Hydrodynamic and Spectral Simulations of HMXB Winds

Christopher W. Mauche

Duane A. Liedahl

Shizuka Akiyama

Lawrence Livermore National Laboratory

Tomasz Plewa

University of Chicago

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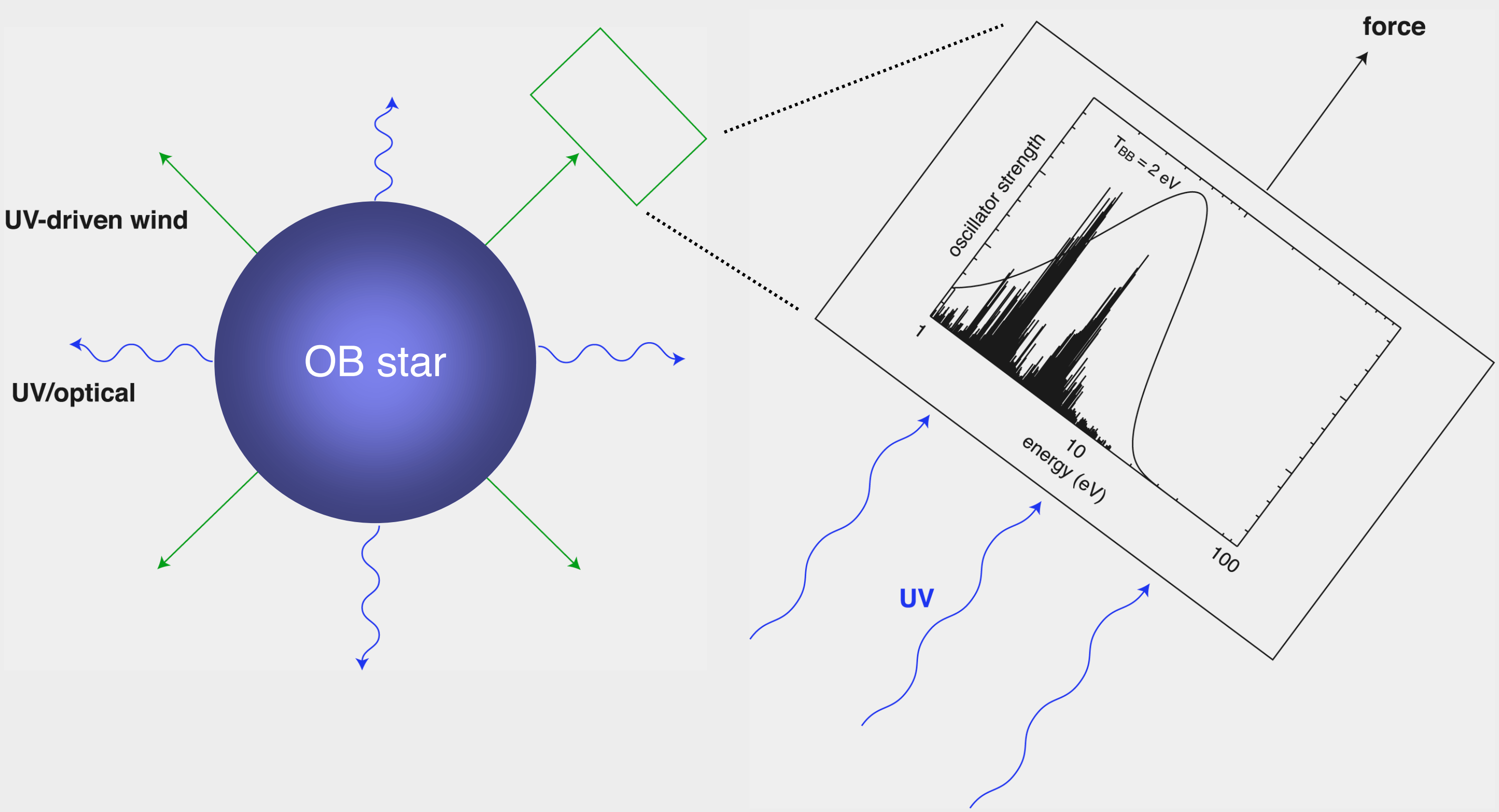
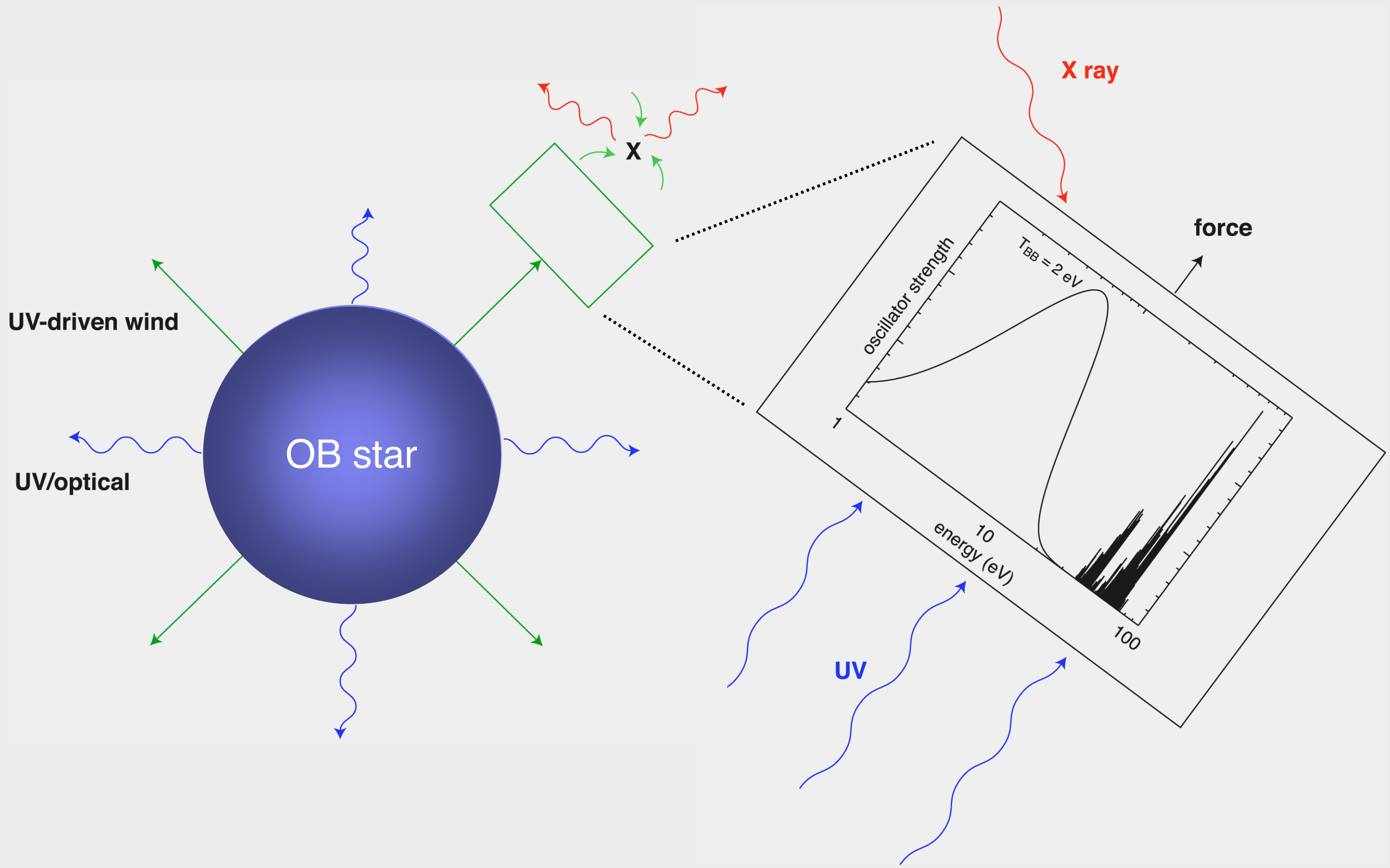
The wind of an isolated OB star is driven by radiation pressure on line opacity that overlaps with the stellar spectrum

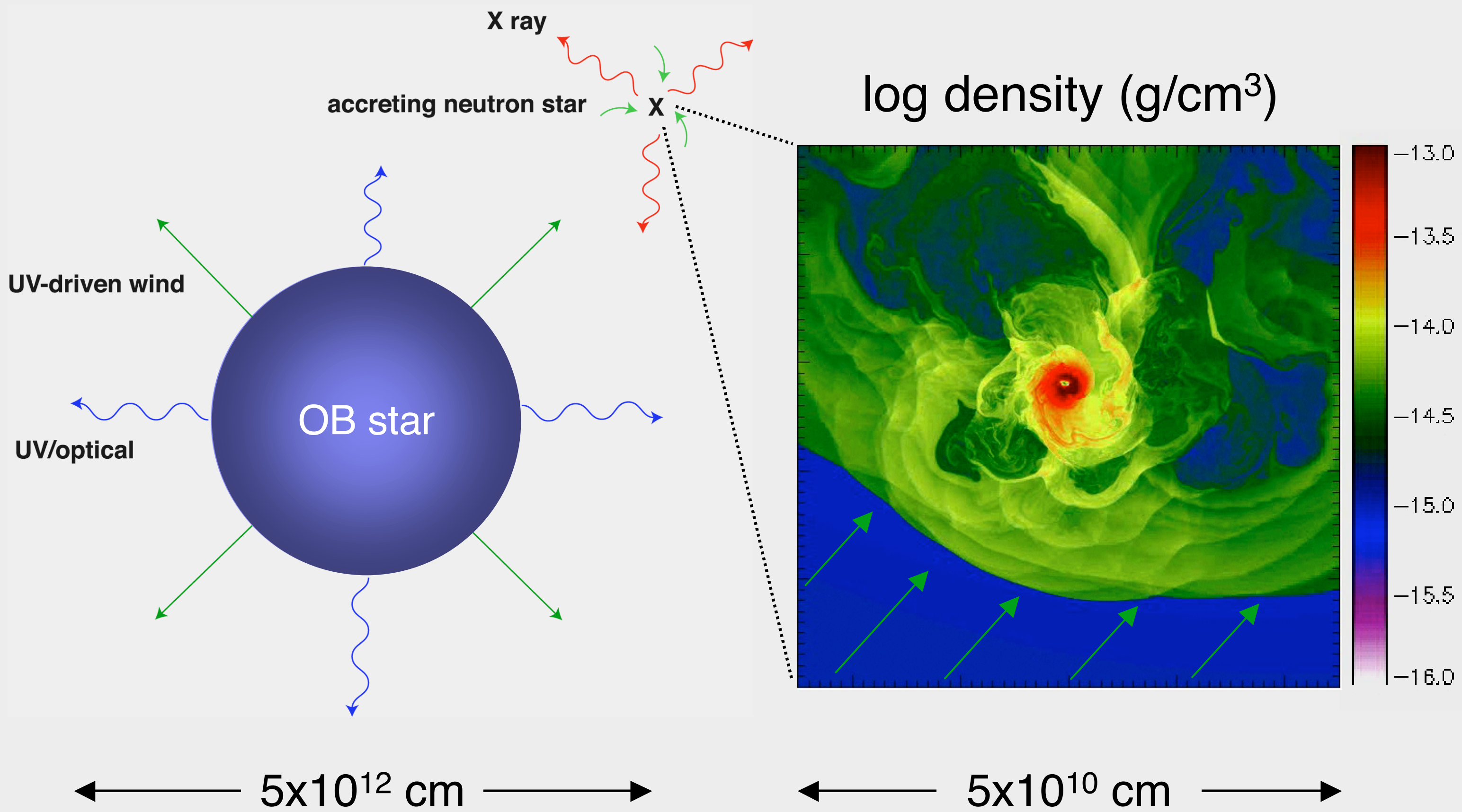
Castor, Abbot, & Klein (1975): “CAK”



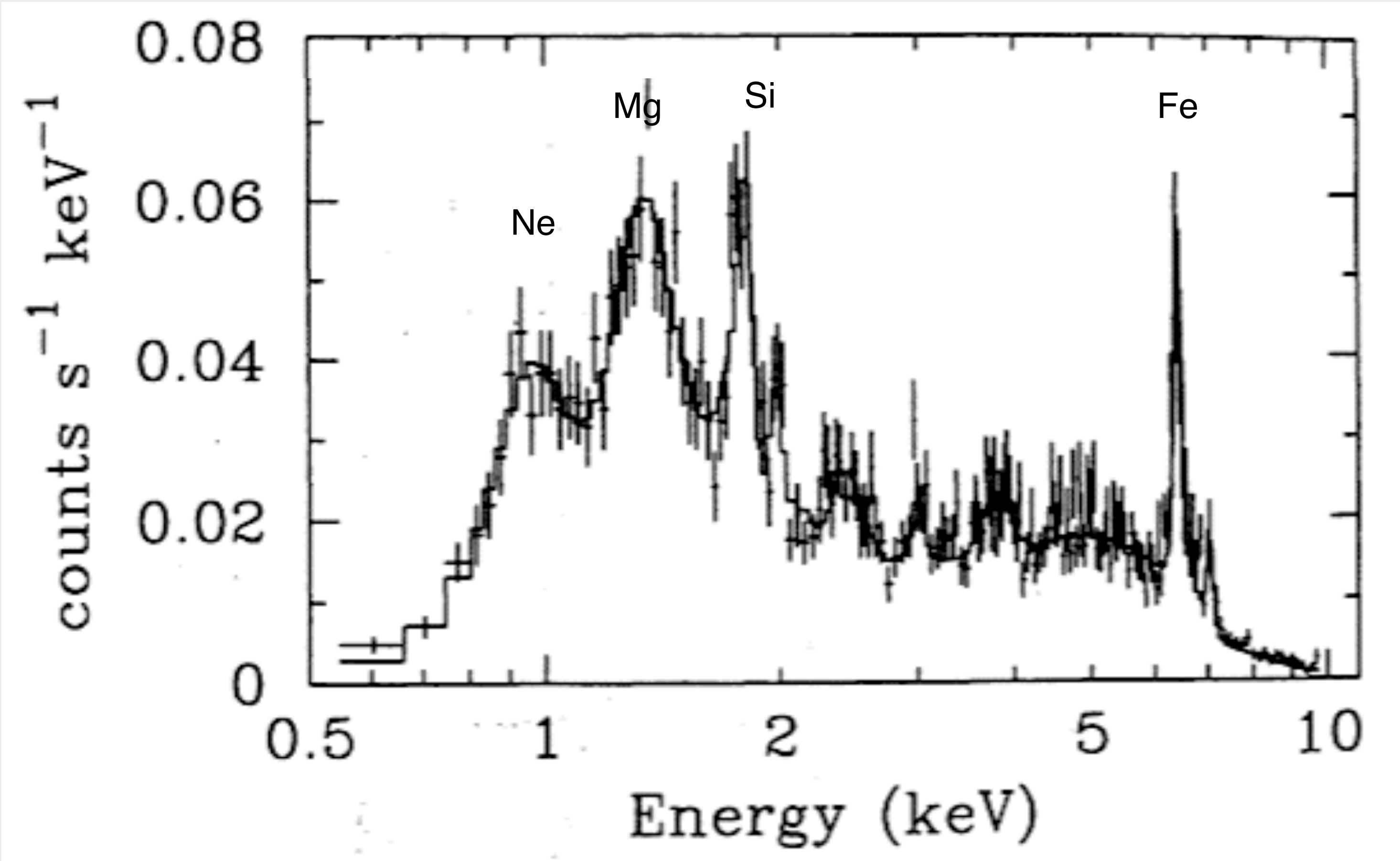
In an HMXB, X-ray photoionization destroys the important sources of UV line opacity, significantly reducing the radiative driving of the wind



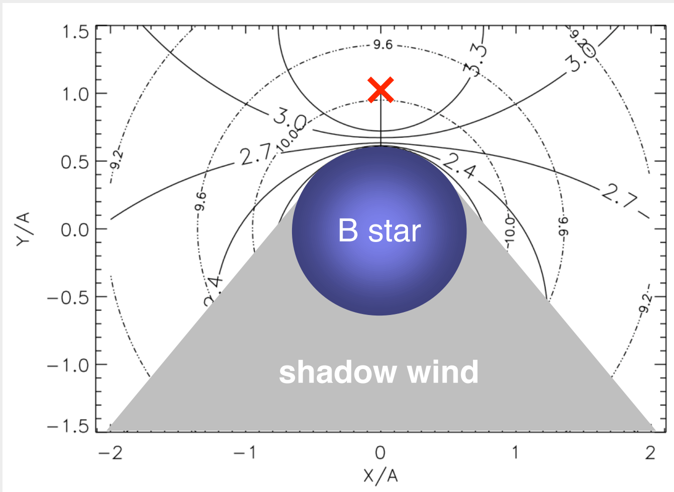
Despite these complications, in Vela X-1, the L_X~$4x10^{36}$ erg s^{-1} is consistent with accretion onto the neutron star from the wind of the B0.5 Ib supergiant



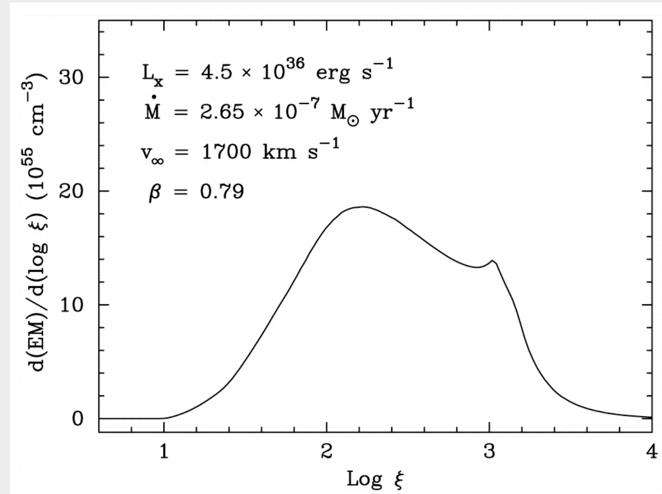
Using *ASCA* data, Nagase et al. (1994) demonstrated that the eclipse spectrum of Vela X-1 is dominated by emission lines of He-like Ne, Mg, Si, … Fe



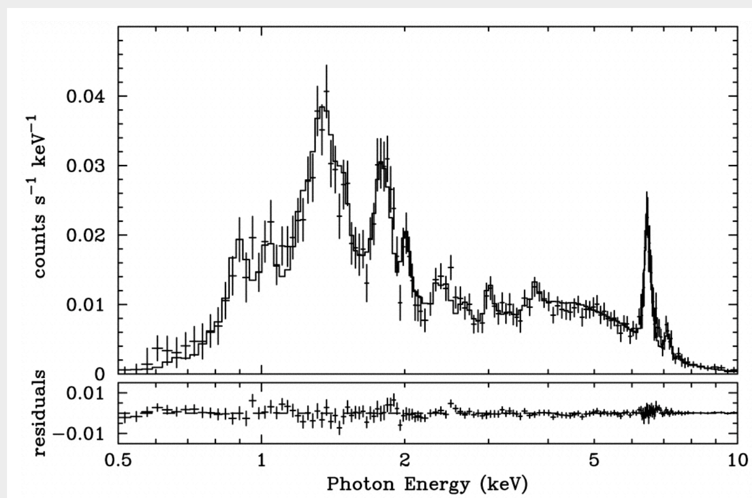
Sako et al. (1999) analyzed of the *ASCA* spectrum of Vela X-1 in eclipse using the DEM distribution of a generalized (but otherwise unperturbed) CAK wind



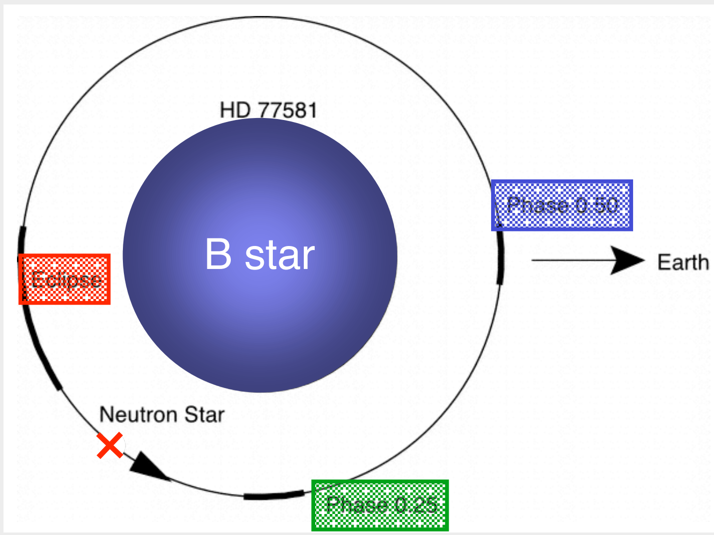
L_x
$\dot{M}$
V_∞
β

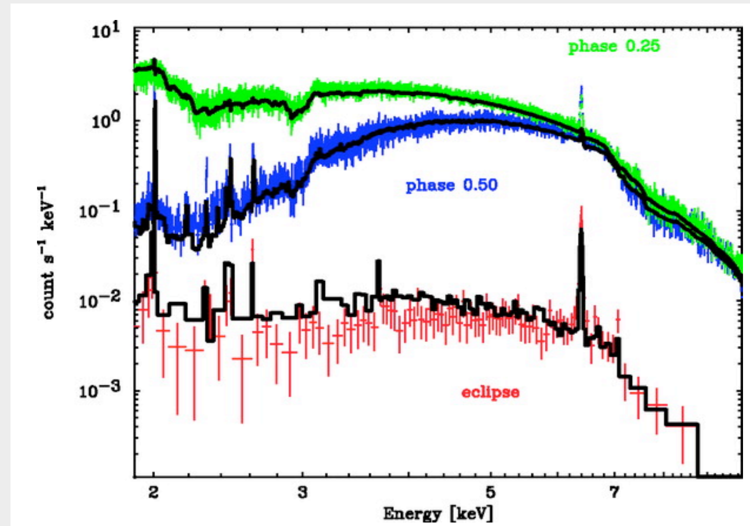


$$\xi = L_x/nR^2$$
$$n = \dot{M}/4\pi\mu V r^2$$
$$V = V_\infty(1-R_*/r)^\beta$$



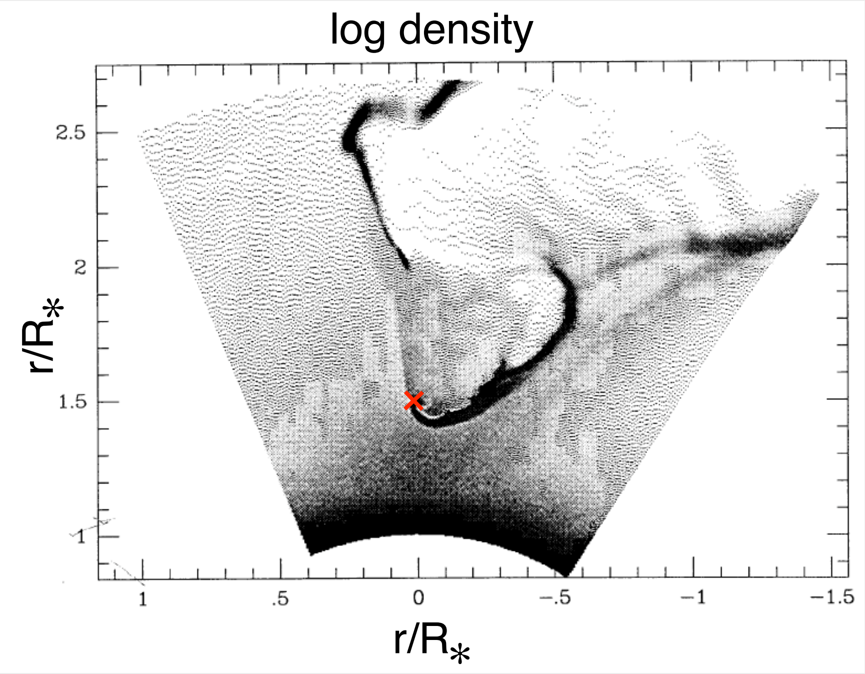
Using similar assumptions and a MC simulator, Watanabe et al. (2006) modeled of the *Chandra* HETG spectra of Vela X-1 at 3 orbital phases





Assuming canonical values for L_x, V_∞, and β, Watanabe et al. derived $\dot{M} = 1.5$–$2\mathrm{x}10^{-6}$ $M_\odot$/yr (~ 6 times that of Sako et al. 1999 [?]).

Blondin et al. (1990–1995), using 2- and 3-D hydrodynamic calculations, showed that wind accretion in HMXBs is far more complex …



Models were used primarily to model/interpret the binary phase-dependent photoelectric absorption.

To account for this complexity, we are developing a 3-D radiation hydro-dynamic model of the winds of HMXBs

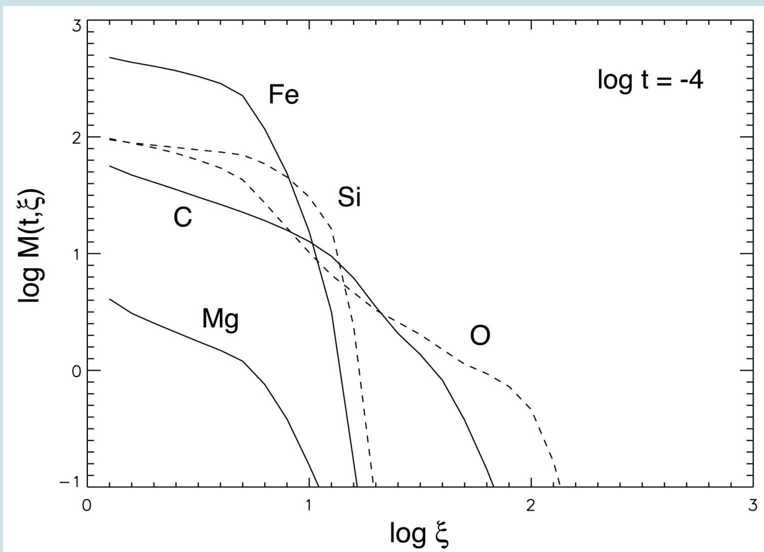
The model includes:

- **XSTAR** photoionization calculations: $f_{ij}(\xi, T)$, Γ, Λ
- **HULLAC** atomic models:
  - Improved calculations of the radiative force multiplier M
  - X-ray emission models for X-ray photoionized plasmas
- **FLASH** AMR hydrodynamic calculations including:
  - gravity
  - rotation
  - Compton and photoionization heating Γ,
  - Compton and radiative cooling Λ, and
  - radiative acceleration for X-ray photoionized plasmas
- **Monte Carlo** radiation transport

Radiative driving of the wind is accounted for via the force multiplier formalism (Castor, Abbott, & Klein 1975)

Force multiplier M is determined on a 3-D lattice (T, ξ, t – 21x51x41)

Force multiplier for selected ions



$$F_{rad} = F_{elec}\,(1+M)$$

$$M = \Sigma\, \Delta\nu\, (F_\nu/F)\,(1-e^{-\eta t}) \,/\, t$$

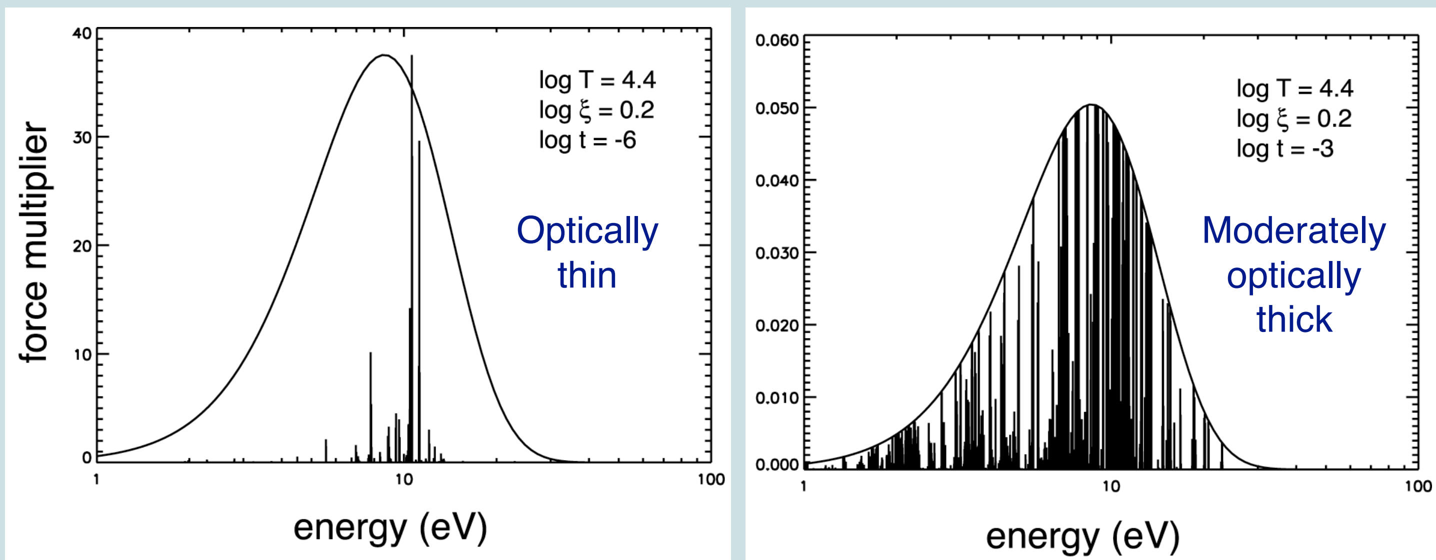
$$t = \rho\kappa_e v_{th} (dv/dr)^{-1}$$

η: atomic physics:

HULLAC models:
- 166 ions of 13 elements
- 35,000 energy levels
- 2,000,000 atomic lines (visible – X-ray)
- explicit level populations

FLASH models will (do not yet) account for the reduction in the radiative driving due to finite wind optical depth

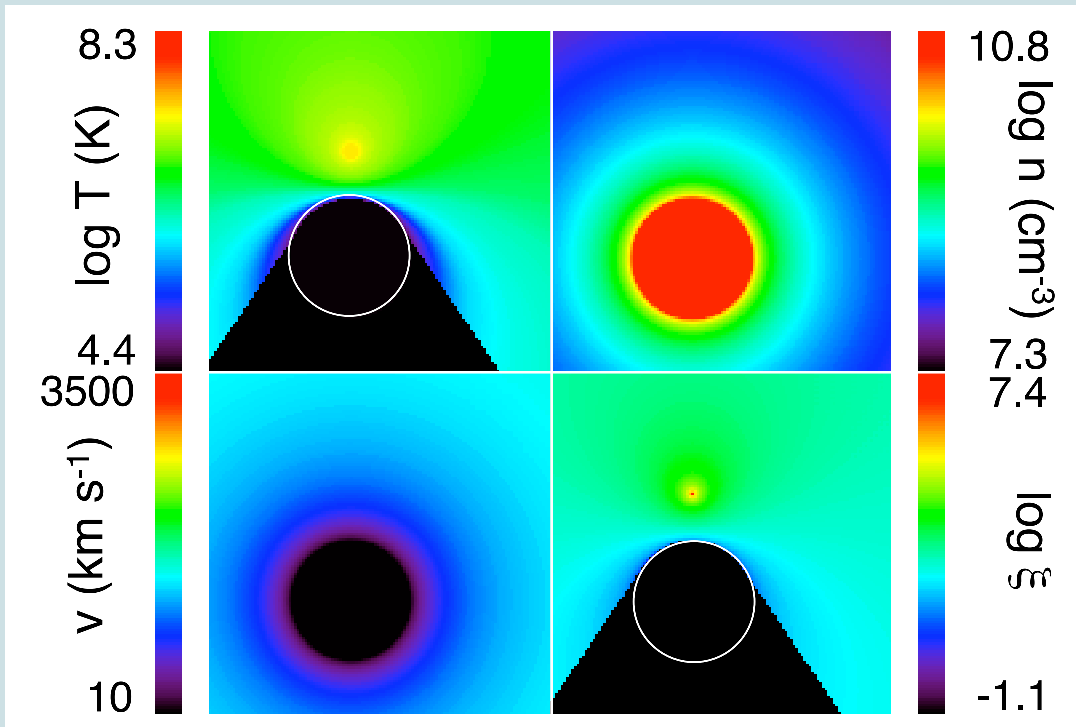
Spectral breakdown of Si II force multiplier for different *t*



Line saturation reduces the radiative driving, dramatically affecting the wind dynamics.

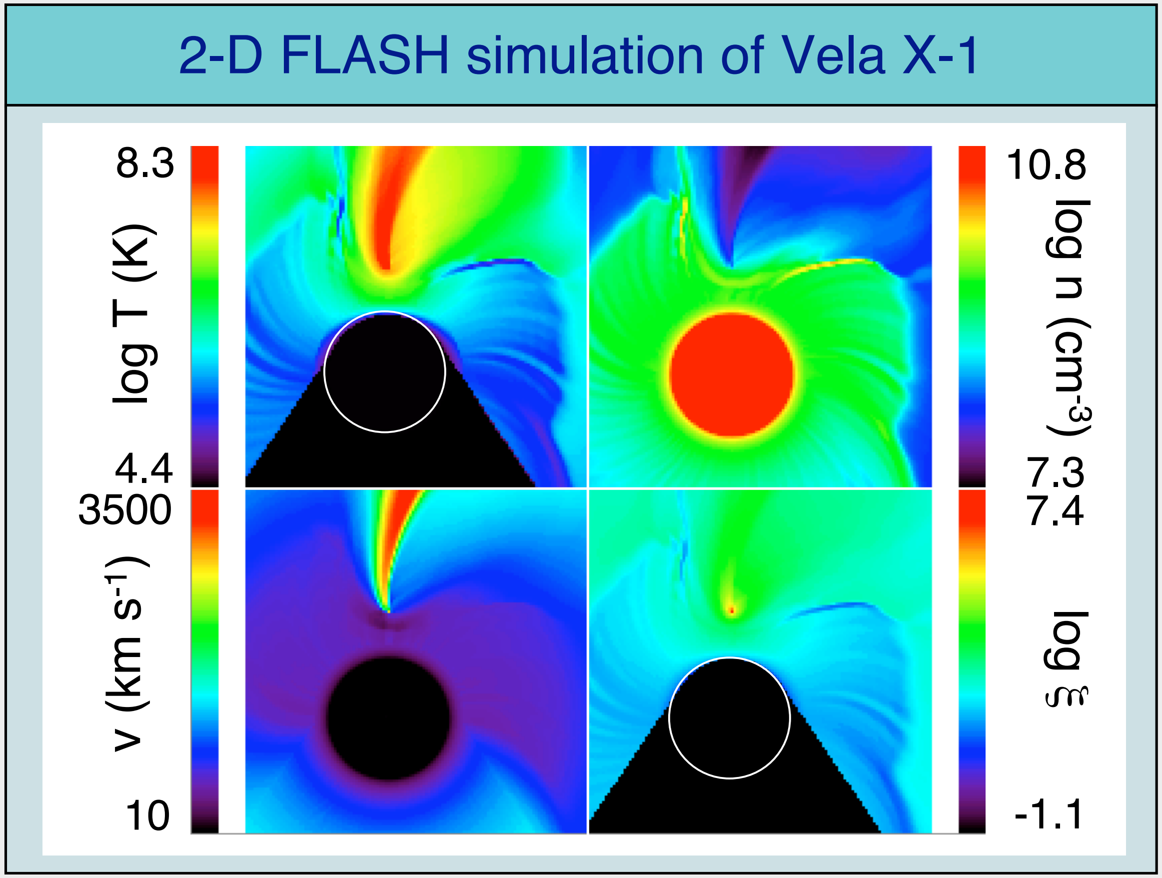
FLASH simulations result in time-varying spatial maps of temperature *T*, density *n*, velocity *v*, and ionization parameter ξ

2-D FLASH simulation of Vela X-1



Asymmetries affect the predicted X-ray spectrum in ways that cannot be captured by simple models.

FLASH simulations result in time-varying spatial maps of temperature *T*, density *n*, velocity *v*, and ionization parameter ξ



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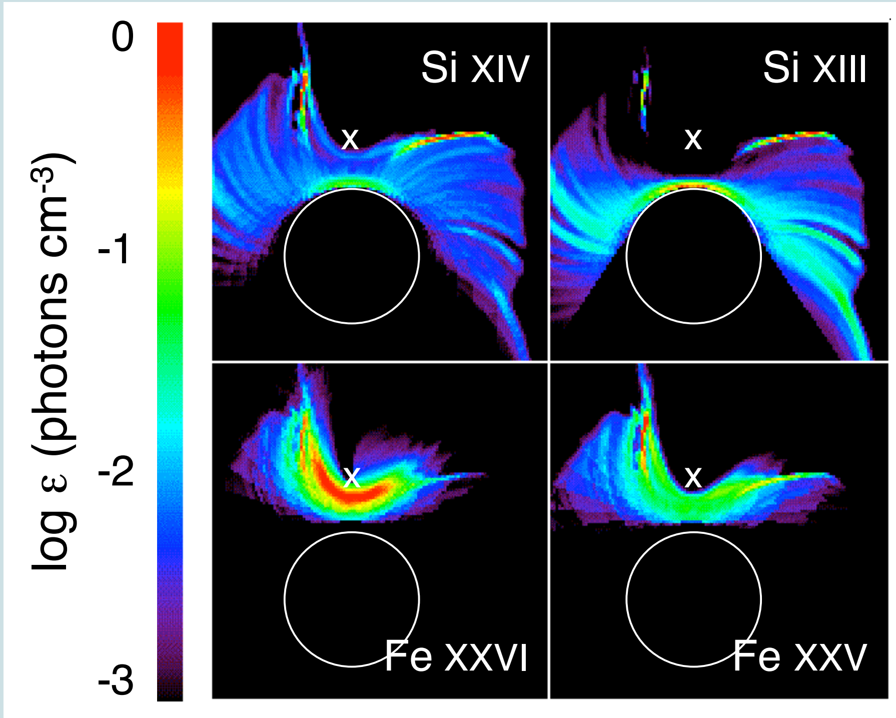
Physical quantities can be used to produce maps of the emissivity distributions in various emission lines

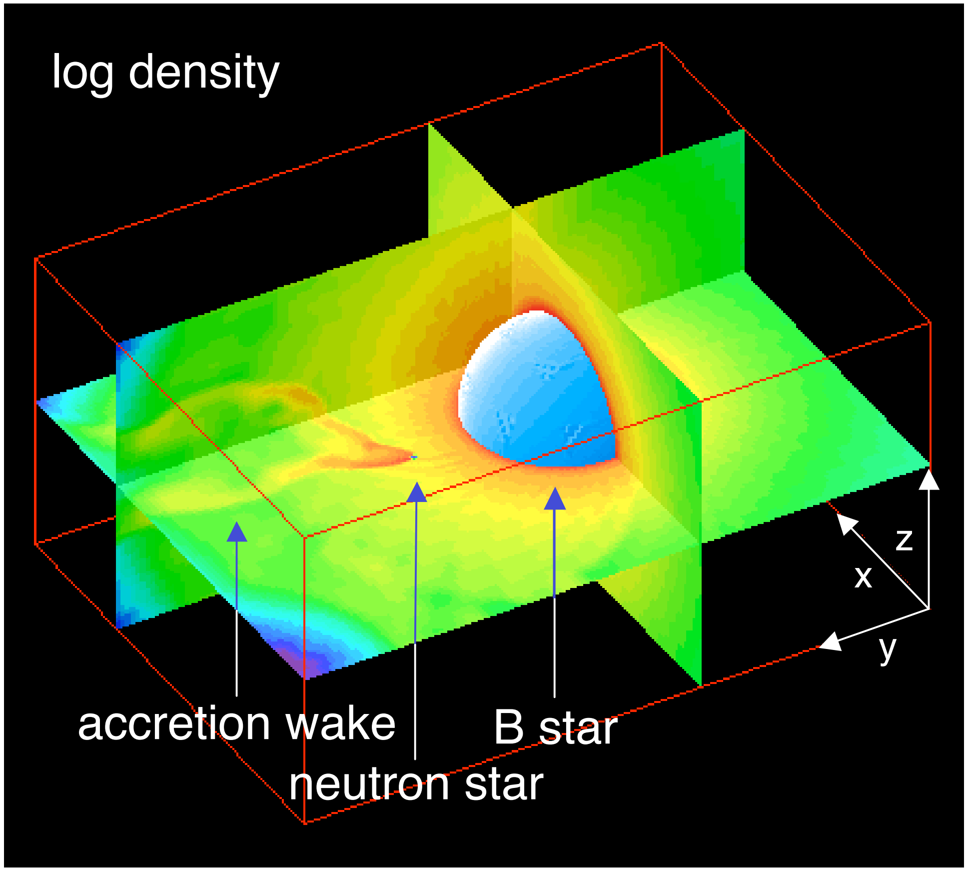
Emissivity maps of H- & He-like Si & Fe



Emissivity maps constrain the location of the emission regions via the binary-phase dependence of the X-ray spectra.

FLASH 3-D simulations are being run to produce the required 3-D grids of temperature *T*, density *n*, velocity *v*, and ionization parameter ξ

3-D FLASH simulation of Vela X-1



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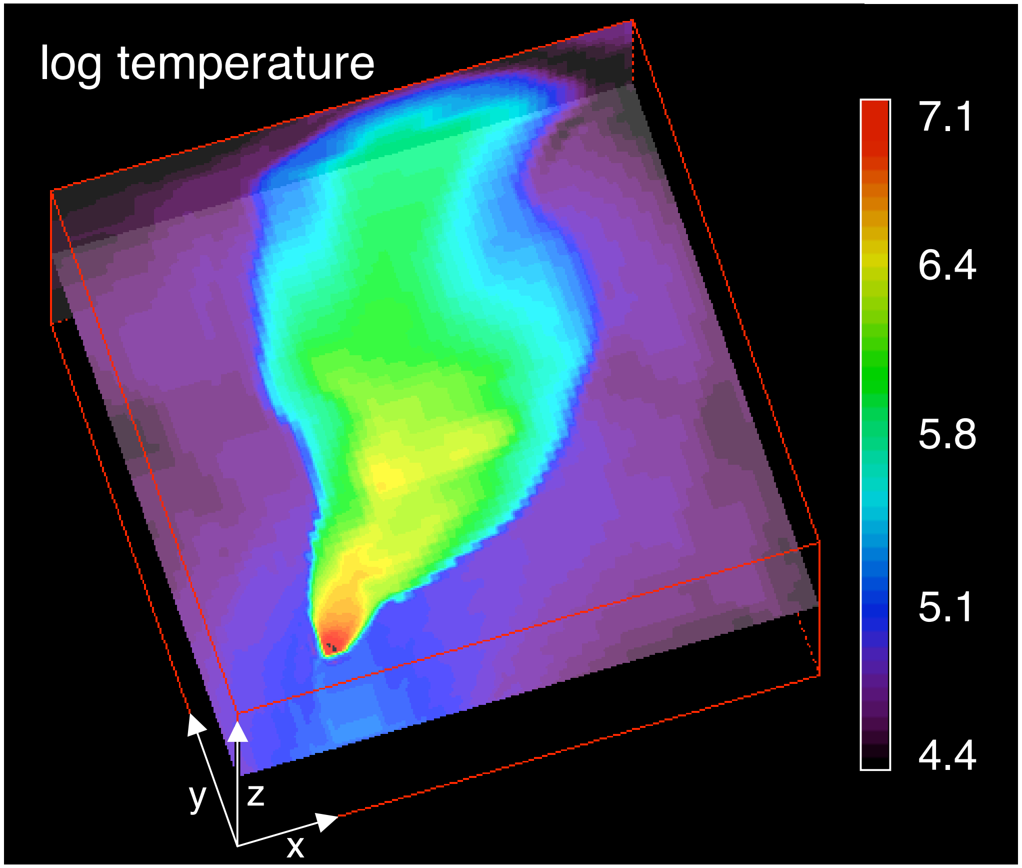


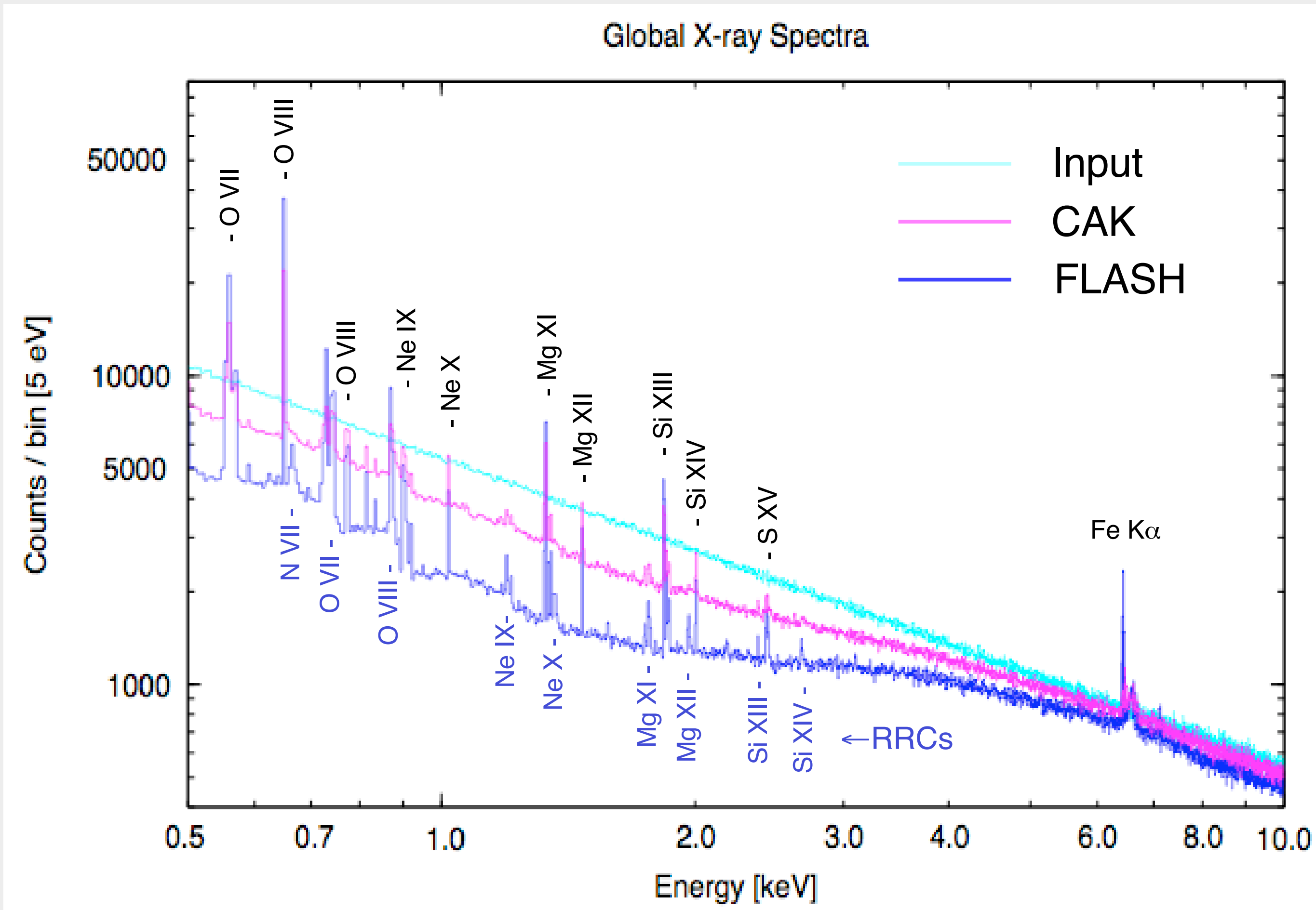
The FLASH 3-D grids of T, n, v, and ξ are fed into our* Monte Carlo radiation transfer code to produce synthetic X-ray spectral models

The Monte Carlo code accounts for:

- Continuum opacity for 446 subshells of 140 ions of the 12 most abundant elements
- RRC and recombination line cascades following photo-absorption by K-shell ions
- Fluorescent line emission following inner-shell photo-absorption by M-shell ions
- Compton scattering
- Line scattering with partial redistribution
- Doppler shifts due to the velocity field

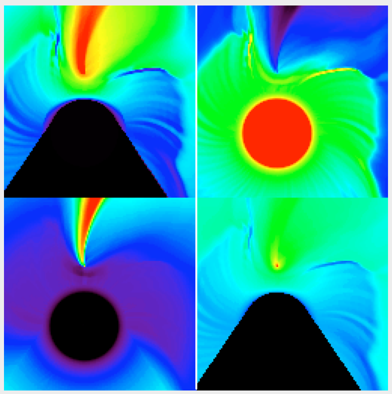
*Mauche, Liedahl, Mathiesen, Jimenez-Garate, & Raymond (2004, ApJ)

Preliminary results of the Monte Carlo code show dramatic differences between an unmodified CAK wind model and a full-up 3D FLASH model

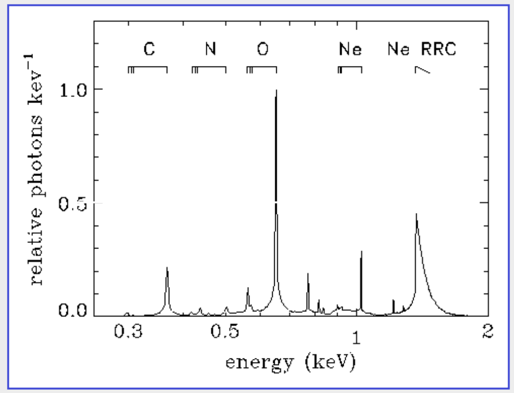


Long exposures are required to 1) cover a large fraction of a binary orbit (8 d) and 2) produce the required *phase-resolved* high SNR X-ray spectra

FLASH
Hydrodynamic
Simulations



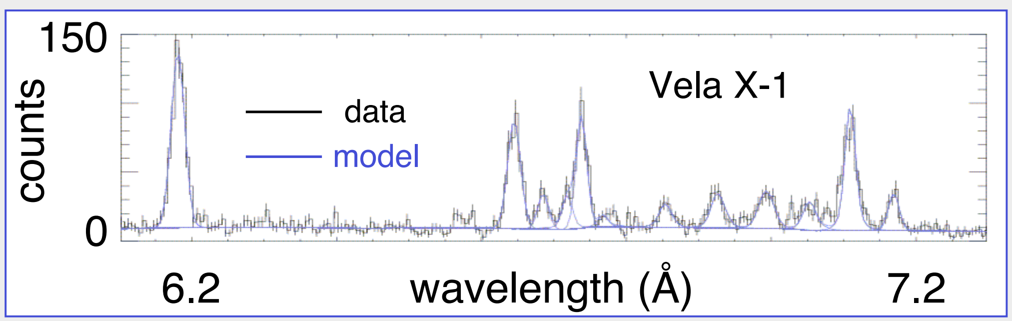
HULLAC Atomic Models
& Monte Carlo
Radiation Transfer



High-Resolution
X-ray Spectra
(*Chandra, XMM*)

Theoretical spectra

Observed spectra



Acknowledgements

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