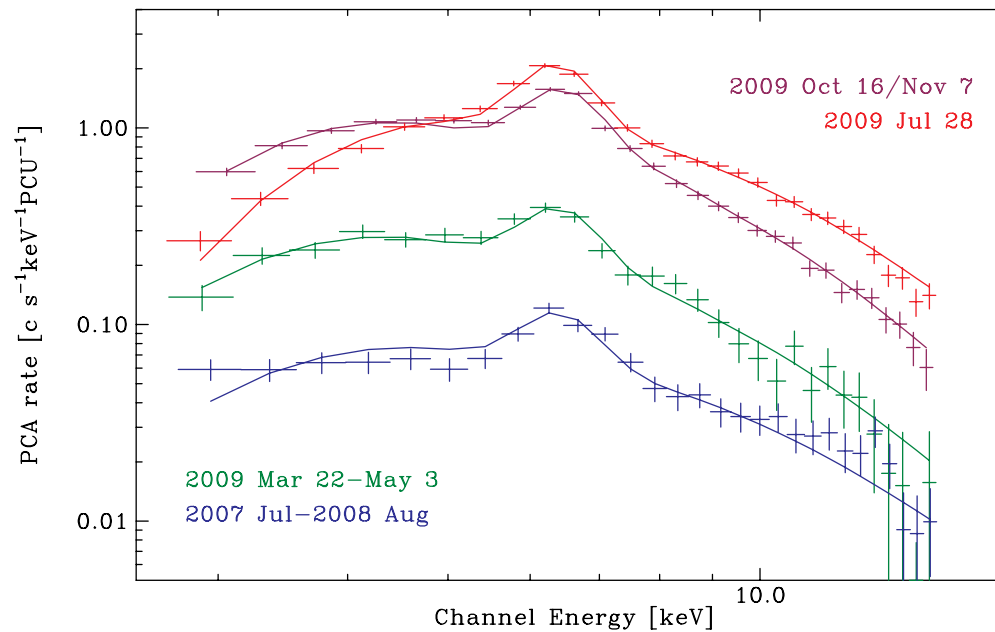
# Puzzle 1: RS Oph in Quiescence



(from Nelson et al. 2011, submitted)

- The fit requires a soft component, probably from the nova shell, and a harder component, from accretion

# A comparison: CH Cyg

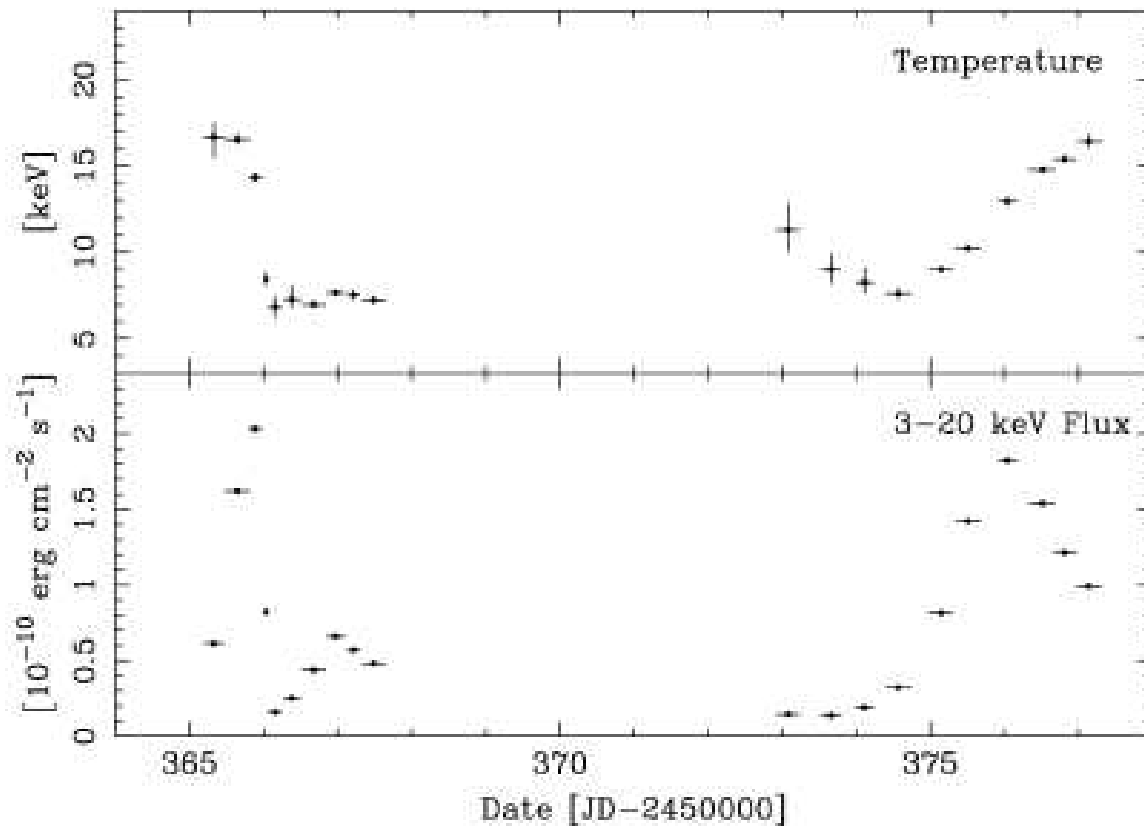


- Several symbiotic stars has now been detected in the BAT and INTEGRAL surveys, including CH Cyg which has a relatively low mass white dwarf.
- The recurrent nova T CrB in particular has one of the hardest X-ray spectra known of any accreting white dwarfs, presumably due to its high mass ( $\sim 1.3 M_{\odot}$ ) white dwarf.

# Why faint, and why soft?

- RS Oph is a recurrent nova, and thought to have a  $\sim 1.3 M_{\odot}$  white dwarf, accreting at a high rate.
- T CrB, another recurrent nova, is detected in the BAT survey at an estimated  $L_{X,bol} = 2 \times 10^{34} \text{ ergs s}^{-1}$  (Kennea et al. 2009), with  $kT \sim 18 \text{ keV}$  for a 1-T model fit.
- Yet the the X-ray luminosity of RS Oph is lower ( $L_{0.3-10keV} \sim 2 \times 10^{33} \text{ ergs s}^{-1}$ ) and the temperature is significantly lower (1-T fit:  $kT \sim 2.4 \text{ keV}$ ; cooling flow fit:  $kT_{max} \sim 5 \text{ keV}$ , where 60 keV is expected for an  $1.3 M_{\odot}$  WD).

# Puzzle 2: SS Cyg in Outburst



(from Wheatley, Mauche & Mattei 2003)

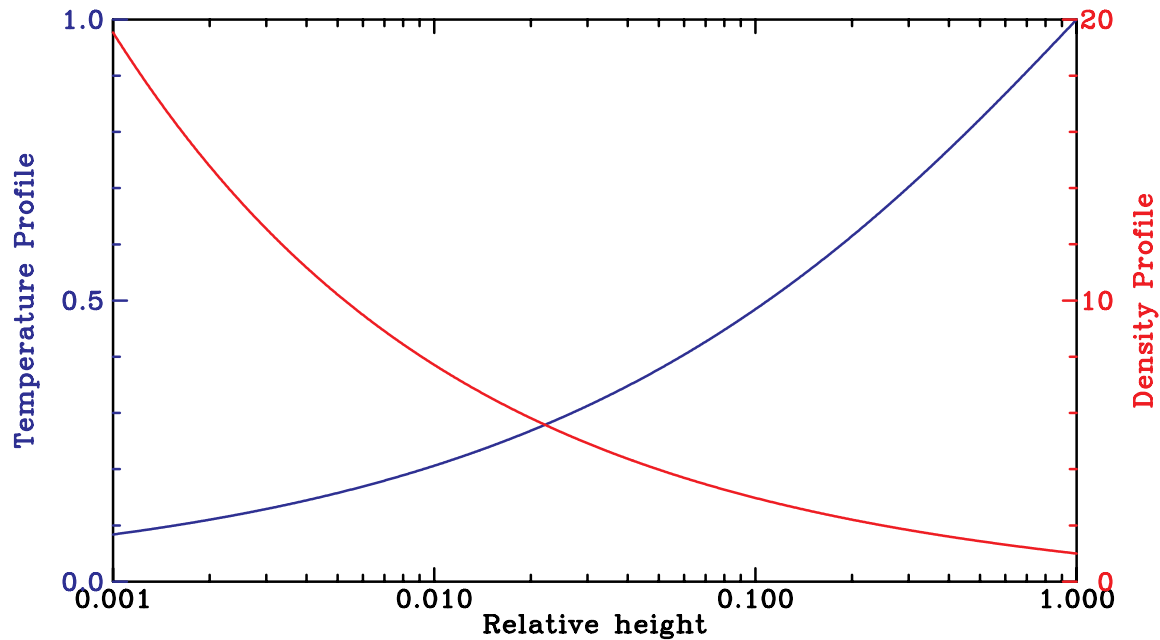
# Why softer?

- In the Patterson & Raymond (1985) picture, both quiescent and outburst hard X-rays are from the optically thin (part of) boundary layer.
- The gravitational potential is the same, and the shock height should be roughly similar.
  - Single-temperature fits to Ginga and RXTE data result in  $kT \sim 17$  keV in quiescence and  $kT \sim 7$  keV in outburst
  - Cooling-flow fits to ASCA data result in  $kT_{max} \sim 36$  keV in quiescence and 10.5 keV in outburst
  - Temperature decrease by a factor of 2.5–3.5 needs explanation.
  - The luminosity also decreases.

# Proposed Solution

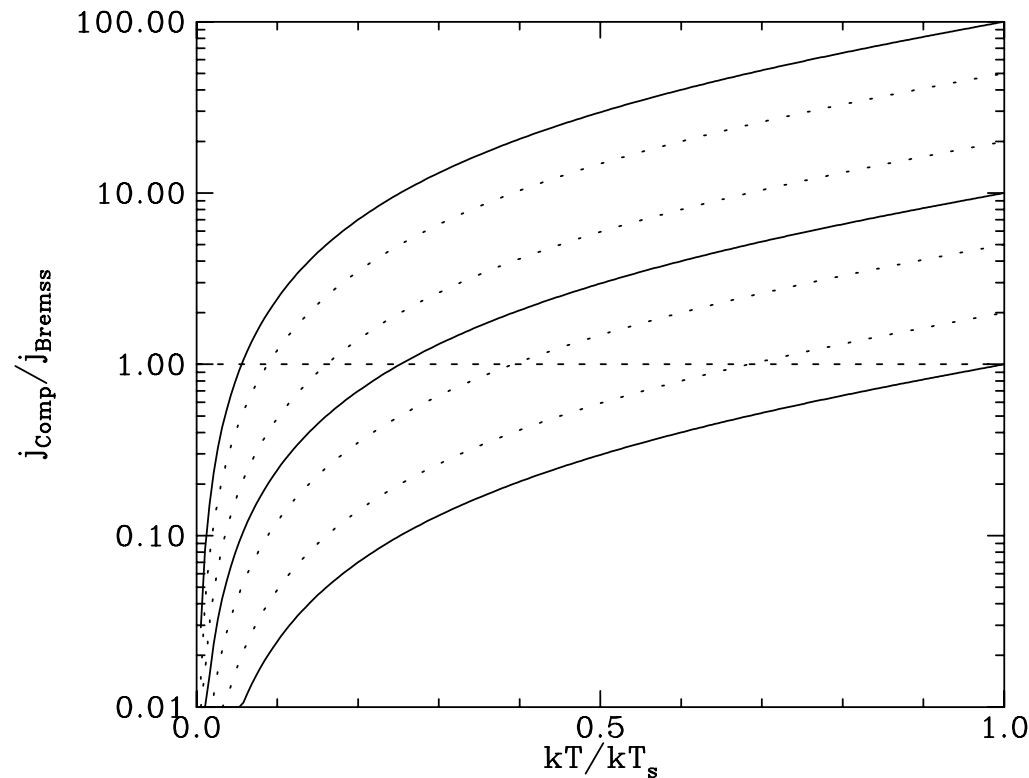
- Additional soft photons (from, e.g., the optically thick boundary layer) act as seed photons for Compton cooling.
  - $\tau$  is still low, but each electron interact with multiple photons.
- We do not have a full model of the boundary layer
  - Assume Aizu model column laid on its side
  - Assume strong shock but from  $v_{Kep}$ , not  $v_{ff}$
  - Add second cooling term, using the Wu et al. (1994) prescription with  $\alpha=1/2$ ,  $\beta=3/2$  as appropriate for Compton cooling.
- The relative importance of Compton cooling is a function of physical position within the post-shock region/ $kT/\rho$ .

# kT and density profiles



- Near the shock, the temperature is high, and the density is low, so X-ray emissivity is low.
- Note the X-axis is logarithmic - the bulk of the X-ray emission is from just above the white dwarf surface.

# Implication for Compton Cooling



- We assume various fluxes for the seed photons.
- Relatively speaking, Compton cooling is more efficient for the highest temperature (lowest density) regions.

# Consequences

For the case which starts with  $j_{Comp}/j_{Brems} = 10.0$  at just below the shock

- Cooler regions are denser, and  $j_{brems} \propto n_e^2 kT^{1/2}$  — the ratio becomes progressively smaller as density increases.
- Cross-over occurs at  $kT \sim 0.25 kT_s$
- Approximation: Plasma cools from  $kT_s$  to  $0.25kT_s$  exclusively via Compton cooling, the rest exclusively via Bremsstrahlung
- Observed  $L_X$  is also  $\sim 25\%$  of what it would have been without Compton cooling
- If cooling flow fit is used,  $kT_{max} \sim 0.25 kT_s$ ; normalization (accretion rate) corresponds to  $L_{Brems} + L_{Comp}$ .

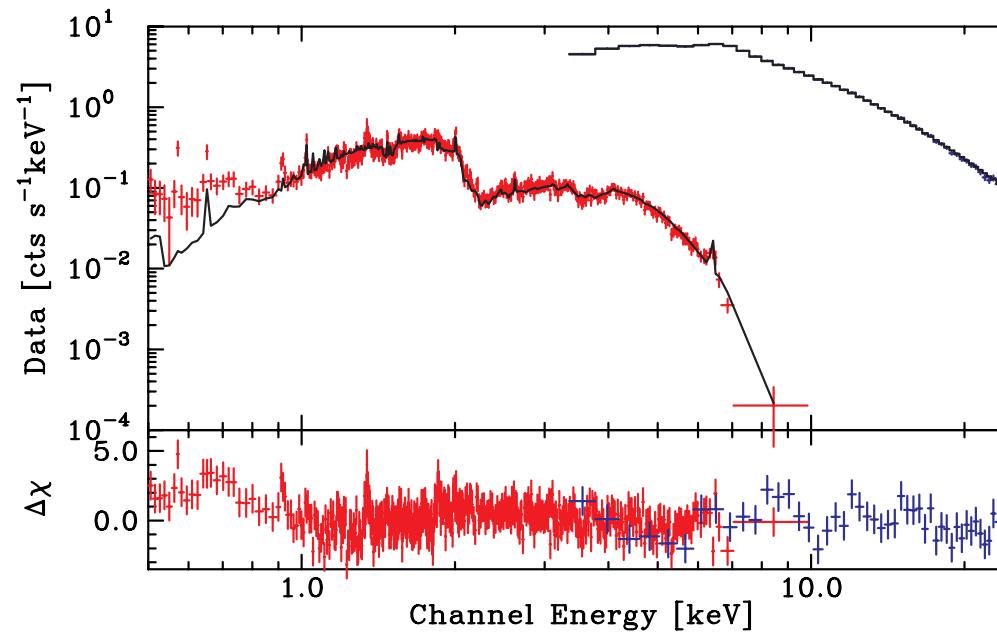
# Application: SS Cyg in Outburst

- Wheatley, Mauche & Mattei (2003) reports  $L_{soft} \sim 7.5 \times 10^{33}$  ergs s<sup>-1</sup>, presumably from the optically thick boundary layer
- $L_{Brems} \sim 2.0 \times 10^{32}$  ergs s<sup>-1</sup> and  $kT_{max,q} \sim 3.5 \times kT_{max,o}$ . In our picture, then,  $L_{Brems} + L_{Comp} \sim 7.0 \times 10^{32}$  ergs s<sup>-1</sup>.
- So the use of the curve that starts near  $j_{Comp}/j_{Brems} = 10.0$  is self-consistent.
- The Compton cooling interpretation passes the sanity check, as long as the X-ray source is right next to the soft source, with little geometrical dilution of soft photons.

(Luminosities scaled to a fiducial distance of 166 pc)

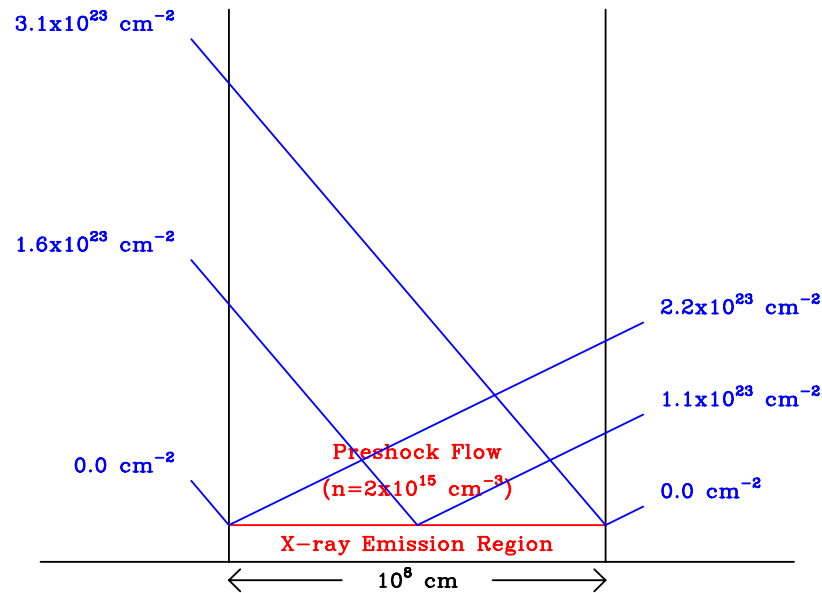
- This implies, however, that outburst X-rays in SS Cyg would be eclipsed when viewed from a high inclination angle.
- The inclination of Z Cha may be so high ( $i = 81.8^\circ$ ) that any boundary emission is hidden from our view at all phases in outburst by the thickened rim of the disk (cf. UX UMa at  $71^\circ$ ).

# Two Types of CV X-ray Spectra



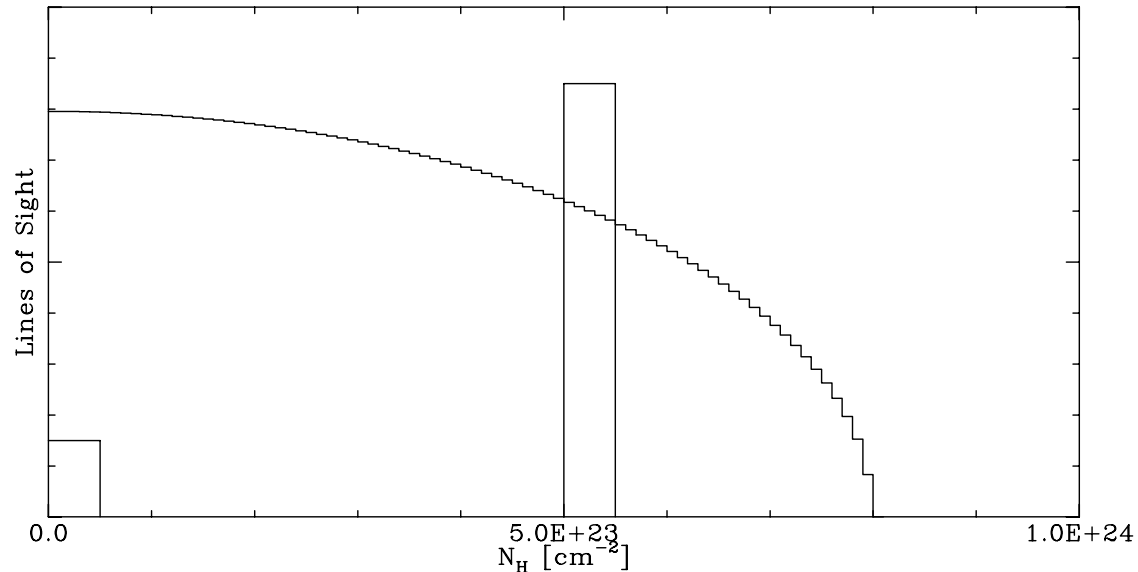
- Mukai et al. (2003) classified Chandra HETG spectra of CVs into “cooling flow” and “photoionized” types.
- However, the photoionization model used in that paper is unphysical for CVs.
- In reality, RXTE PCA+Chandra HETG spectrum of “photoionized” CV, V1223 Sgr, can be fitted with a cooling flow model plus complications.

# What complications?



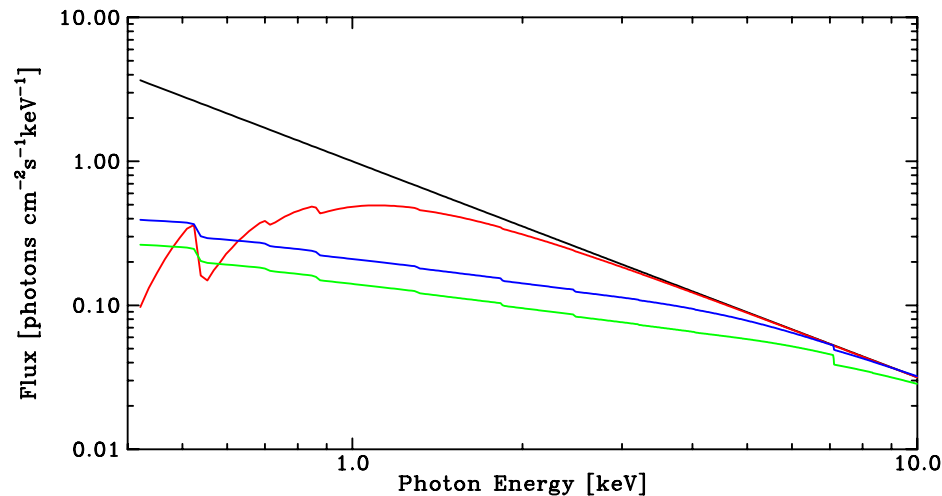
- Warm absorber edge (OVII)
- Photoionized lines (mostly He-like)
- Reflection
- Complex absorber

# The complex absorber



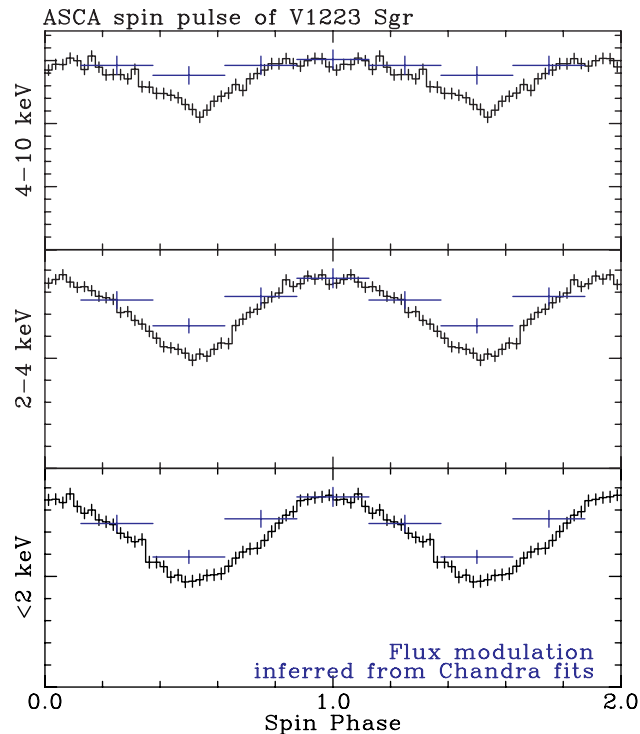
- The histogram shows the histogram of the numbers of line of site in each  $N_H$  bin, for a simulated accretion column with an elliptical cross section.
- Many people fit the data with a partial covering absorber.
  - This is not going to work, if your data quality is high.
  - This can even lead to incorrect claim of cross-calibration errors.

# Power-law like absorber



- Single- $N_{\text{H}}$  absorber produces an exponential cut-off.
  - Changing  $N_{\text{H}}$  changes the cut-off energy up and down.
  - Partial covering absorber has exponential cut-off at two energies.
- If the  $N_{\text{H}}$  histogram is a power-law form, the resulting absorber is close to a power-law in energy. Changing  $N_{\text{H,max}}$  results in an additional absorber that is gray over much of the energy range of interest.

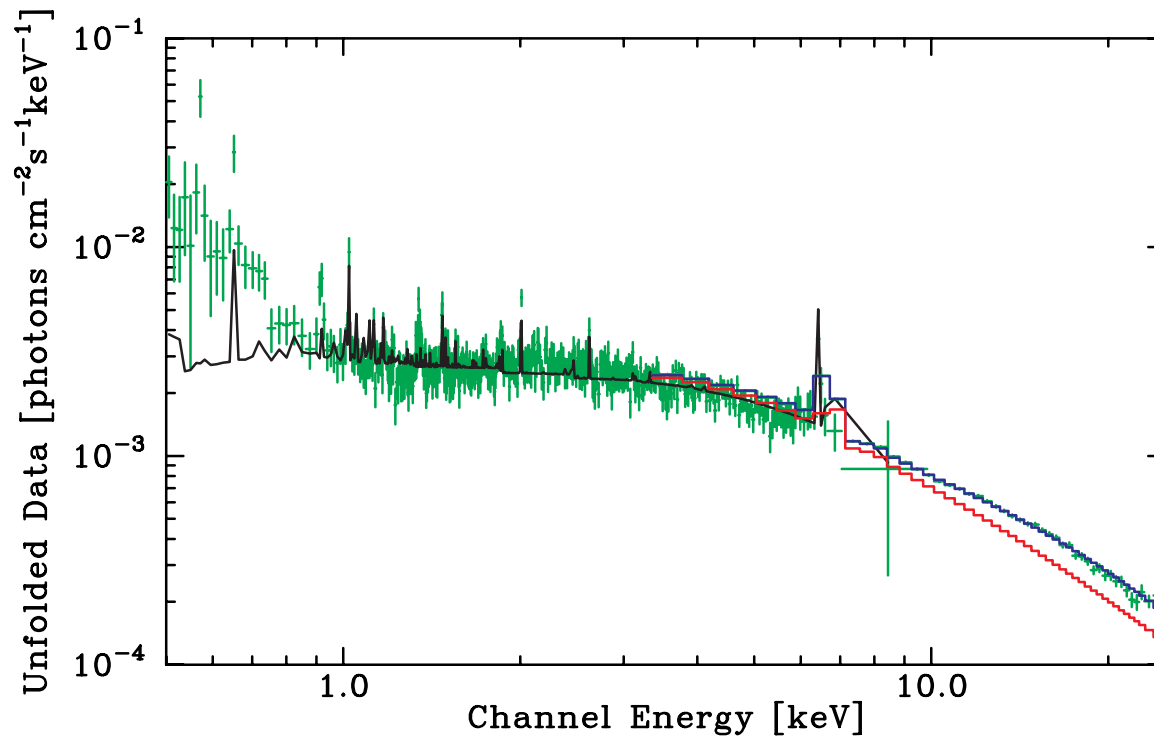
# Spin modulation



This fits in with the well-known energy dependence of spin modulation depths of IPs

- Spin modulation is more pronounced at lower energies.
- Energy dependence is not as steep as it would be if it was caused by a simple photoelectric absorber.

# Putting it all together



For V1223 Sgr, cooling flow + reflection/6.4 keV line + complex absorber model works well, except for the OVII edge and He-like lines of medium z elements.

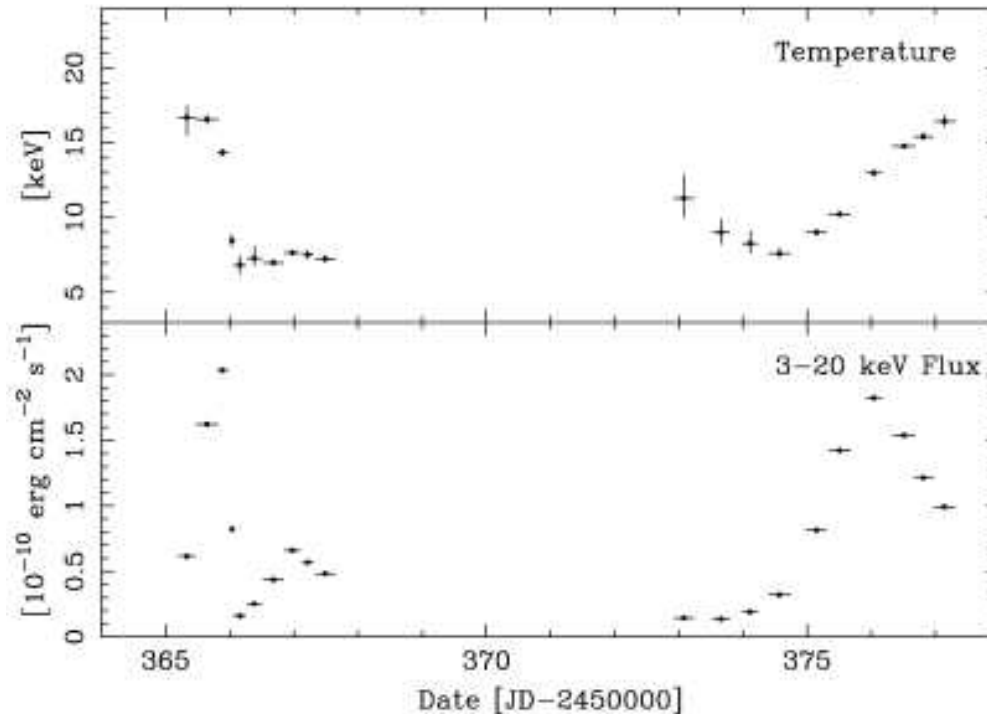
# Timescales of CV Variability

Proportional counter instruments can only study X-ray bright CVs, but are capable of relatively fast timing studies of every detectable CVs.

- Long-term: Some CVs and Symbiotic Stars have high and low states (AM Her type systems, VY Scl systems, symbiotic stars...)
- Outbursts of classical and recurrent novae: Unpredictable timing, X-ray evolution over days to months.
- Interoutburst cycles of dwarf novae:  $\sim 1$  week to months to years
- Outburst of dwarf novae: a few days to  $\sim$  a month
- Orbital period of CVs:  $\sim 10$  min to  $\sim 2$  days.
- Spin period of white dwarfs:  $\sim 30$  s to  $\sim 1$  hr.

What is the preferred scheduling regime for ASTROSAT, and how responsive will it be to TOOs?

# SS Cyg in Outburst Revisited



The episodes of increased X-ray flux at the rise and late decline of SS Cyg in outburst has not been detected in another dwarf nova, even though several campaigns exist which would have detected such episodes (SU UMa, VW Hyi, WW Cet).

# Possible ASTROSAT Projects

- X-ray characterization of hard X-ray discovered magnetic CVs and candidates.
- X-ray bright eclipsing CV of any subtype (there aren't that many).
- X-ray spectroscopy of several more dwarf novae through an outburst
  - Can we test the Compton cooling interpretation somehow?
- X-ray observations of bright a bright classical or recurrent nova in outburst.
- Spin-resolved spectroscopy of magnetic CVs: study of reflection and complex absorber.
- ...