The X-ray Emission of Magnetic Cataclysmic Variables

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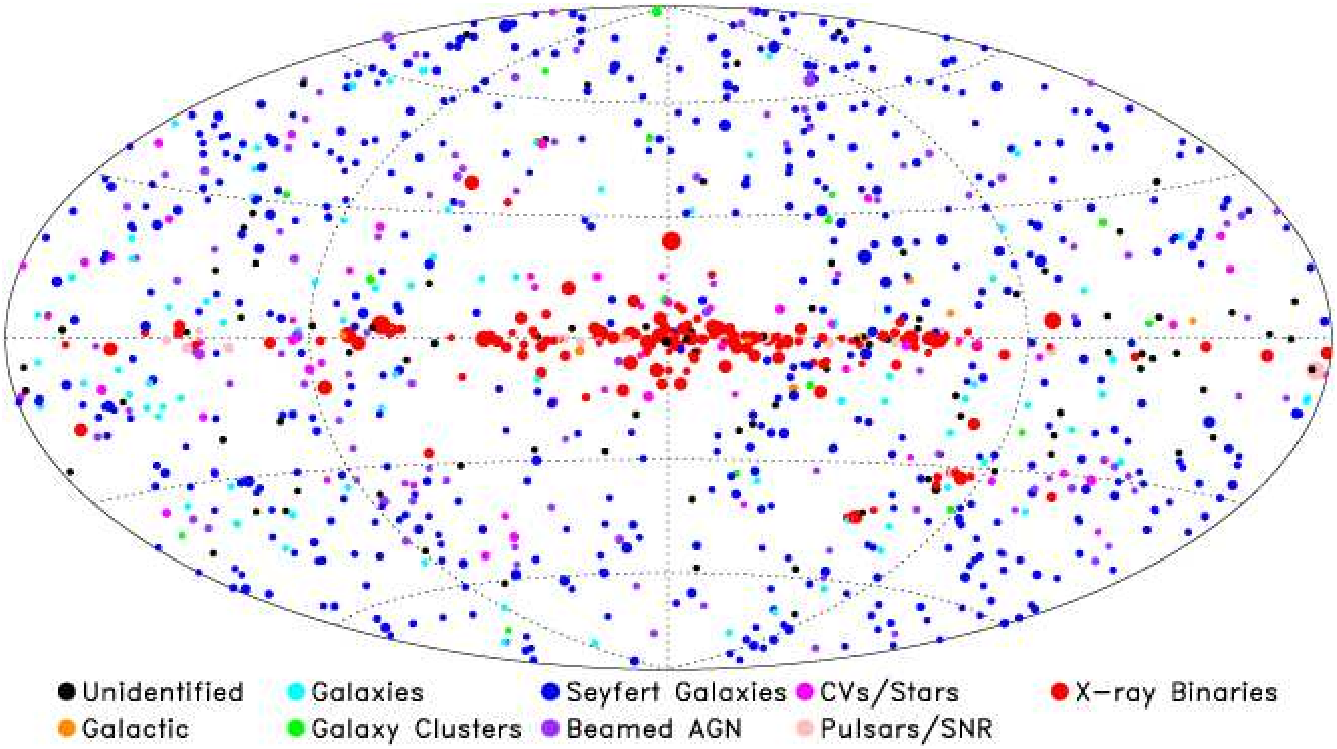
CVs among 2–10 keV Sources



(http://heasarc.gsfc.nasa.gov/docs/swift/results/bs58mon/)

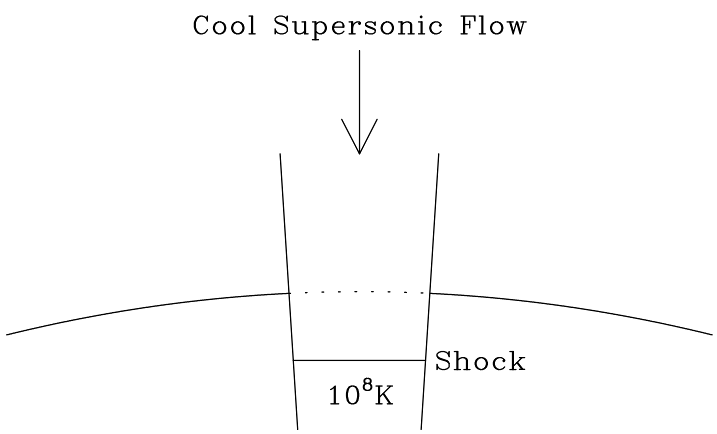
- CVs are a significant minority population of the X-ray sky – both in the 2–10 keV sky (42 of 660 HEAO A-3 catalog sources) and in the INTEGRAL and Swift $>$10 keV catalogs.

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:

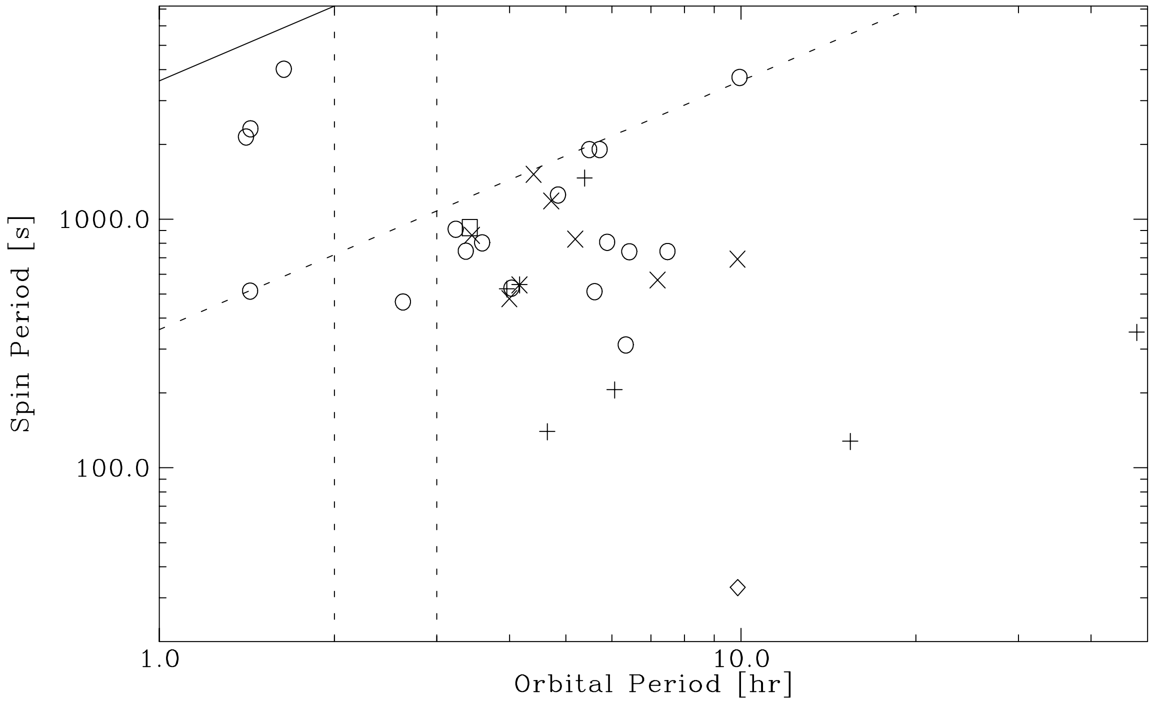
- A brief overview of CV subtypes, space densities, and mCV evolution
- Cooling Flow spectra - what can we learn, and what are the limitations?
- The role of complex absorbers
- The hot blackbody problem



The Global Population of CVs

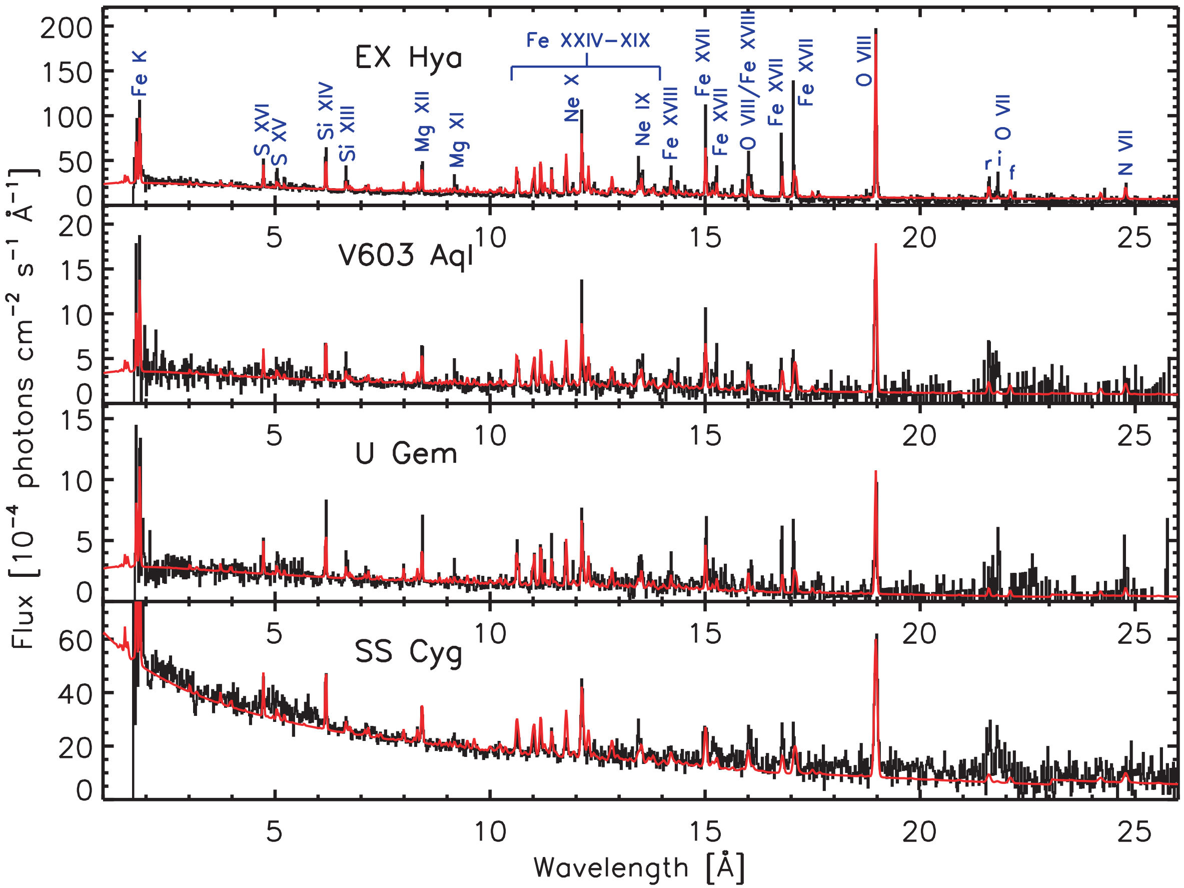
- Most common type: dwarf novae (DNe; non-magnetic, unstable disk): estimated local space density $\sim 5 \times 10^{-6}$ pc^{-3}
- Intermediate Polars (asynchronously rotating magnetic white dwarf, hard X-ray bright): most known IPs are near $L_x \sim 10^{33}$ ergs s^{-1}, $\sim 1 \times 10^{-8}$ pc^{-3}
  - Hard X-ray surveys have efficiently discovered such IPs out to ∼1.5 kpc.
  - Additional fainter ($L_x \sim 10^{31}$) IP population likely at $\sim 1 \times 10^{-7}$ pc^{-3}
- AM Hers (strongly magnetic, synchronized spin, usually soft X-ray and cyclotron dominated): $\sim 1.2 \times 10^{-6}$ pc^{-3}, mostly short orbital period (below the "period gap" of CVs, 2–3 hrs)
- Other non-magnetic CVs: a few $\times 10^{-6}$ pc^{-3}?
- The Galactic nova rate suggests of order 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.

IPs in the P_{orb}–P_{spin} Plane



- CVs with P_{orb} below $\sim$10 hours generally evolve to shorter periods due to angular momentum loss – gravitational wave only (?) below 2 hrs, GW plus magnetic braking above 3 keV.
- P_{spin} should be near equilibrium of accretion and synchronization torques.

Two Types of X-ray Spectra (I)

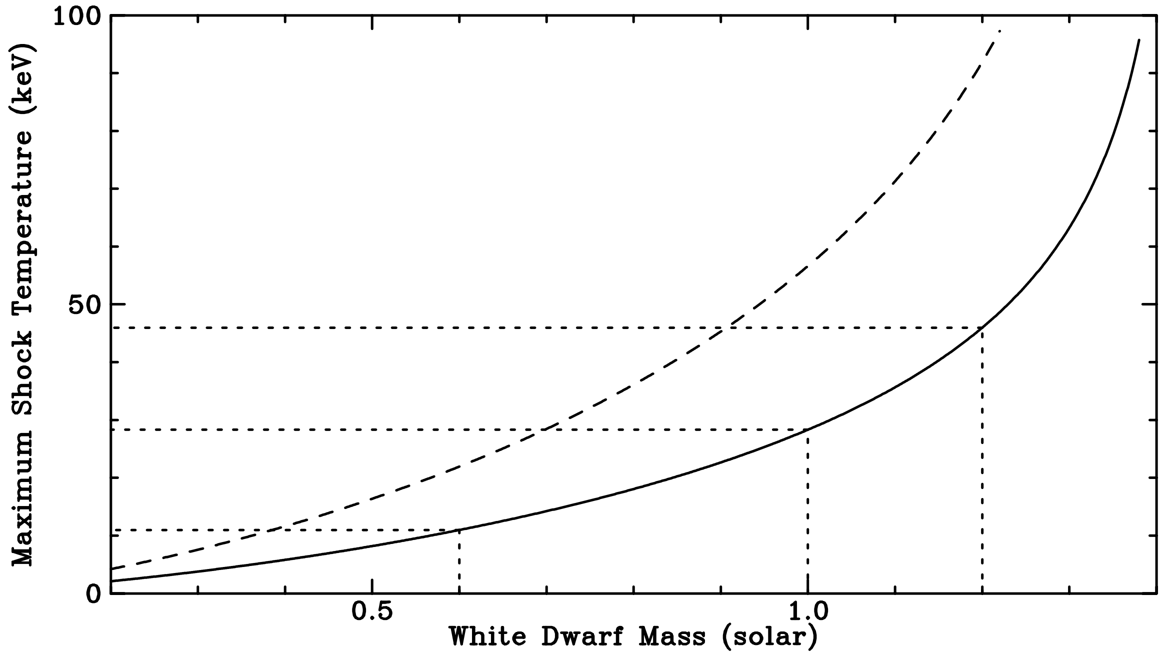


- Most non-magnetic CVs and some magnetic CVs ("fainter IPs") can be fit to first order using the cooling flow model, `mkcflow`

Why Cooling Flow?

- The post-shock plasma in CVs loses energy by emitting X-rays and therefore must cool. For magnetic CVs, the Aizu profile gives the exact solution for cases when only Bremsstrahlung cooling operates.
- "Assuming that the same mass flow rate pertains throughout the cooling flow, the emission measure for each temperature is determined by the time it takes for the matter to radiate away sufficient energy to cool down to the next temperature shell. The differential emission measure is thus proportional to the reciprocal of the bolometric luminosity at that temperature" (Mushotzky & Szymkowiak 1988).
- `mkcflow` correctly accounts for Bremsstrahlung and **line** cooling, unlike the Aizu model and some semi-analytical models.
- There are shortcomings, however:
  - `mkcflow` assumes an *isobaric* cooling flow. There is some compressional heating in real magnetic CVs ($\sim$10% according to the Aizu model).
  - Some post-shock regions are sufficiently tall to experience additional gravitational acceleration and heating.
  - Cyclotron cooling is significant in polars.

The Shock Temperature

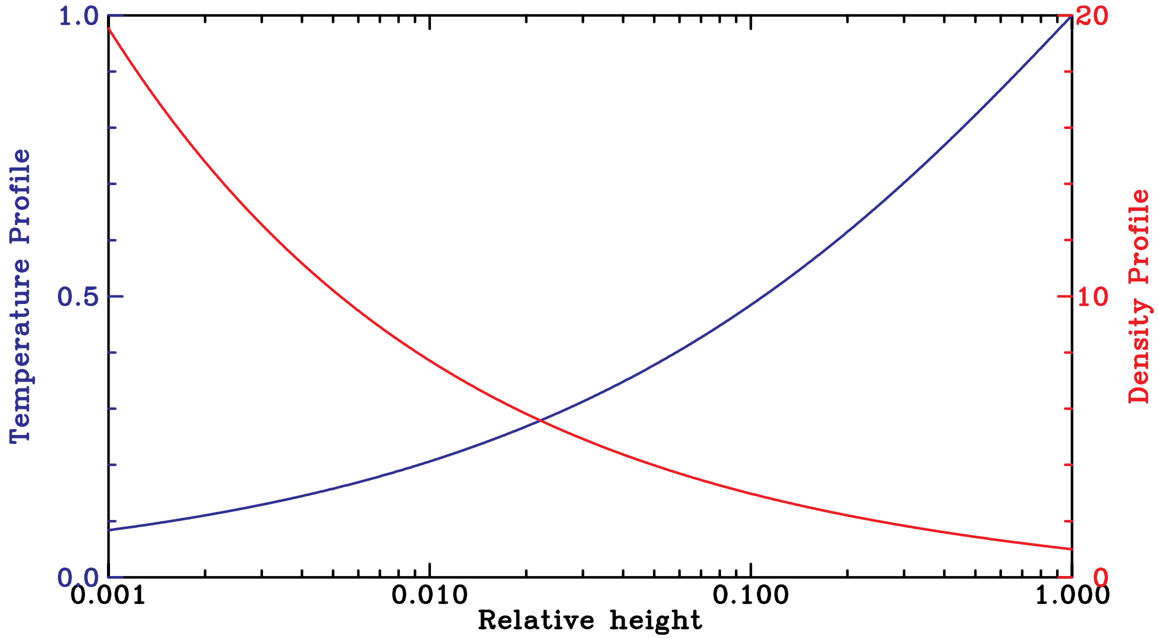


- In the absence of other cooling mechanisms, the measured temperature is a good proxy for the white dwarf mass in magnetic CVs (and probably useful enough for non-magnetic CVs)
- The same spectrum can often be fit with single-T and multi-T models.

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 $L_X < 1/2\ (GM_{WD}/R_{WD})\ \dot{m}$
- Sample numbers for magnetic CVs:
  - M_{WD}=0.6 $M_\odot$: $kT_{X,max}$=22 keV, $L_X < 5.6 \times 10^{32}$ ergs s^{-1} at $\dot{m}$ = 1.0 $\times 10^{-10}$ $M_\odot$ yr^{-1}
  - M_{WD}=1.0 $M_\odot$: $kT_{X,max}$=56 keV, $L_X < 1.5 \times 10^{33}$ ergs s^{-1}
  - M_{WD}=1.3 $M_\odot$: $kT_{X,max}$=126 keV, $L_X < 3.4 \times 10^{33}$ ergs s^{-1}
- X-ray observations provide lower limits for M_{WD} and $\dot{m}$, or allow measurements of these quantities if we can elimiate other cooling mechanisms.
- Multiple groups have used X-ray spectroscopy to determine the white dwarf mass in magnetic CVs.

kT and density profiles

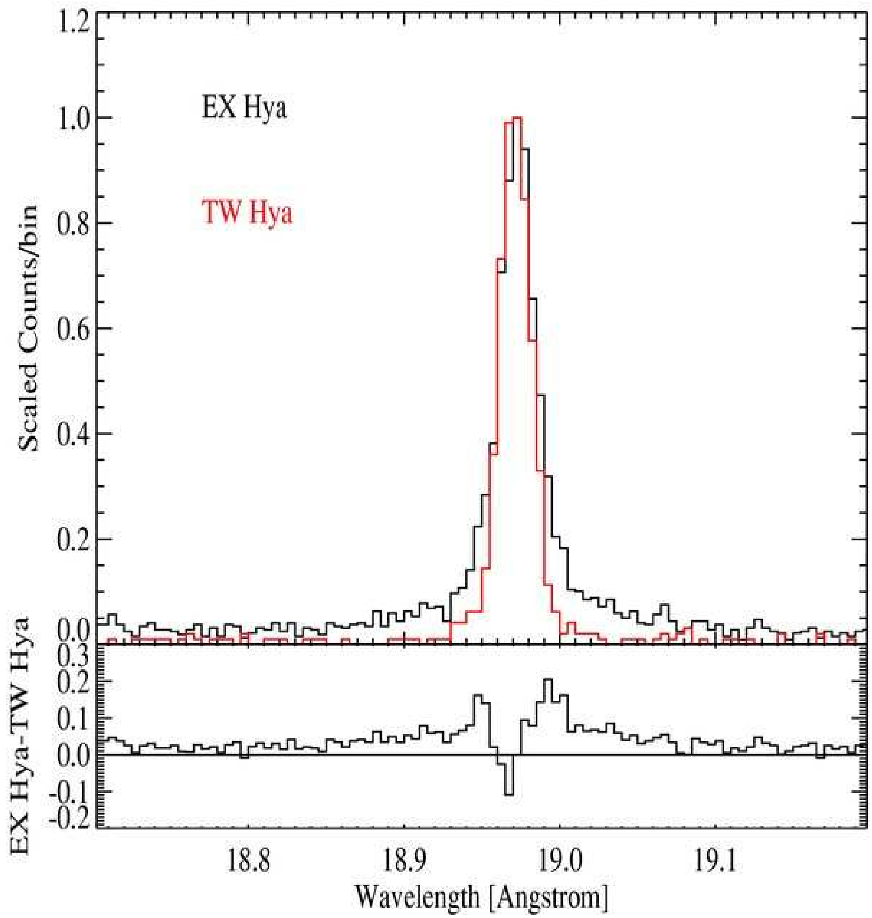


- Near the shock, the temperature is high, and the density is low, so X-ray emissivity is low.
- Note the X-axis is logarithmic - the bulk of the X-ray emission is from just above the white dwarf surface.
- X-ray lines are expected from the slow moving plasma - bulk velocity $\ll v_{ff}$.

Deep X-ray Spectroscopy of EX Hya

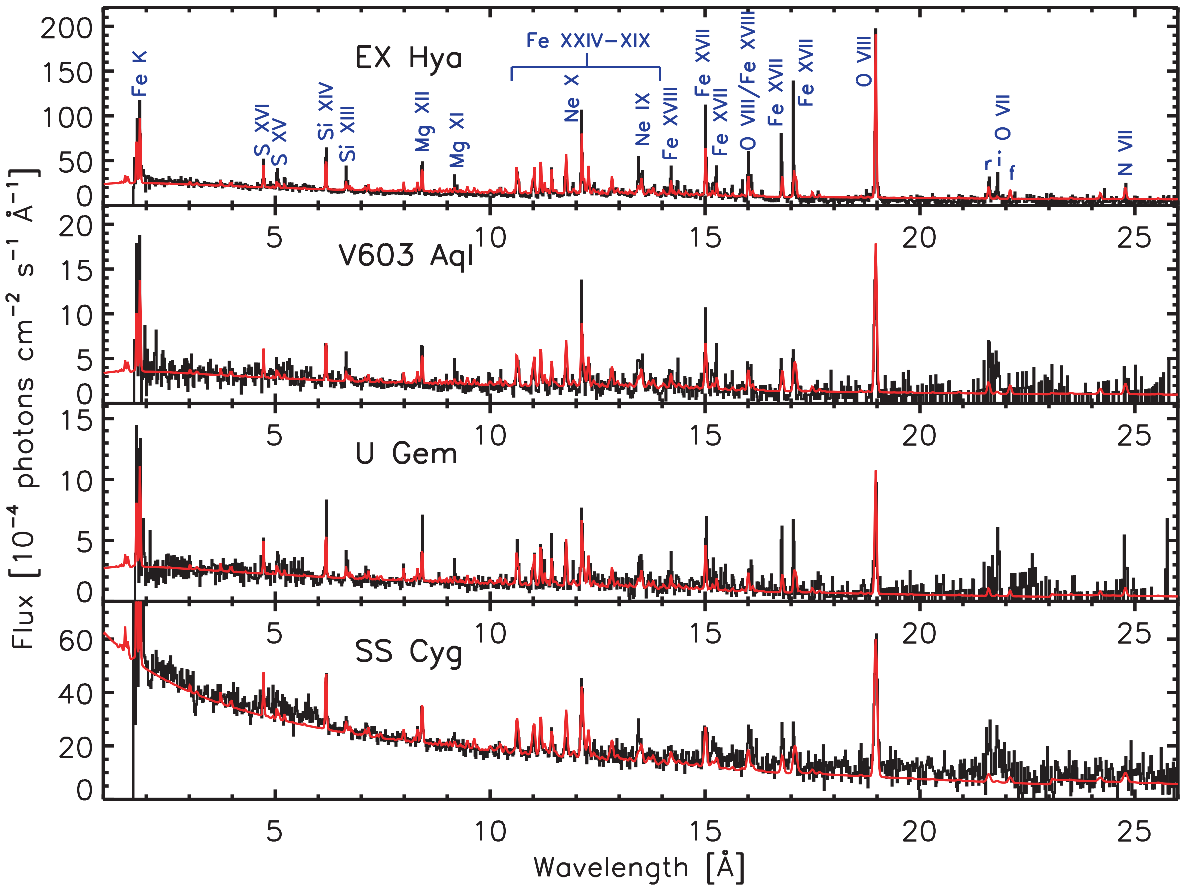
- EX Hya is the best known (and brightest) example of the low luminosity IPs, with over $>$0.5 Msec of *Chandra* HETG data.
- Mauche et al. investigated Fe L density diagnostics, and high density was confirmed.
  - Even higher densities are expected for high luminosity IPs; the most useful density diagnostic is probably the He-like Fe K
- Hoogerwerf et al found orbital radial velocity modulation (but not on the spin period).
- Luna et al. found a narrow and a broad componet.
  - The narrow component from the cooling flow (already slowed down)
  - The broad component from photoionization of the pre-shock low
- Ongoing work by Luna, Brickhouse, Mauche et al. have found the differential emission measure distribution of EX Hya to show a clear departure from that expected in a pure cooling flow.

Broad and Narrow Components



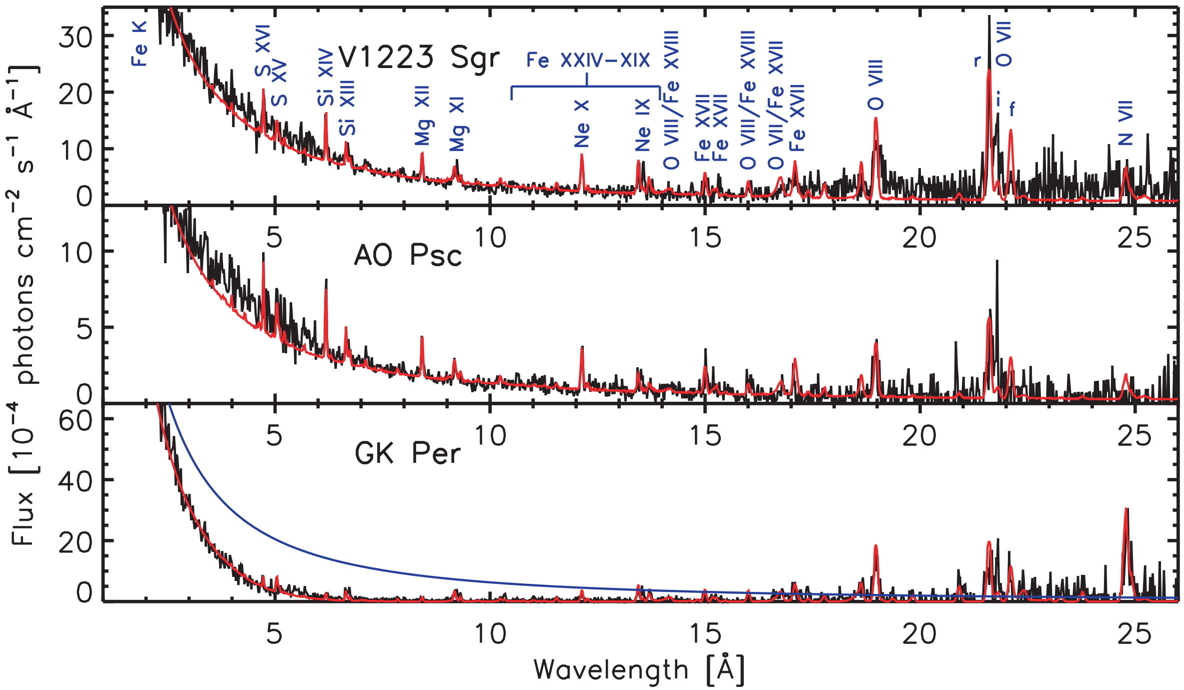
- A comparison of line profile between EX Hya and TW Hya.

Cooling Flow Summary



- The much harder continuum of SS Cyg suggests a more massive white dwarf
- Note the poor agreement for the OVII triplet in these systems

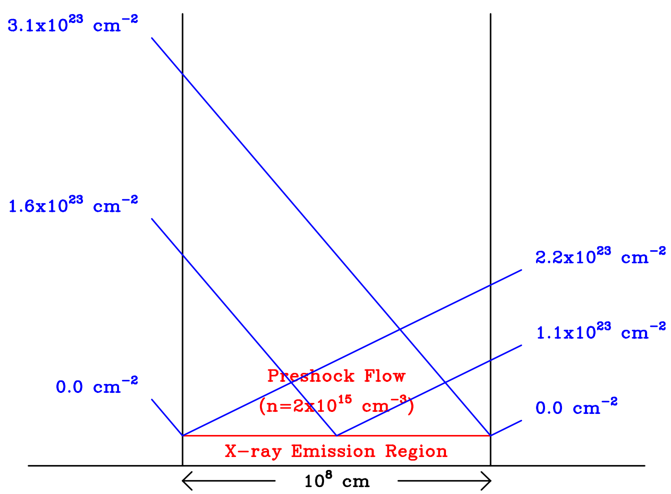
Two Types of X-ray Spectra (II)



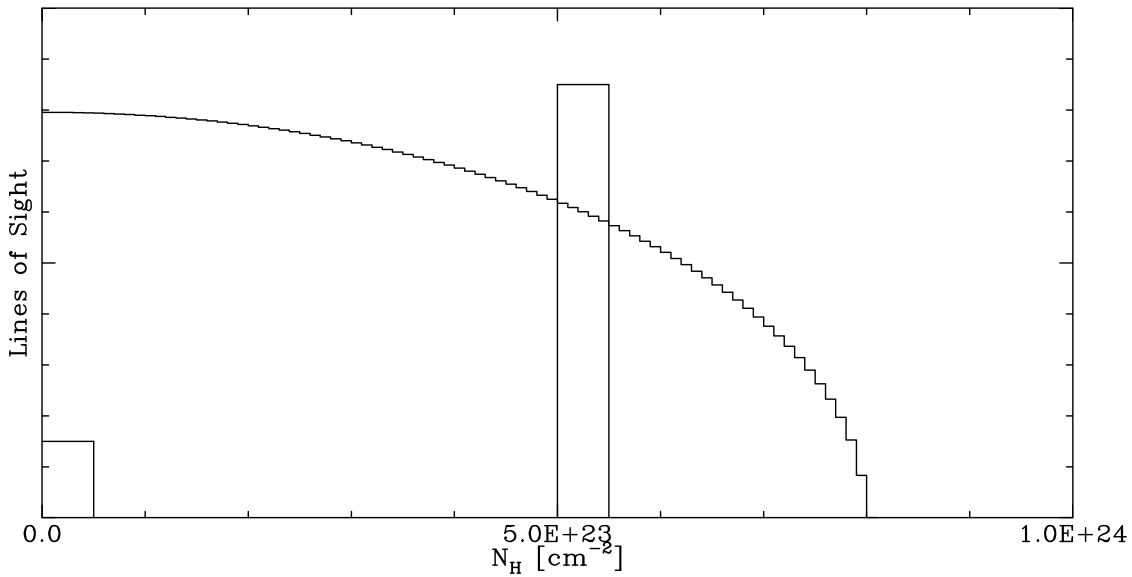
- Luminous magnetic CVs have spectra that cannot be readily fit by the `mkcflow` model.
- Mukai et al. (2003) characterized this as the “photoionized” type.
- However, the power-law continuum that Mukai et al. used are clearly unphysical for magnetic CVs.

Complex Absorber in magnetic CVs

- Hard (>10 keV) X-ray spectra of these same “photoionized” CVs are in fact consistent with the same thermal origin.
  - Reflection becomes an important, although hitherto poorly constrained, complication.
- Medium energy (0.5–10 keV) X-ray spectra show complex absorbers, which are usually fitted using partial covering absorber model(s). However, this is wrong.
- The main absorber in magnetic CVs are located in the immediate pre-shock flow.

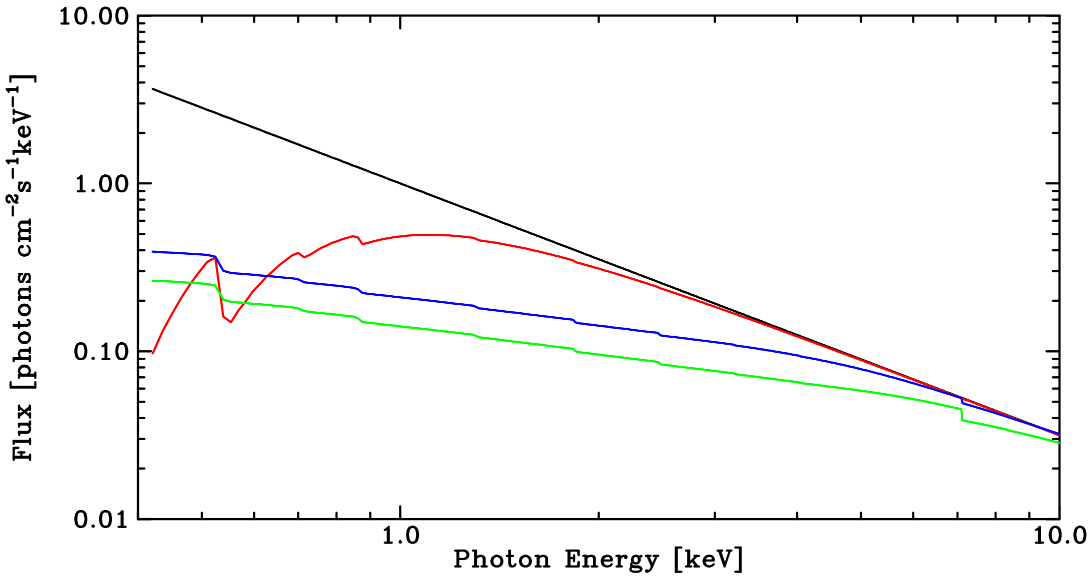


The N_H Histogram



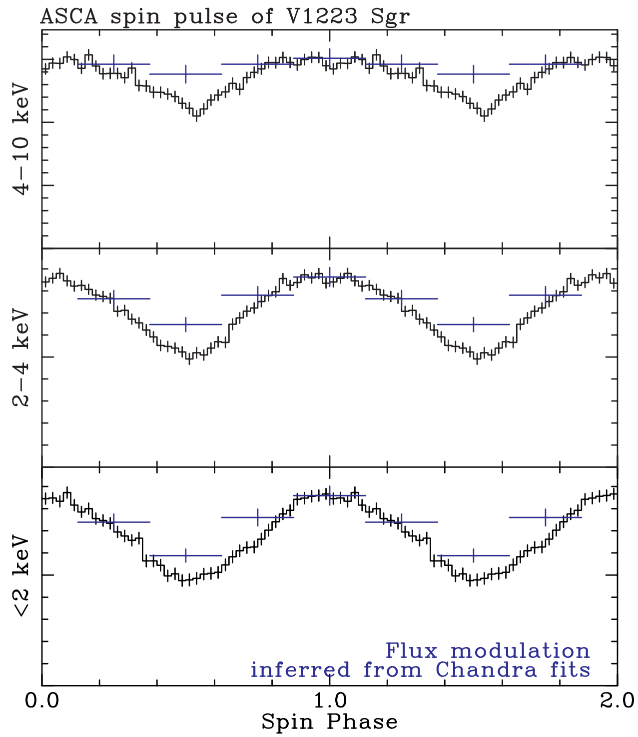
- In an accretion flow with an elliptical footprint, of the number of lines of sight for a given N_H has a continuous distribution, unlike the discrete partial covering absorber model.
- Done & Magdzirz (1998) created the pwab model, in which the number of lines of sight for a given N_H is a power-law function of N_H

Power-law like absorber



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

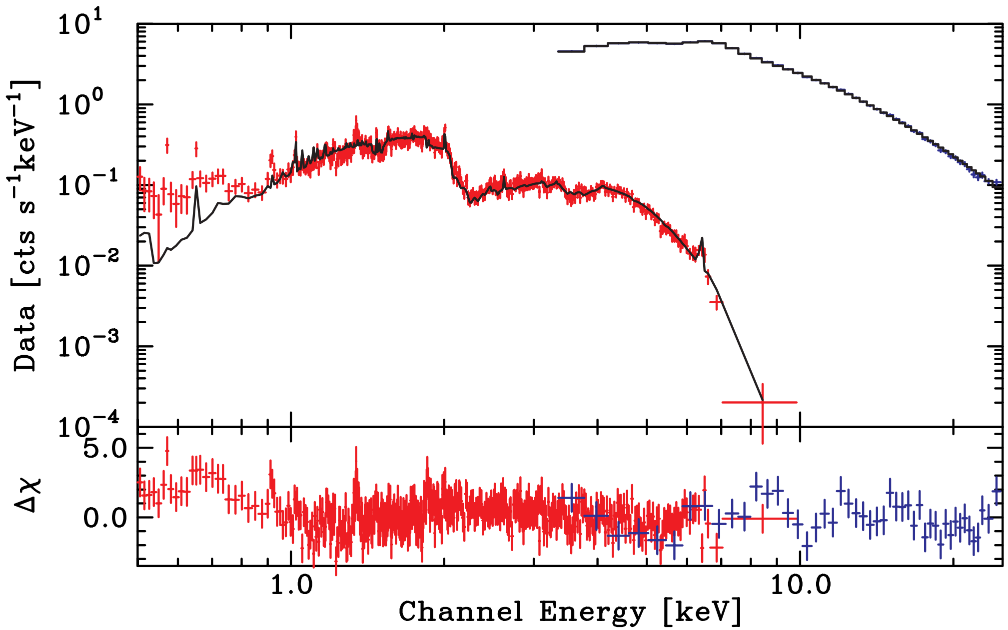
Spin modulation



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

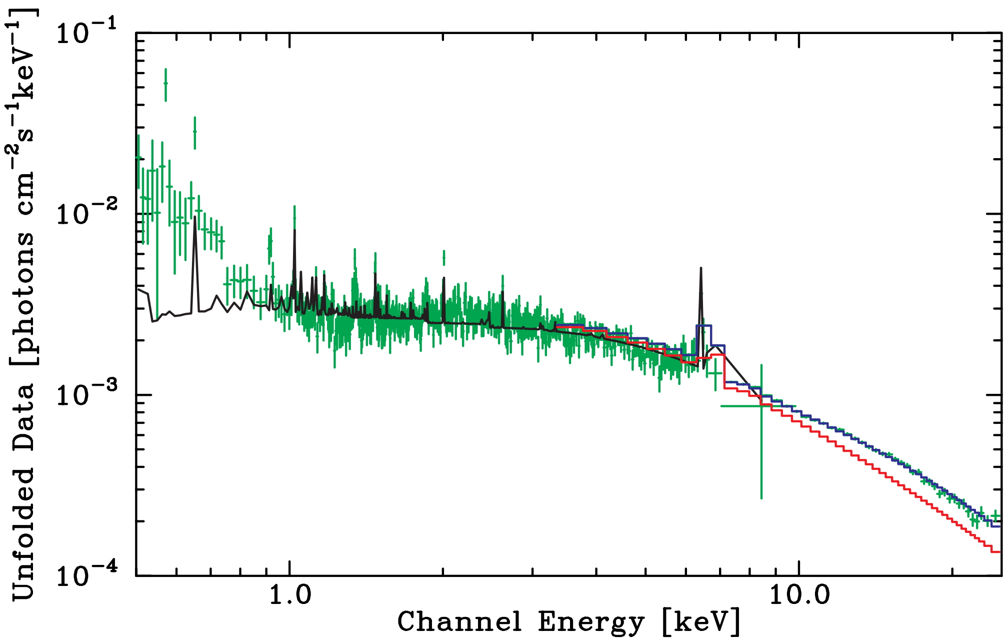
- Spin modulation is more pronounced at lower energies.
- Energy dependence is not as steep as it would be if it was caused by a simple photoelectric absorber.

The Spectrum of V1223 Sgr



- The *RXTE* PCA+*Chandra* HETG spectrum of "photoionized" CV, V1223 Sgr, can be almost fitted with `pwab(mkcflow)`
- One also needs: reflection, Fe Kα 6.4 keV line, photoionized lines (mostly He-like lines of medium-Z elemensts), and an OVII edge.

The Unfolded View

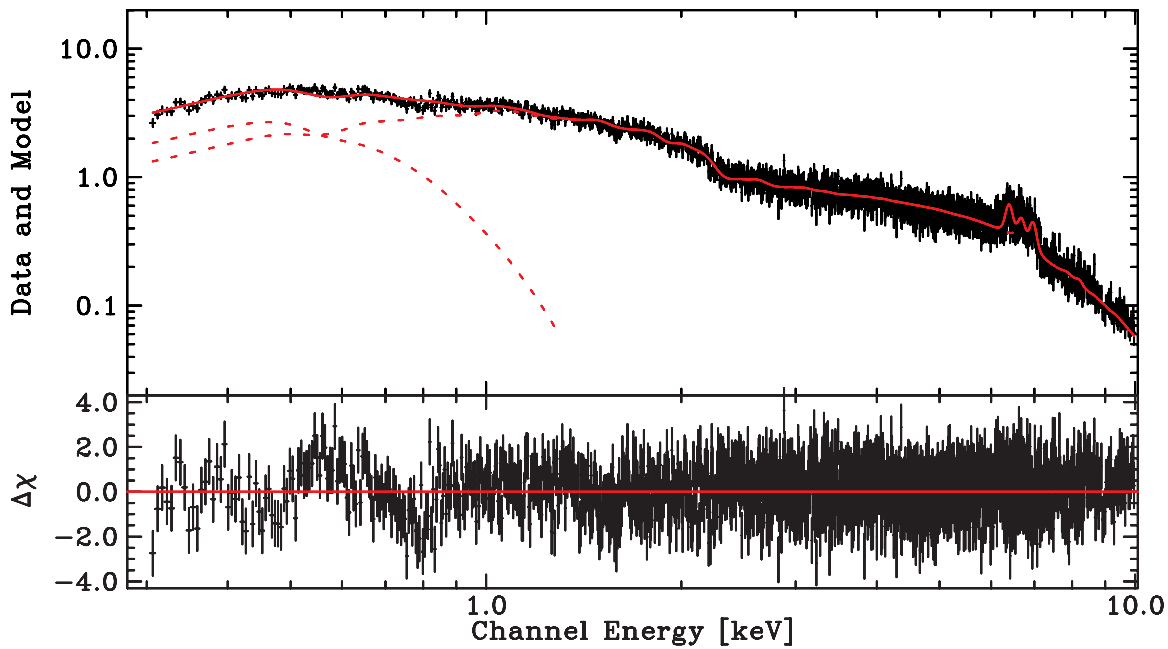


- The "central engine" of magnetic CVs is powerful enough to ionize medium Z elements in the immediate pre-shock flow. The viewing geometry then dictates the relative importance of the photoionized lines and warm absorber edges.
- The warm absorber edge may well be a universal feature of X-ray spectra of magnetic CVs, but requires a high S/N, high resolution spectrum. We also need an ionized version of pwab.

The Soft X-ray Component

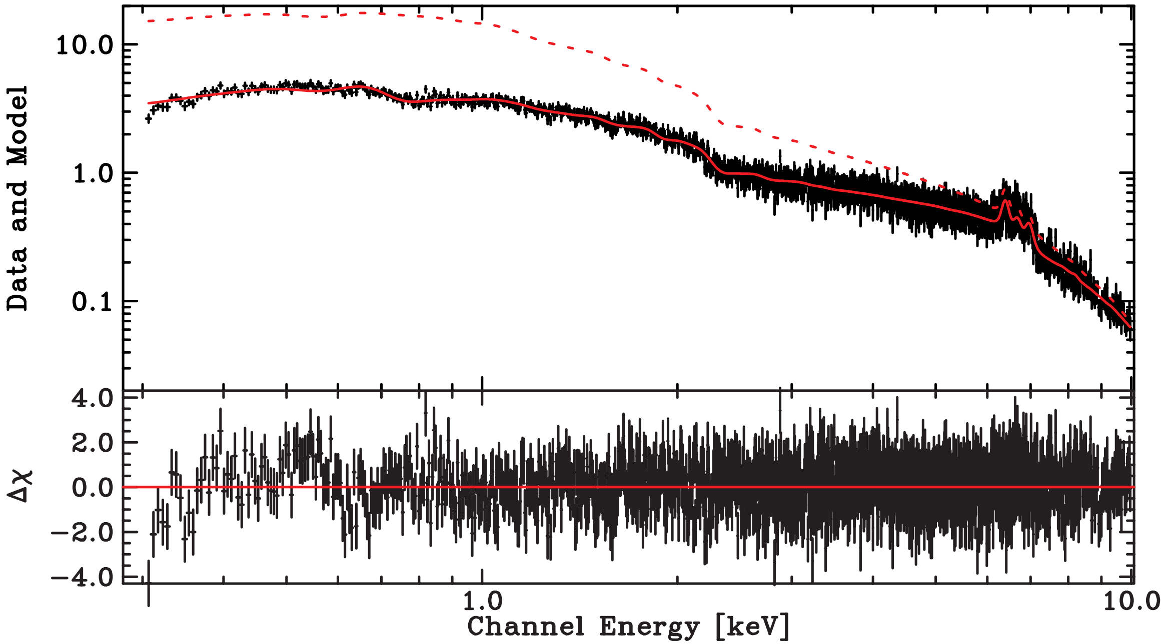
- The white dwarf photosphere below the shock can be irradiated from above and/or directly heated by blobs and become an intense soft X-ray/EUV source.
  - Most polars are dominated by the soft component. Only a small fraction (inc. asynchronous polars) have been detected in hard X-ray surveys.
  - The question of soft-to-hard X-ray luminosity balance has been discussed for many years.
- Soft IPs were originally discovered using *ROSAT* data (Haberl & Motch 1995). In the *XMM-Newton* era, more subtle soft component (never dominating over the hard at any energies) have been claimed in many IPs (e.g., Evans & Hellier 2007).
- Note the difference in claimed kT: many polars have kT$\sim$30 eV. First soft IPs had kT$\sim$50 eV, and the lates tabulation includes values as high as 100 eV.
- Mauche (1999), using the *EUVE* spectrometer, determined kT of 15–25 eV in 9 polars.
  - In 3 of them, *XMM-Newton* values are $\sim$10 eV higher.
  - When one fits the Wien end of a pwab(bbody) with a bbody, one often obtains a kT that is higher than the input value. Is this what is going on?

The Hot Blackbody Problem



- Local version of the Eddington argument limits the temperature of a blackbody on a white dwarf surface. Only massive (>1 $M_\odot$) white dwarfs can have hot (kT>80 eV) blackbody components.
- Evans & Hellier measured kT=117^{+33}_{-44} eV for V2400 Oph from a fit like the above, while the white dwarf mass infered from the hard component is 0.62–0.81 $M_\odot$. This is a clear contradiction.

An Alternative Interpretation



- The same spectrum can be fitted using complex absorbers with two warm absoerber edges. (Similarly for *ASCA* and *Suzaku* data without requiring a blackbody.
- For IPs with a subtle, hot blackbody component, this offers the possibility of a competing interpretation. We need a high resolution, high S/N spectra to confirm this.

Conclusions

- The “central engine” of magnetic CVs is a multi-temperature optically thin emission.
  - `mkcflow` offers a convenient approximation of this. Other, more specialized models do exist.
  - The deep *Chandra* observations of EX Hya show the limit of this approach, and offers a glimpse of what future X-ray observatories may be able to achieve.
- The complex absorber is a fact of life for all high accretion rate IPs.
  - pwab offers a convenient approximation of this. However, we need a more sophisticated model.
  - The photoionized lines do exist, so are warm absorber edges.
- The soft component is almost certainly seen through the same complex absorbers.
  - Need to reassess the kT and L that have beeen inferred for the soft component.
  - There is a distinct possibility that some claimed soft components are not real.