High Resolution X-ray spectroscopy of Cataclysmic Variables

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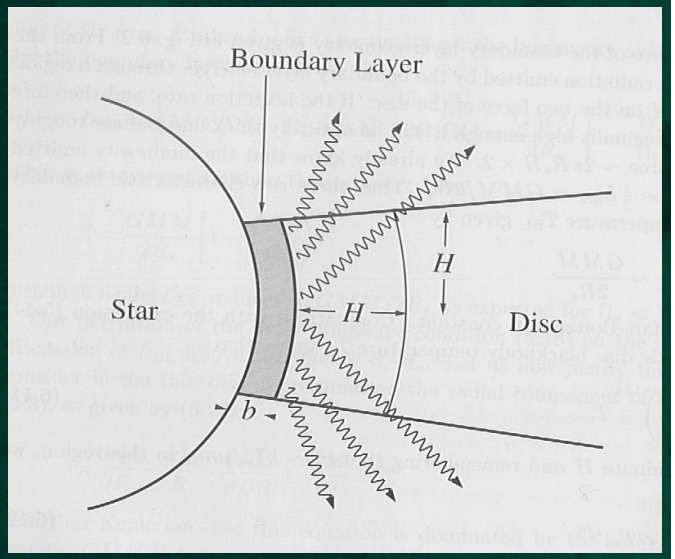
Wideband X-ray Astronomy: Frontiers at IUCAA, Jan 13, 2010

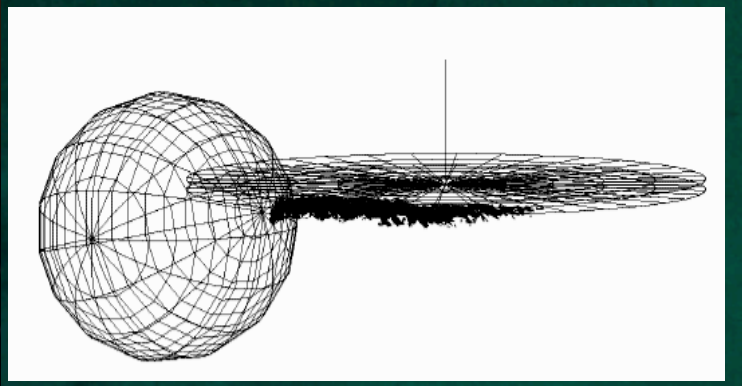
Non-magnetic CVs: Dwarf Novae

1. Accretion Disk (5000 K – few x 10^4 K) Optical to far UV. Half of the gravitational potential energy of the accreting material is released.

2. Boundary layer (between WD and inner edge of the disk)

High accretion rate ~ 10^{-8} $M_\odot$/yr – EUV, soft X-ray
Low accretion rate ~ 10^{-11} $M_\odot$/yr – hard X-ray

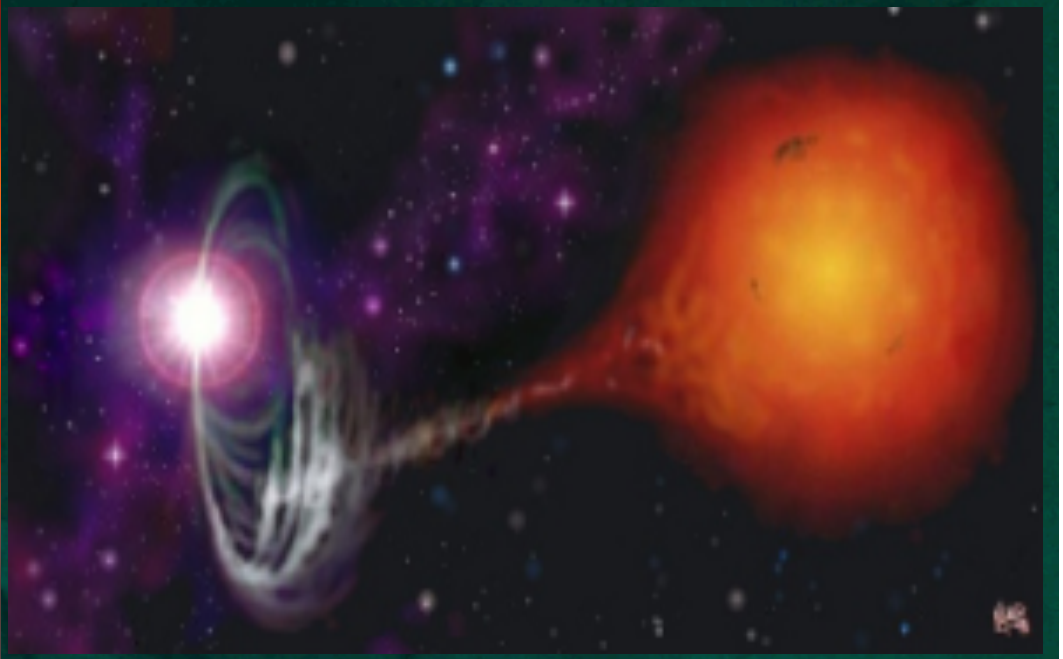




Magnetic CVs

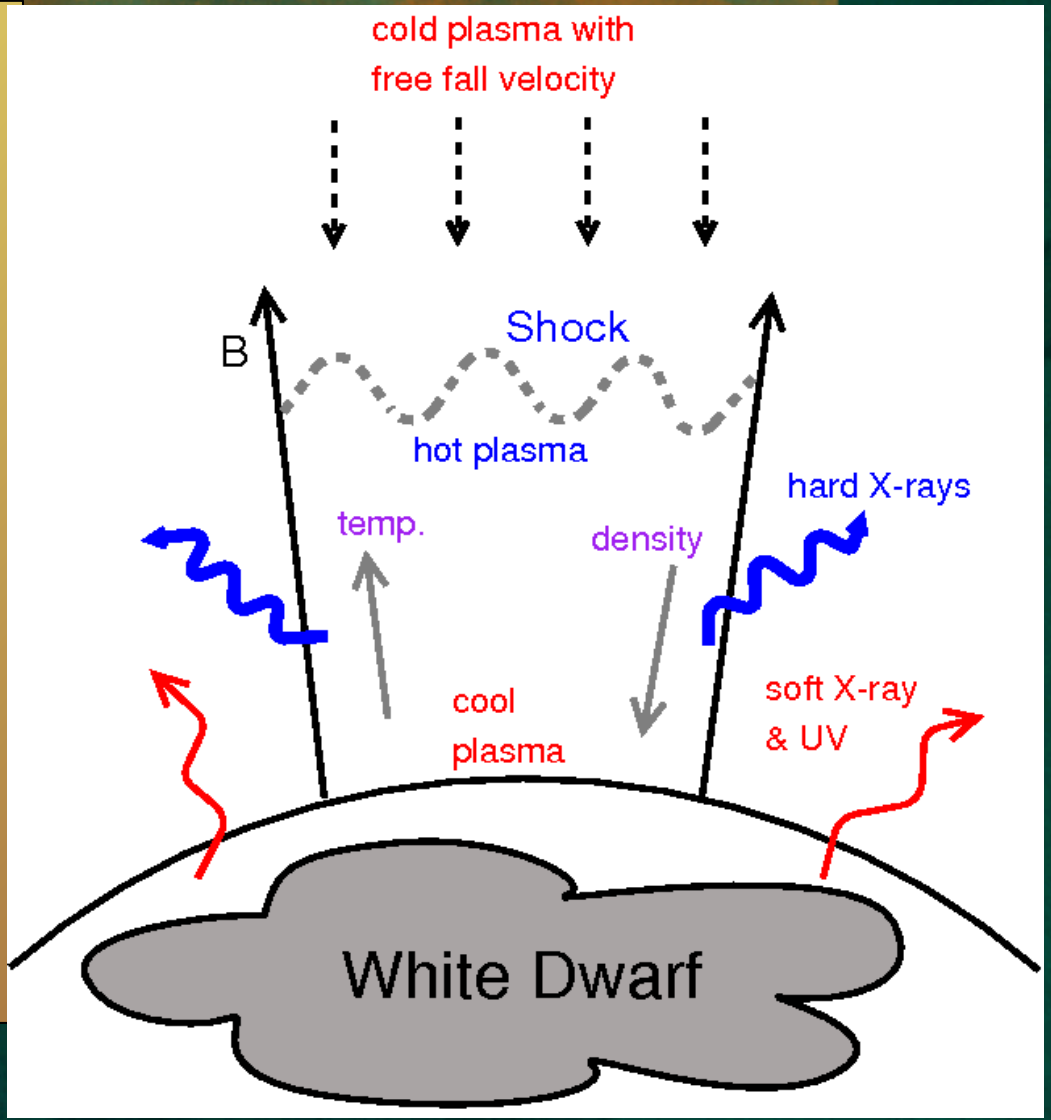
Intermediate Polars (IPs)

Polars

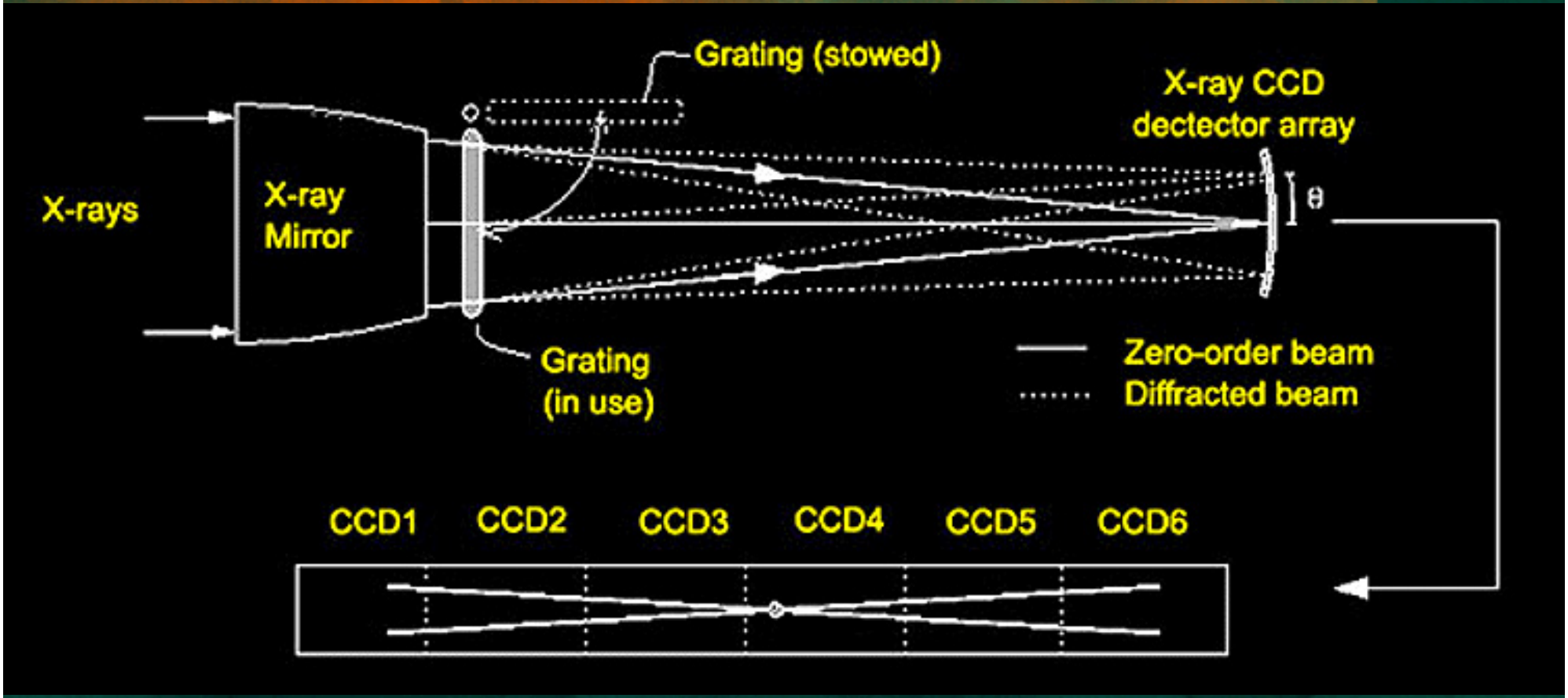


Magnetic CVs

- Accreting material follows magnetic field lines and directly falls onto the white dwarf.
- Forms a strong shock near the surface of the white dwarf.
- Continuous temperature distribution
- Temperature and density gradient
- Line emission from post-shock plasma

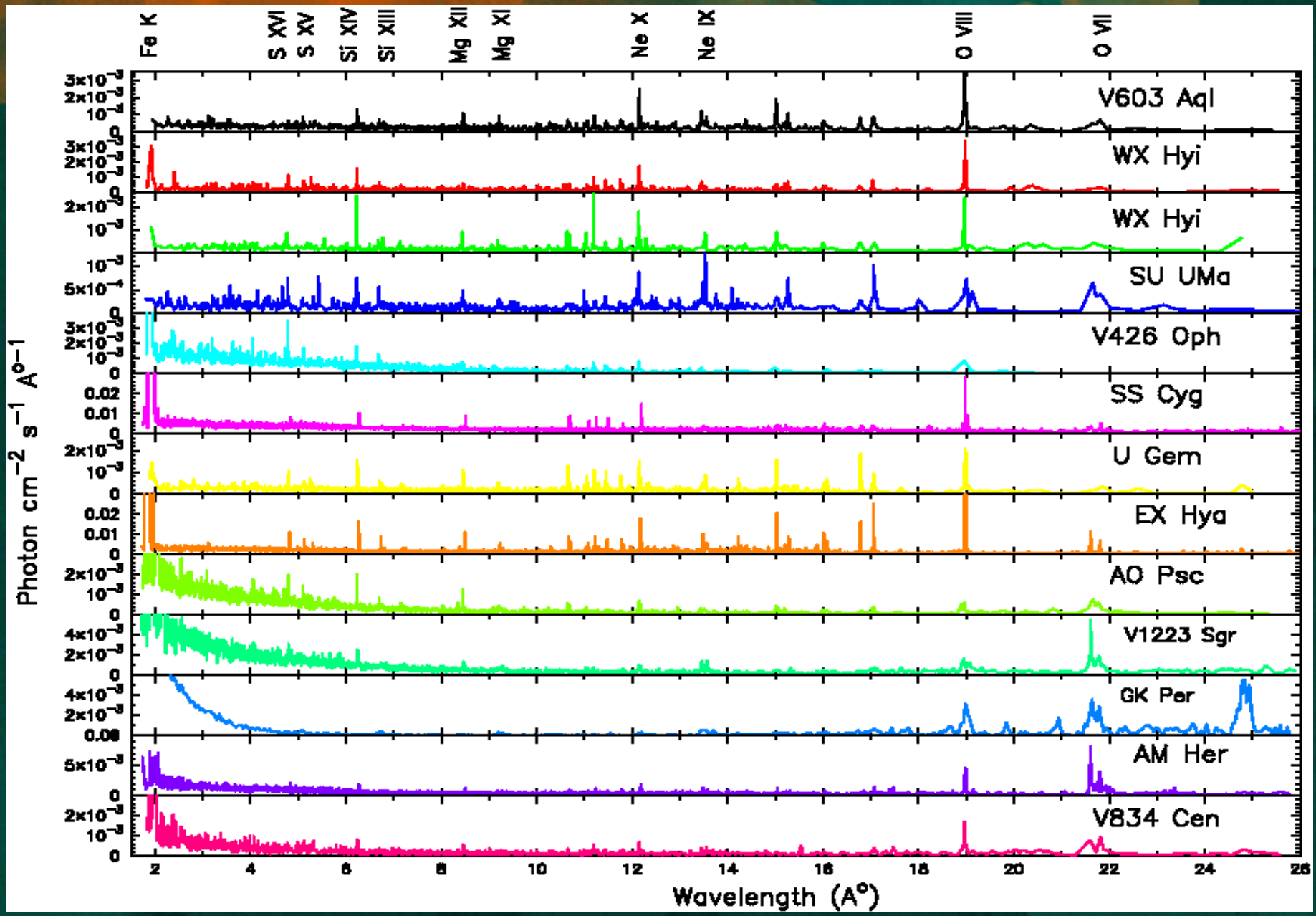


Chandra Gratings: HETG, LETG



HETG: Energy band 0.4-10 keV.
Resolving power ($E/\Delta E$) varies from ~800 at 1.5 keV to ~200 at 6 keV

MEG spectra of 12 CVs in quiescence



Analyzing high resolution X-ray spectra

1) Global fit approach:

- To find a plasma model that better represent the observed spectrum in terms of emission lines
- To estimate the temperature distribution in the emitting regions

2) Line-by-line fit approach:

- Using several Gaussians representing emission lines
- To study the line profile in detail and obtain line parameters like position, width and flux
- Using line ratios to study the temperature, density, ionization stage, emission geometry, opacity in the emitting plasma
- To understand the dominant physical process in plasma and accretion physics.

Fe Kα Line Study of non-Magnetic CVs

Chandra ±1 order HEG spectra for 6 CVs

Fe Kα Lines: Fluorescent line @ 6.4 keV → 1 Gaussian
He-like triplets @ 6.7002 (r), 6.6821 (i_1), 6.6673 (i_2)
and 6.6364 keV → 3 Gaussians
H-like doublets @ 6.973 and 6.952 keV → 1 Gaussian

H and He-like lines and their ratio → Regions of highest temperature in the boundary layer of non-MCVs and the ionization temp.

G-ratio = (f+i)/r →sensitive to electron temperature

R-ratio = f/i → sensitive to electron density

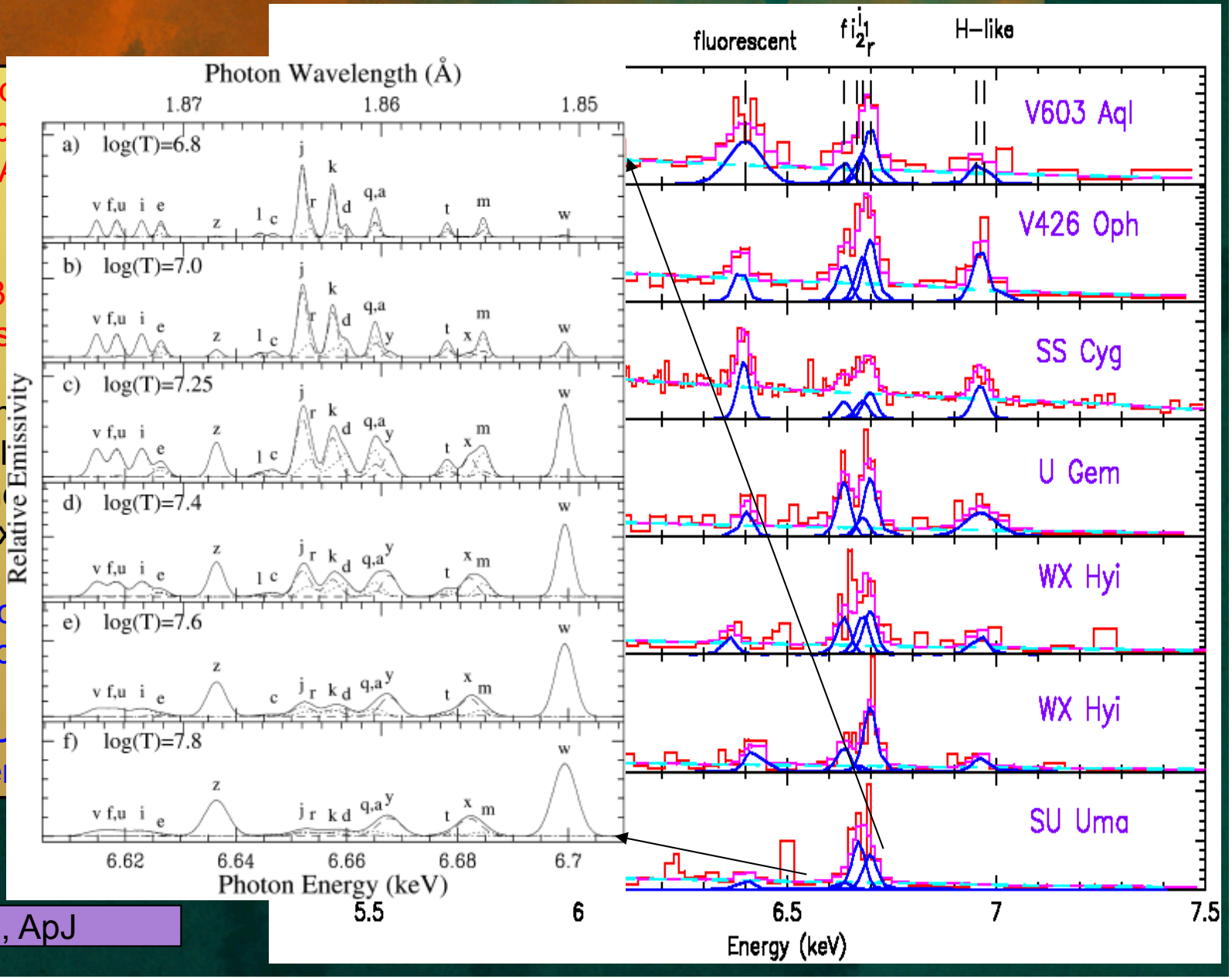
Fluorescent line → cold material and reflection

Fe Kα Lines in Quiescence

Prominent fluoresc
V603 Aql, V426 Op
⇒ reflection from A
surface as seen in
weak absorption.
It is broad in V603
of 1700±1000 km/s

Stronger r-line com
lines in He-like tripl
dominance of prin
the DES with T>3 x

U Gem showed bro
that corresponds to
1400±800 km/s.
It is absent in SU U
plasma is at low te



Rana et al. 2006, ApJ

Fe Kα Lines in Outburst

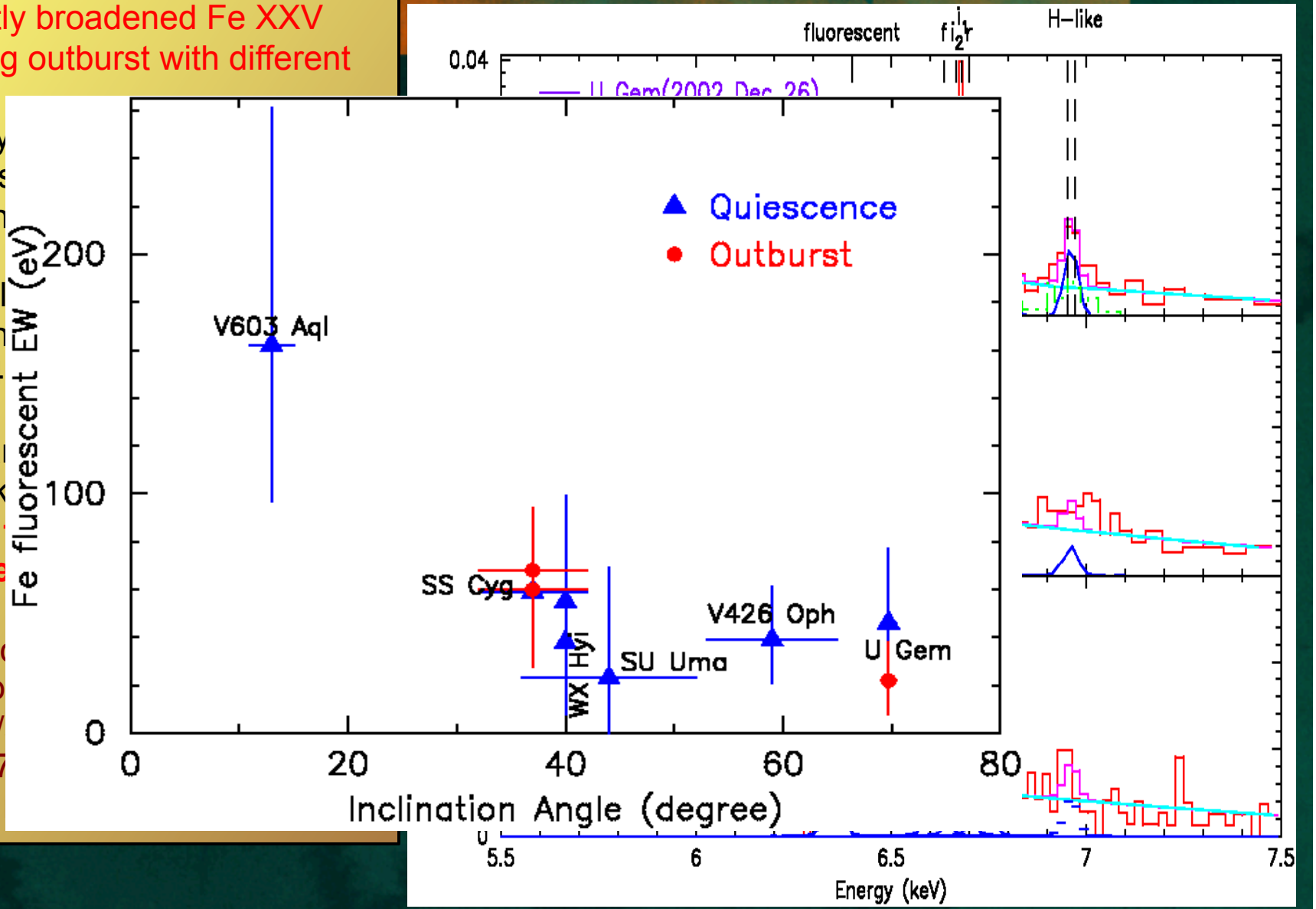
Significantly broadened Fe XXV lines during outburst with different profiles.

U Gem: Sy
Gaussian s
each line h
km/s.

SS Cyg: Fl
shifted r lin
(1120±224
and f lines
O-type sta
galaxy Mrk

**Evidence
during the**

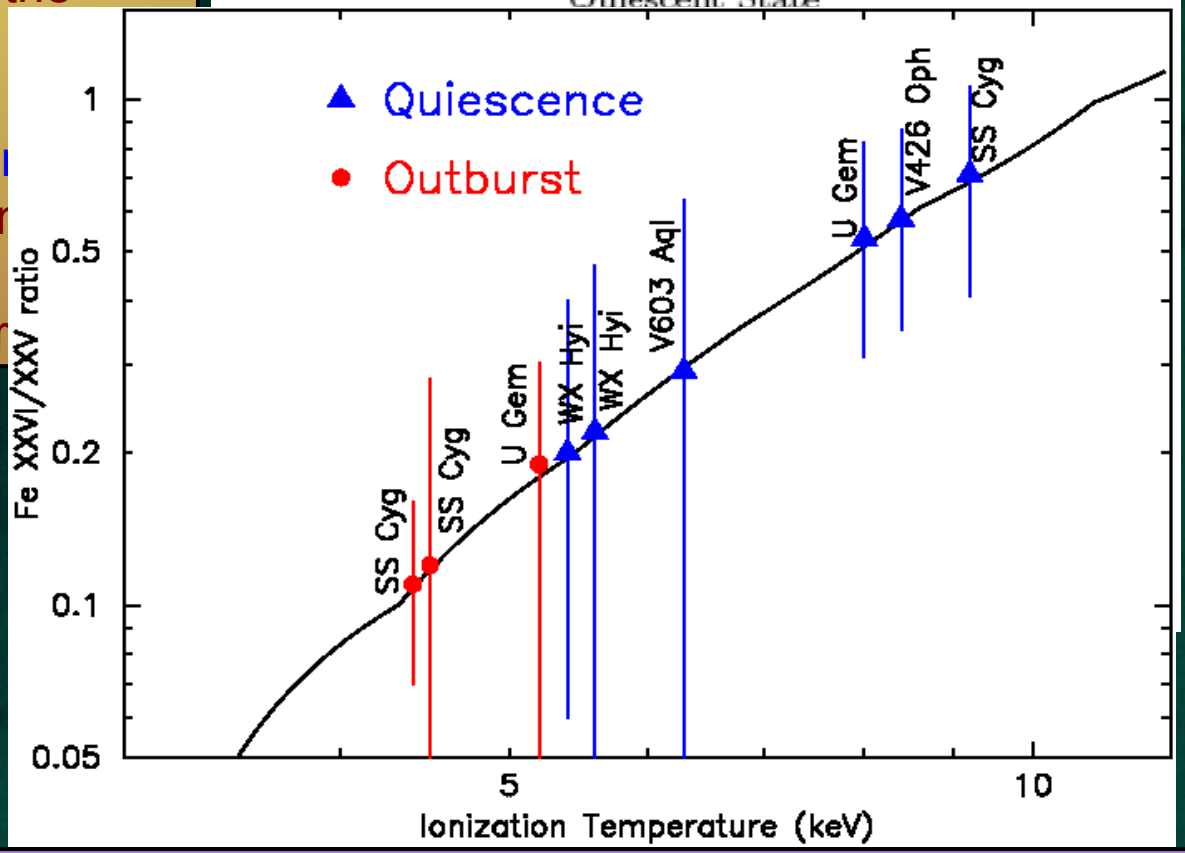
Red-shifte
SS Cyg co
~2300 km/
GK Per: 37
pre-shock



Plasma diagnostics: G and R ratios

- Principal lines can be used to estimate the G & R ratios.
- G-ratio is close to 1 for most of the sources ⇒ the plasma is in CIE.
- SS Cyg has G~2.4 ⇒ hybrid
- SS Cyg, V603 Aql, V426 Oph a
Hyi the R-ratio varies in 0-2.5, he
not constrain the plasma density.
- Better signal-to-noise data are

source	G=(f+i)/r	R=f/i	Fe XXVI/XXV
Quiescent State			



Fe XXVI/Fe XXV line flux ratio provides Ionization temperature.
$kT_{ion} \leq 12$ keV for all non-magnetic CVs studied.
For SS Cyg the kT_{ion} is higher during quiescence than outburst.

G ratio for other elements (O, Mg, S and Si) for 12 CVs

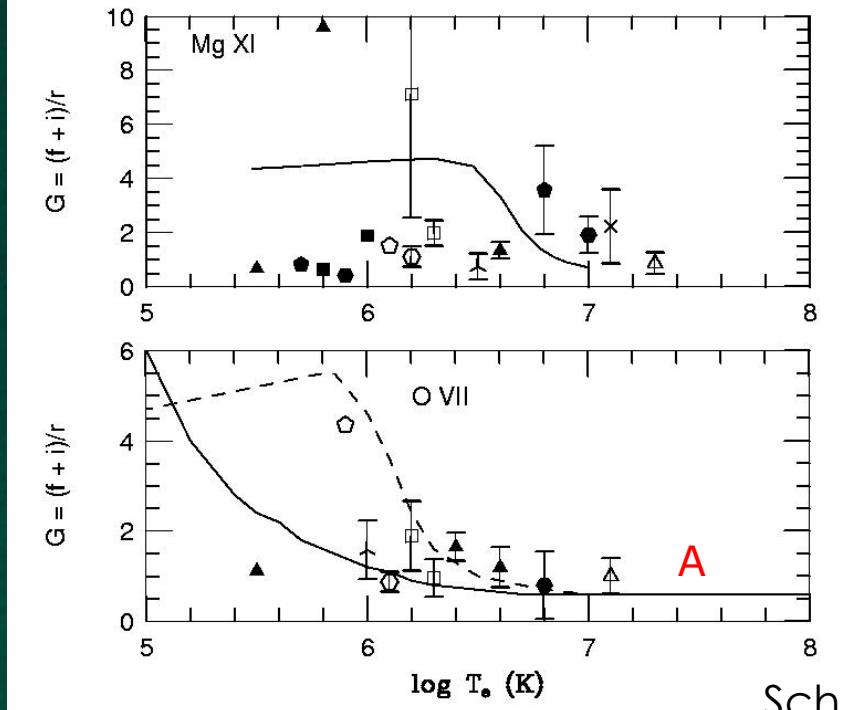
Solid curves: coronal plasma

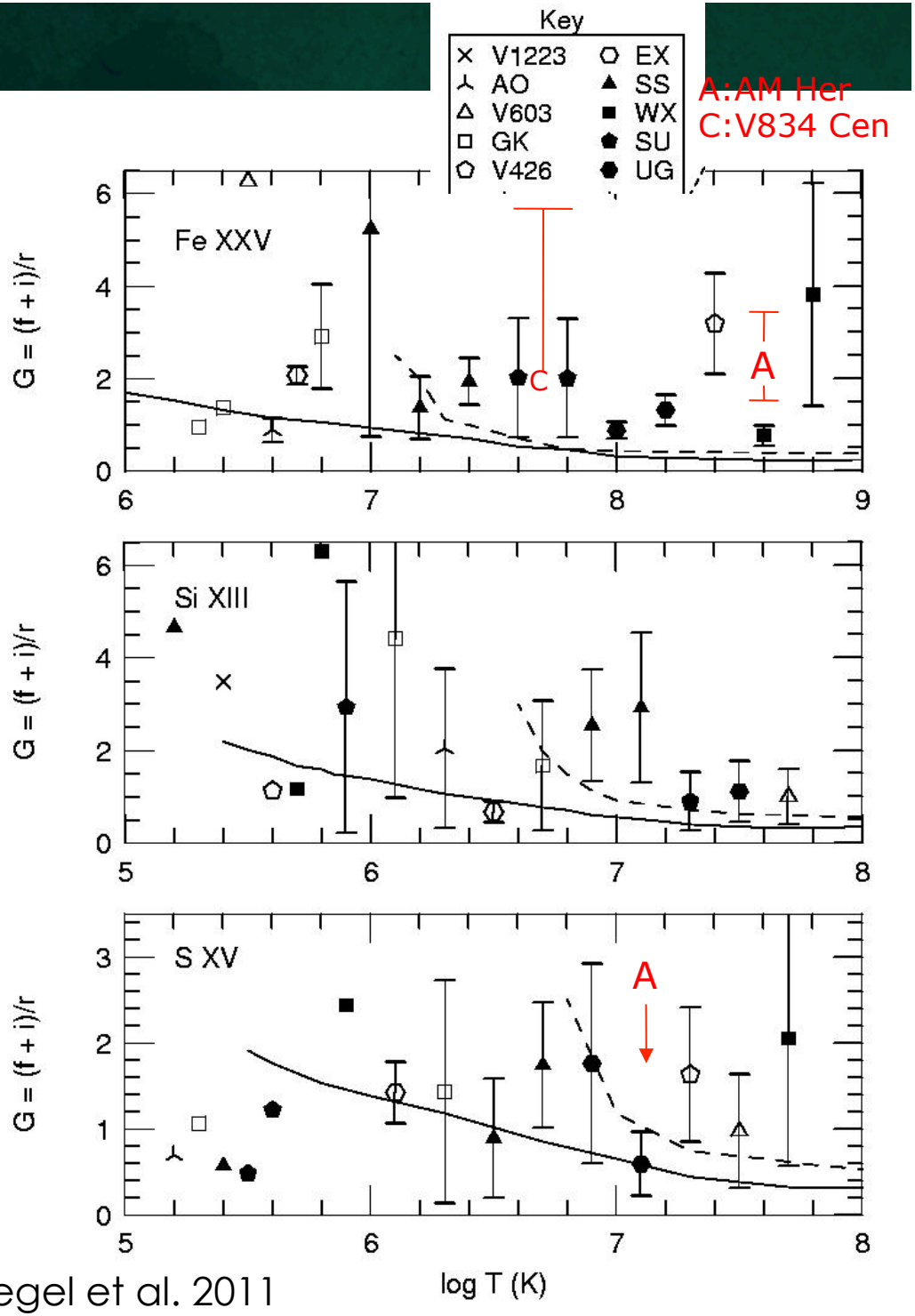
Dashed curves: including satellite lines and under photo-ionization conditions

Bautista & Kallman (2000) Fe, Si, S, O

Porquet & Dubau (2000) Mg

Collisional ionization with low T or photoionization with high T ?





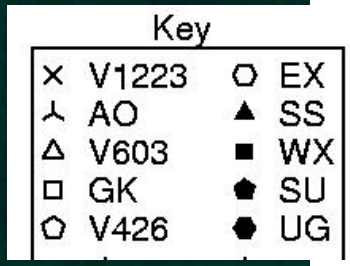
Schlegel et al. 2011

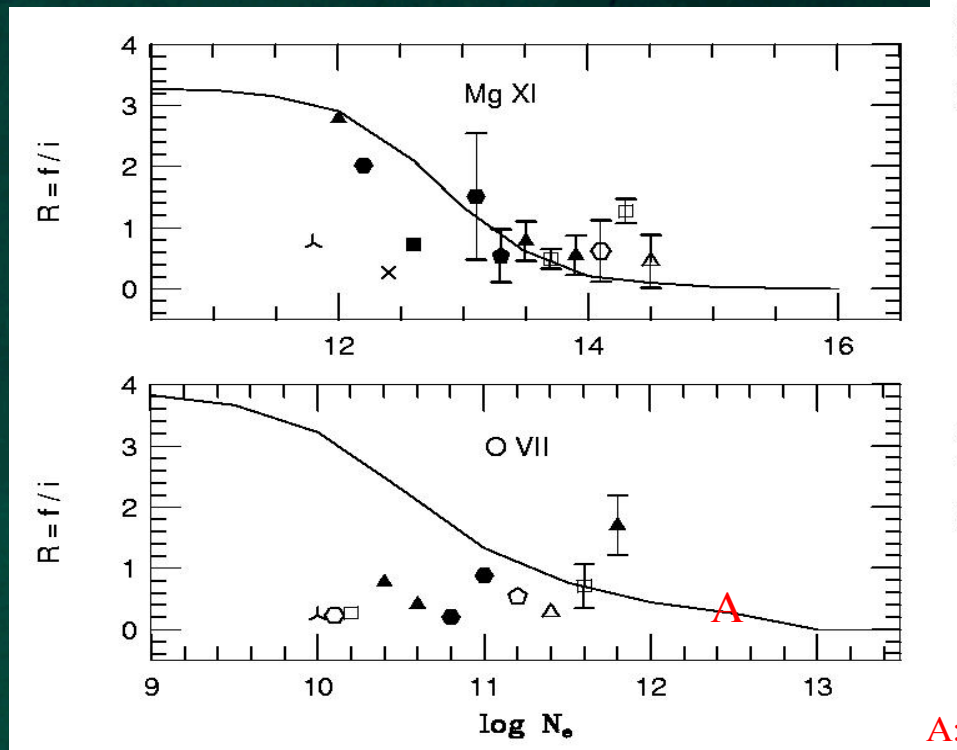
R ratio: Plasma Density

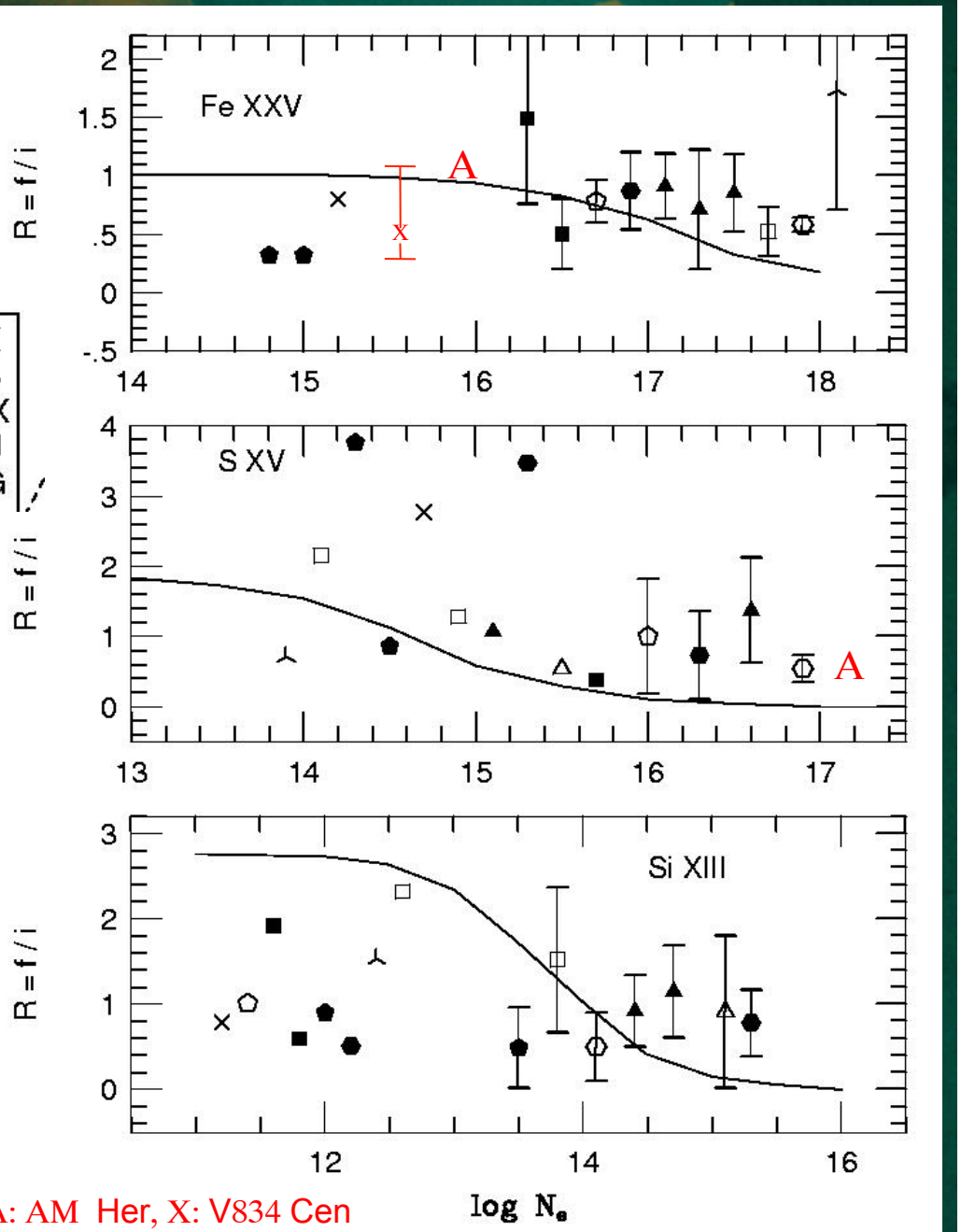
Log Ne for
Fe: > 15-16 cm^{-3}
S : > 14 cm^{-3}
Si: > 11.5 cm^{-3}
Mg: > 12 cm^{-3}
O: > 10 cm^{-3}

Absence of Fe XXI 12.26 A gives log Ne >13

Ratios Immune from UV:
Fe XVII 17.10 to 17.05 &
17.10 to 16.77 Log Ne>14







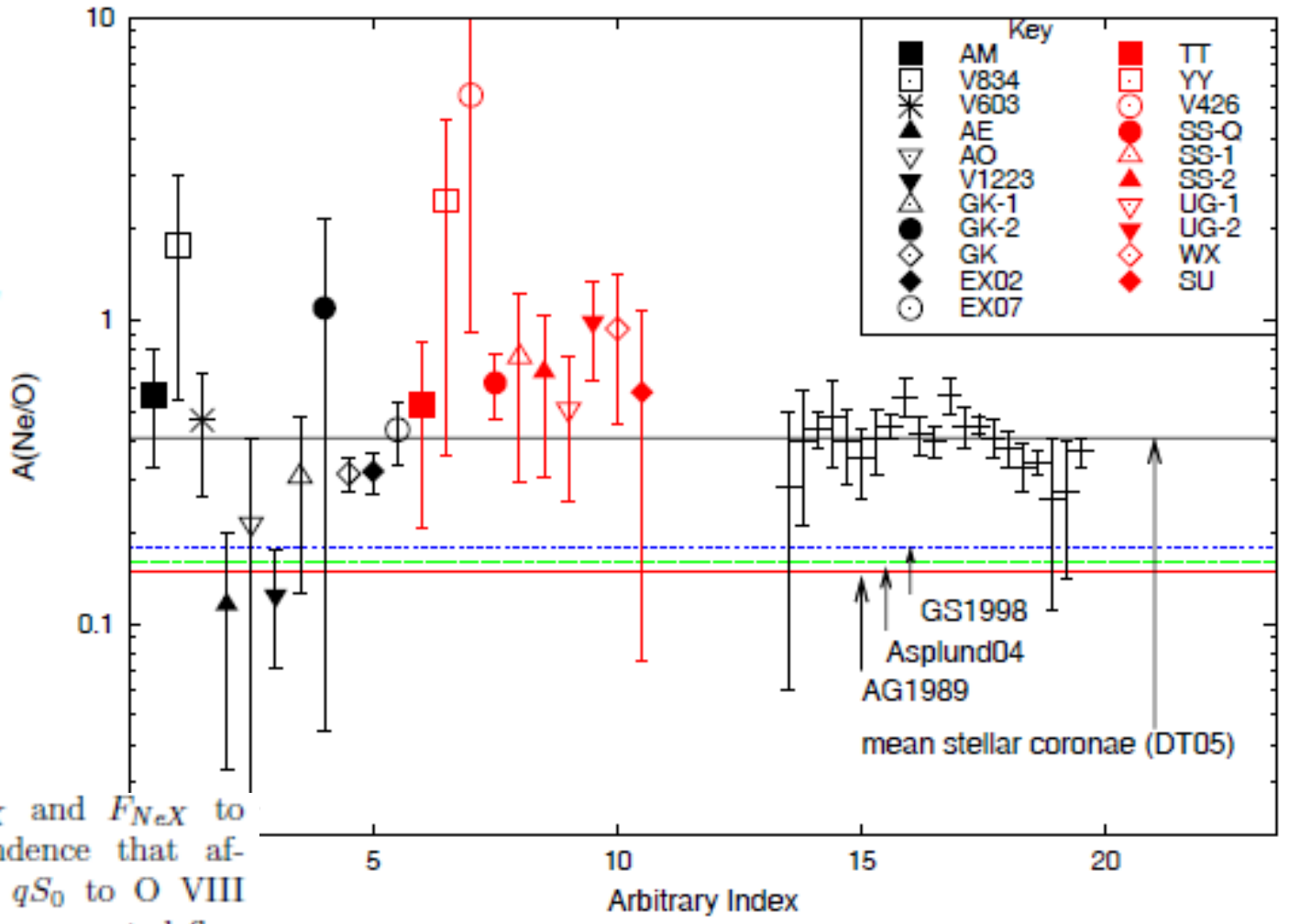
A: AM Her, X: V834 Cen

Ne/O Abundance (12 CVs)

$$\frac{A_{Ne}}{A_O} = \left(\frac{G_O}{G_{Ne}}\right)\frac{F_{Ne}}{F_O}$$

$$F_{ji} = \int_{\Delta T_{ji}} G_{ji}(T)\Phi(T)dT$$

Adopting Drake & Testa(2005) prescription used for Nearby stars.



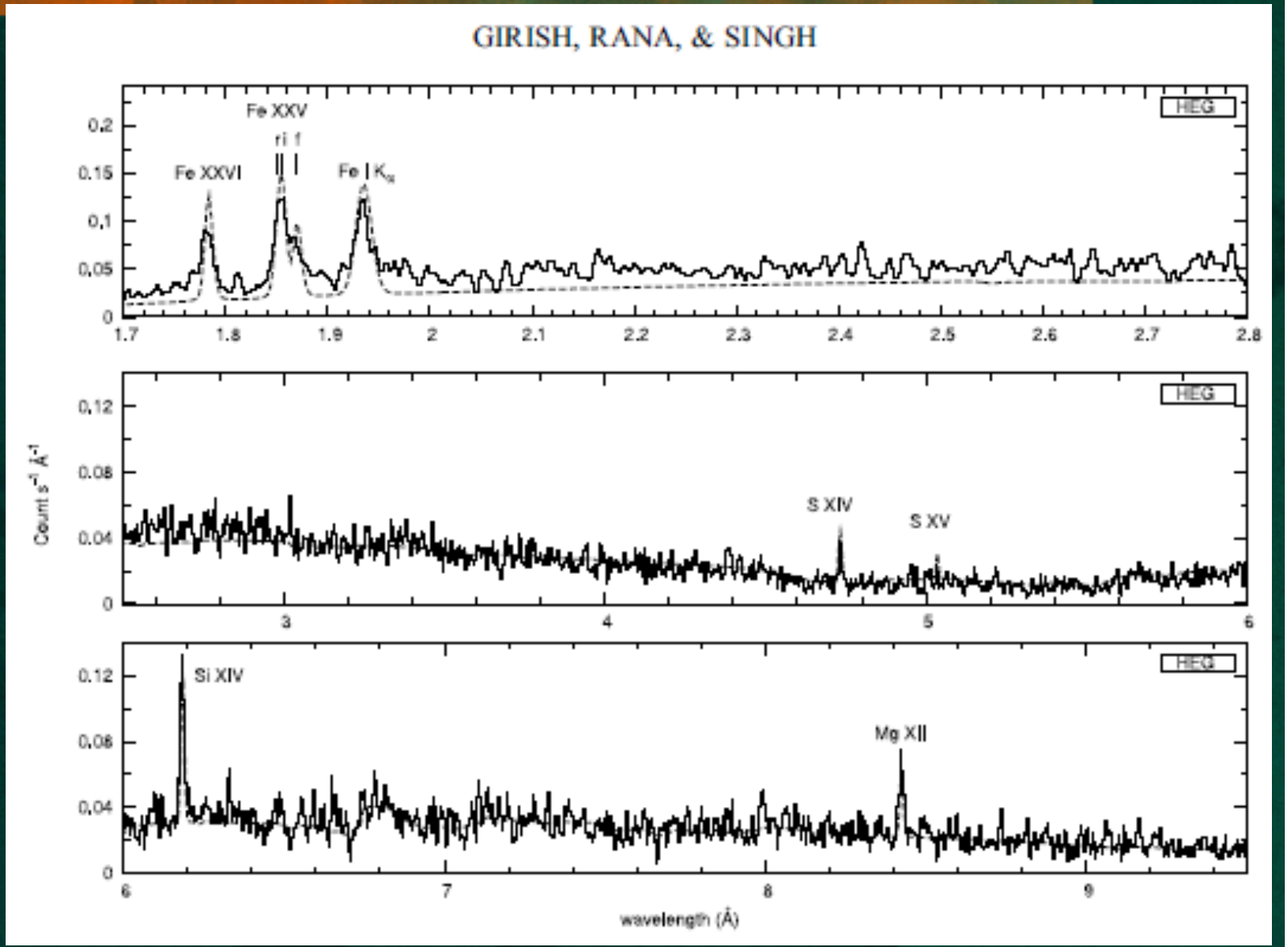
algebraic combination of F_{NeIX} and F_{NeX} to remove the temperature dependence that affects the Ne IX $1s2p^1\ P_1 \rightarrow 1s^2\ qS_0$ to O VIII $2p^2\ P_{3/2,1/2} \rightarrow 1s^2\ S_{1/2}$ ratio. The corrected flux ratio that results is

$$\frac{F_{Ne\ IX} + 0.15F_{Ne\ X}}{F_O}$$

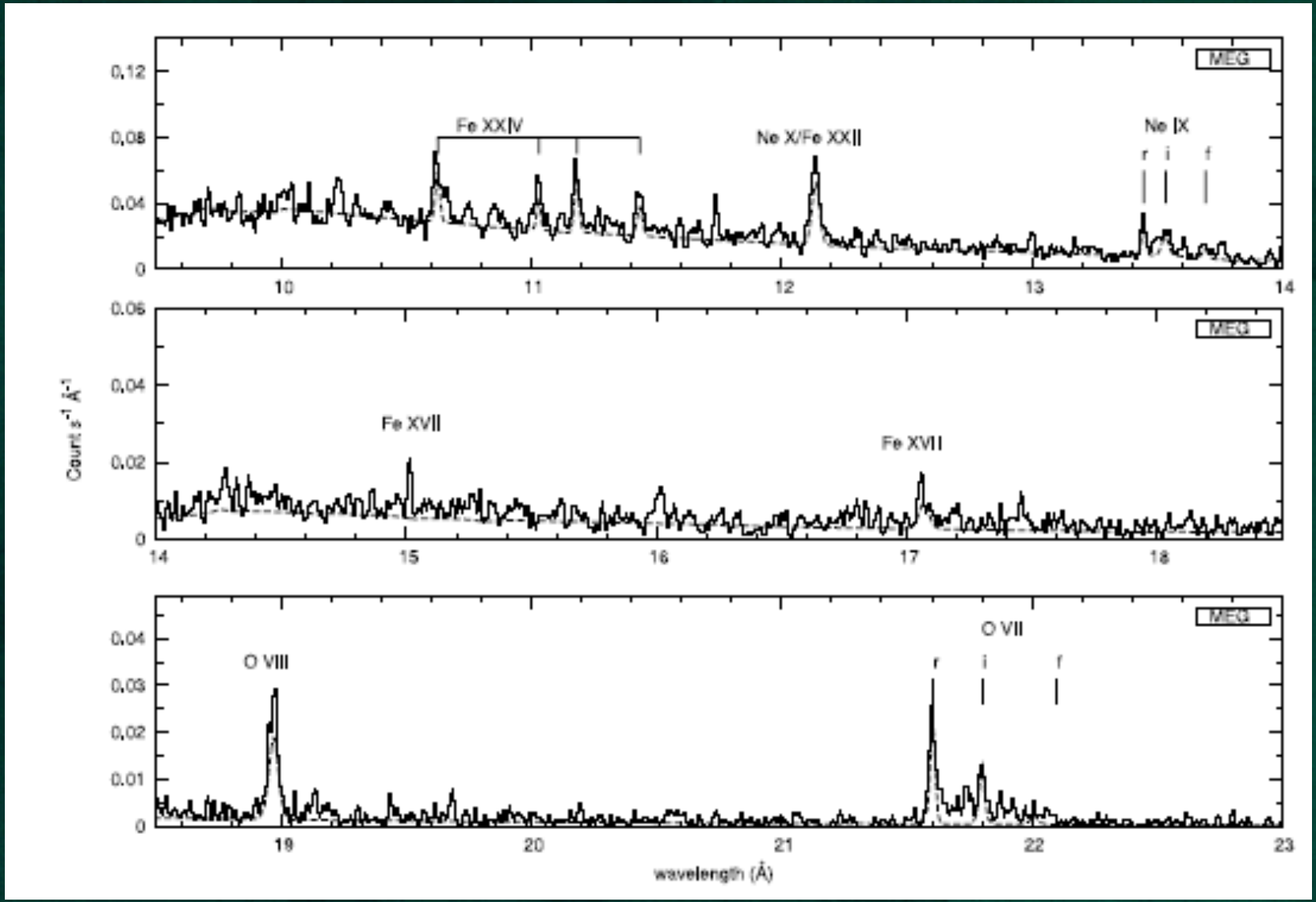
Mean = 0.44+-0.32 IPs and 0.72+-0.18 DNe
ONe models of WDs preferred over CO models of Jose & Hernandz (Schlegel et al. 2011)

Chandra HETG Spectrum of AM Her

- Strong flourescent line of Fe Kα is seen
- Relative strength of r with respect to i indicates the importance of collisional processes
- Flux ratio R = f/i for Ne IX & O VII predicts a density $n_e = 4 \times 10^{12}$ cm^{-3}.
- The ratio G = (f + i)/r for the two ions gives T of 2 MK.



Chandra MEG Spectrum of AM Her

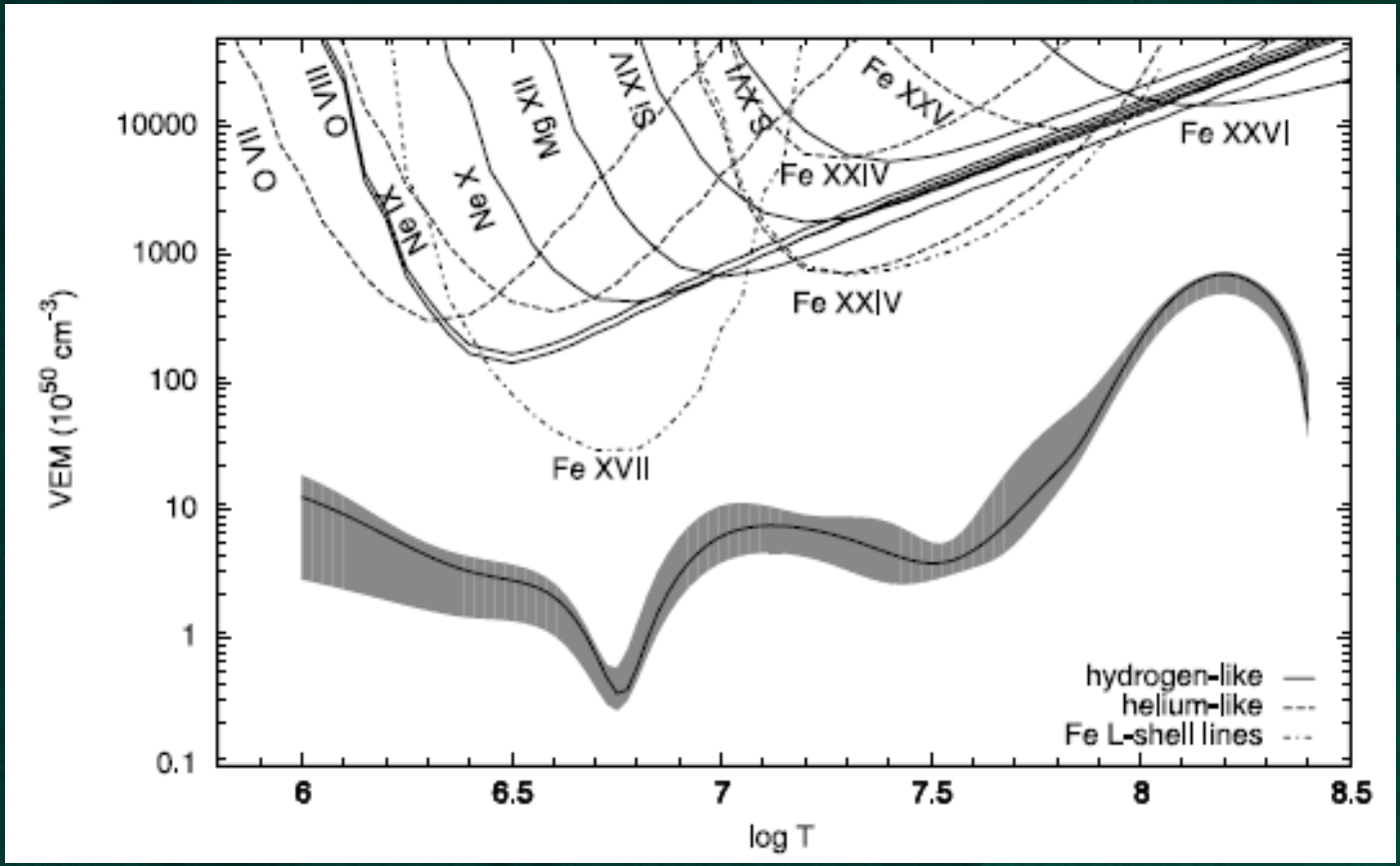


EM Distribution from Line analysis: AM Her

For an optically thin plasma in collisional ionization equilibrium, observed flux (f_L) in feature L is (Griffiths & Jordan, 1998, ApJ, 497, 883) :

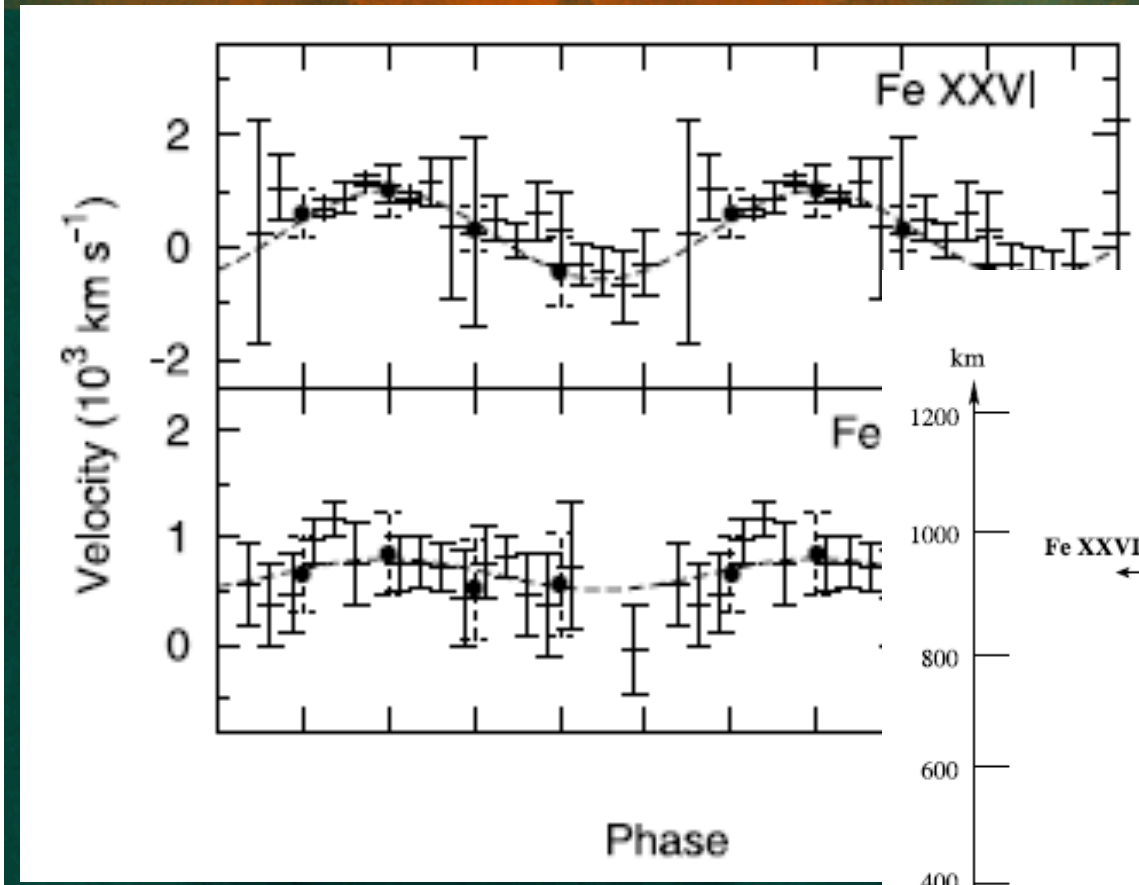
$$f_L = A_L / 4\pi d^2 \; \Sigma \, dV \, G_L(T_e, n_e) n_e \, n_h$$

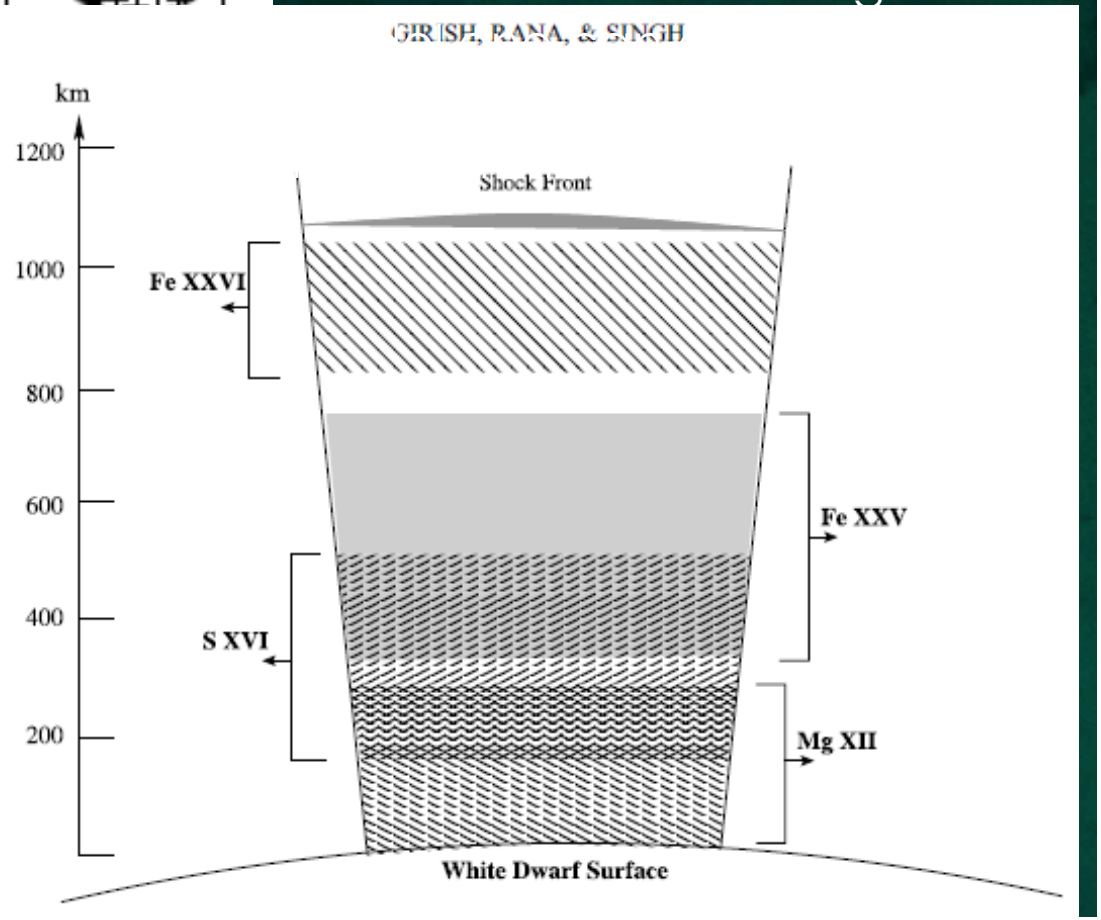
A_L is elemental abundance, G_L emissivity and d is distance.



Phase Resolved Spectroscopy of AM Her

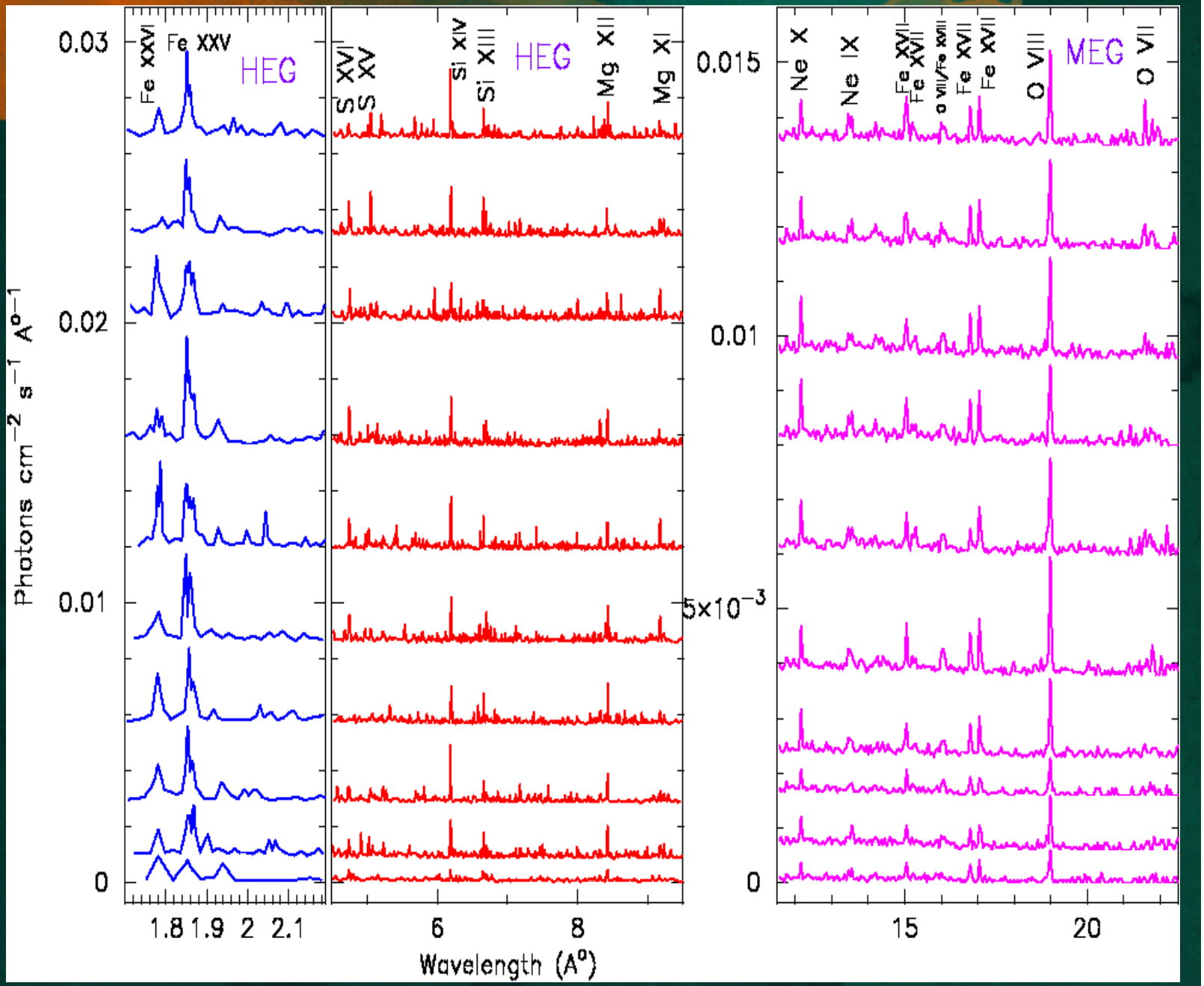
- Line centers of Mg XII, Si XVI, resonance line of Fe XXV, and Fe XXVI emission modulated by 1000 km/s indicating bulk motion of ionised material in the accretion column. Using Aizu





EX Hya: Binary phase resolved spectra (60 ks)

- H-like lines dominate from O to Si
- He-like lines dominate for Fe except during the phases centered on 0.3 and 0.5



EX Hydrae: Spin Phase folding Fe and S lines (500 ks)

Fig. 35.— Light curve for EX Hya folded at the spin phase: (left) Fe XXVI Kα and Fe XXV r; (right) Fe XXV i and f. In this and all subsequent light curves, the filled squares represent the light curve of the neighboring continuum.

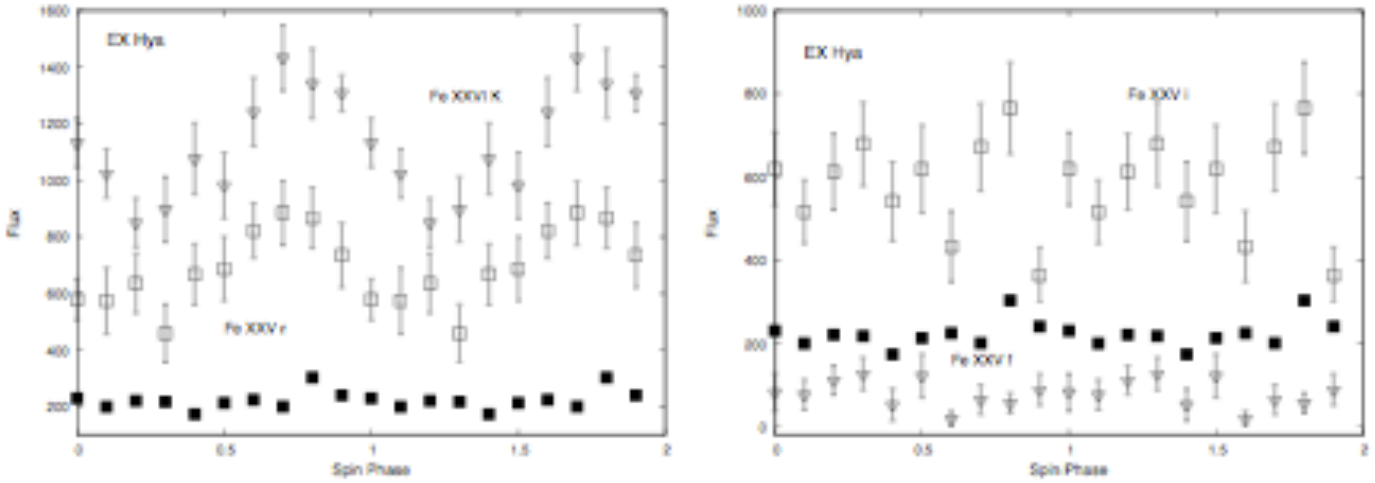
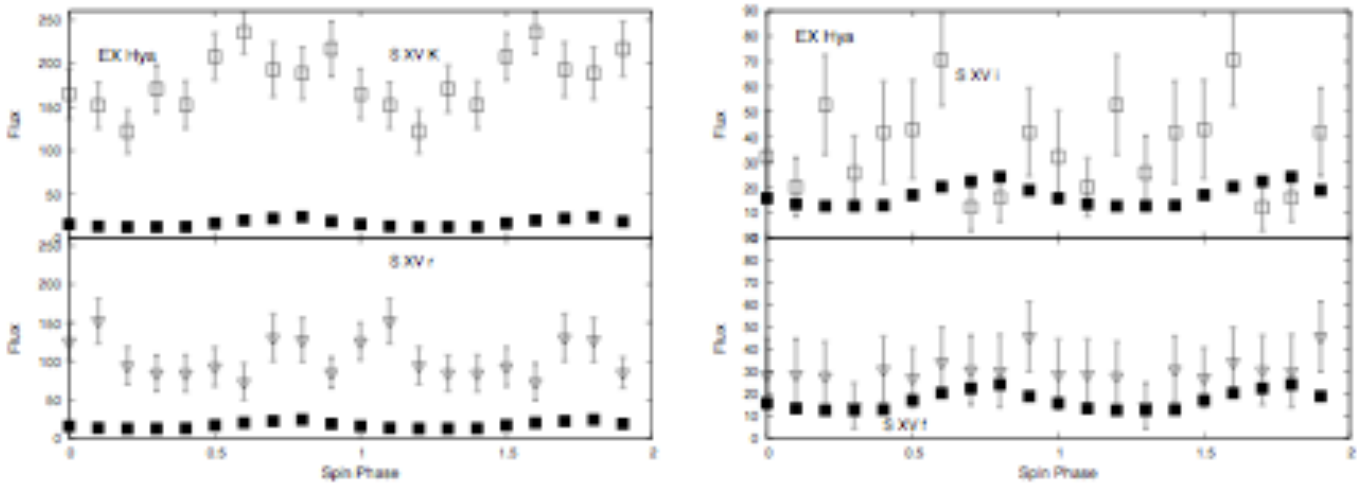


Fig. 36.— Light curve for EX Hya folded at the spin phase: (left) S XVI Kα and S XXV r; (right) S XV i and f. Filled squares = neighboring continuum.



EX Hydrae: Spin Phase folding Si and Mg lines

Fig. 37.— Light curve for EX Hya folded at the spin phase: (left) Si XIV Kα and Si XIII r; (right) Si XIII i and f. Filled squares = neighboring continuum.

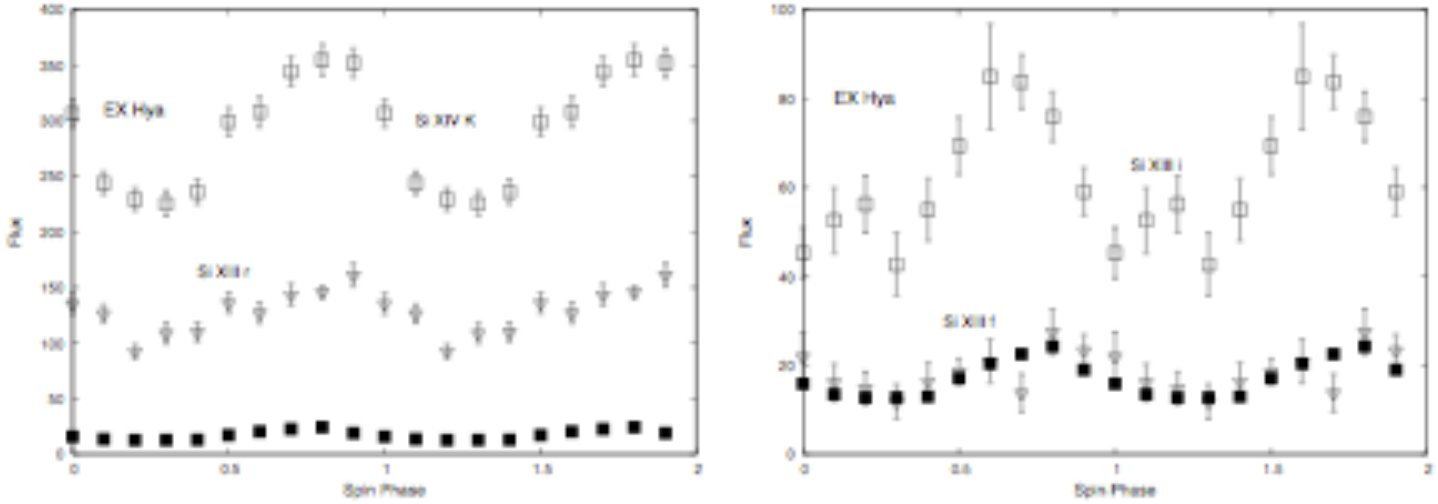
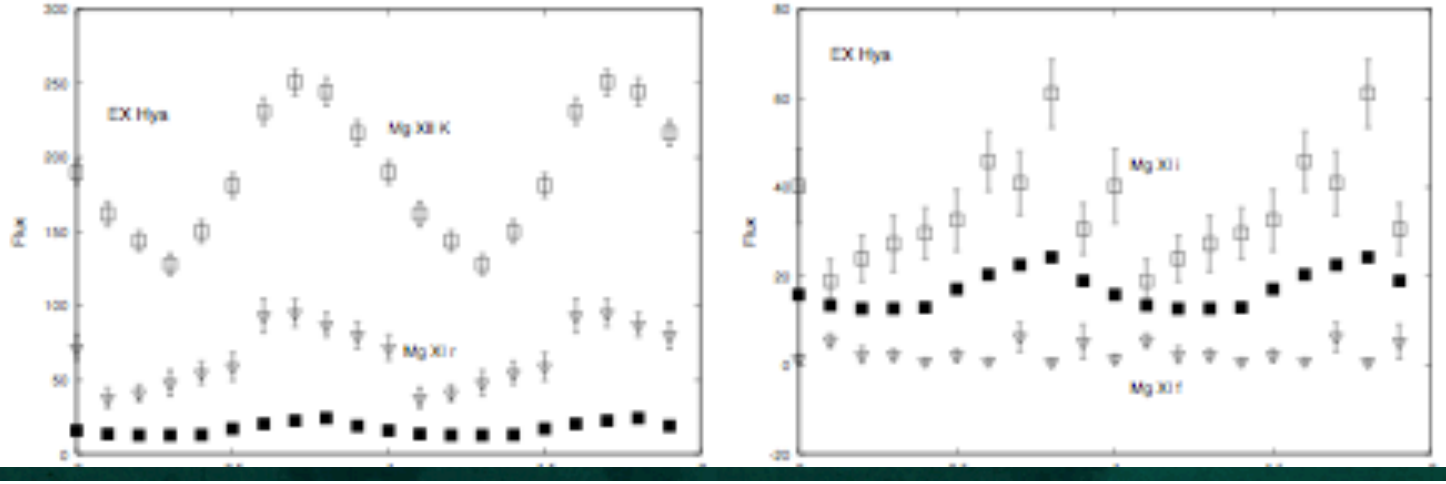


Fig. 38.— Light curve for EX Hya folded at the spin phase: (left) Mg XII Kα and Mg XI r; (right) Mg XI i and f. Filled squares = neighboring continuum.



EX Hydrae: Spin Phase folding Ne and Mg lines

Fig. 39.— Light curve for EX Hya folded at the spin phase: (left) Ne X Kα and Ne IX r; (right) Ne IX i and f. Filled squares = neighboring continuum.

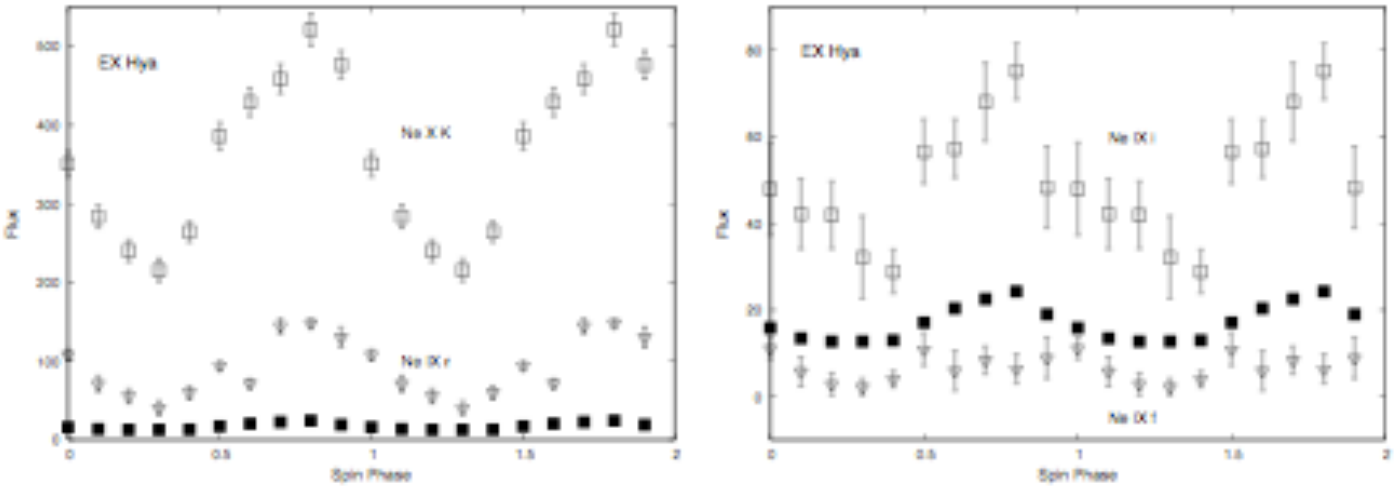
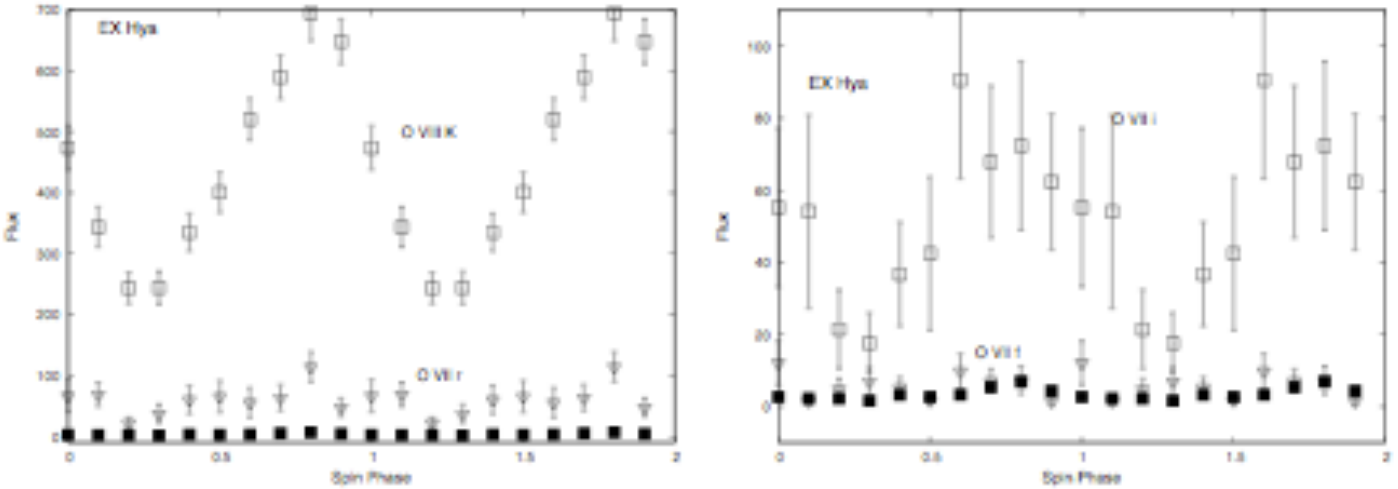


Fig. 40.— Light curve for EX Hya folded at the spin phase: (left) O VIII Kα and O VII r; (right) O VII i and f. Filled squares = neighboring continuum.



EX Hydrae : Spin phase modulation

The Kα line exhibits a larger fractional variation than do any of the triplet lines at the lower ionization energies (e.g., Ne, O) than at the high ionization energies (e.g., Fe, S).

A comparison of the Fe and O lines shows:

- Fe XXVI Kα line essentially tracks the Fe XXV r line in amplitude and phase.
- In contrast, the O VIII Kα line varies by ~75% while the O VII triplet r line is relatively constant within the errors, varying by perhaps ~20%.
- Work in progress

Conclusions

- Collisionally ionized plasmas appear to dominate the X-ray spectra of several CVs (magnetic as well as non-magnetic)
- High densities are required in most CVs
- Significant broadening of Fe XXV is seen U Gem in outburst indicating high velocity gas.
- Broadening is also seen in Fluorescent Fe in U Gem but during the quiescence state
- Broad Fe XXV line with a flat-top profile is seen in SS Cyg in outbursts: high velocity winds or outflows are indicated
- Fluorescent Fe line is red-shifted by ~2300+-500 km/s in SS Cyg

Conclusions

- Ne/O Abundance: ONe models of WDs preferred over CO models
- AM Her: Phase resolved spectroscopy shows that the line centers of Mg XII, SI XVI, resonance line of Fe XXV, and Fe XXVI emission modulated by 1000 km/s indicating bulk motion of ionised material in the accretion column
- EX Hya: phase resolved spectroscopy shows modulation of line intensities from O to Fe with varying degrees for different ionization stages
- Need large areas with very high resolution

Collaborators

- V. R. Rana (former TIFR student, now at Caltech, NuStar Group)
- V. Girish (TIFR Post-doc, now at ISAC, Bangalore)
- E. M. Schlegel and H. V. Shipley (U of Texas-San Antonio)
- P. E. Barrett (US Naval Observatory)

Thanks

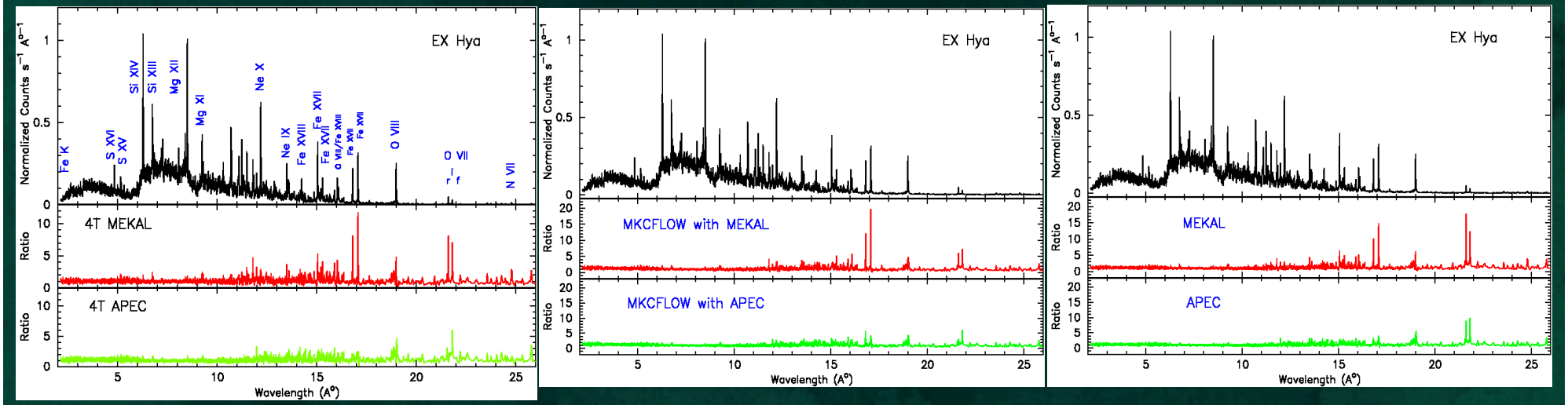
Global Fit Approach

EX Hya: Brightest IP observed with Chandra HETG
APEC & MEKAL: Two competing plasma codes

Discrete temperature (4T)

Cooling flow model

Stratified accretion column multi-temp



- APEC model provides better fit to emission lines in overall MEG wave band. In particular 5-15 Å wave length range and Fe XVII lines around 17 Å.
- Improvement in the fit is independent of the spectral models used.
- This is most likely due to deficiencies in the MEKAL with respect to APEC plasma code.