Spreading and Mixing on Accreting White Dwarfs

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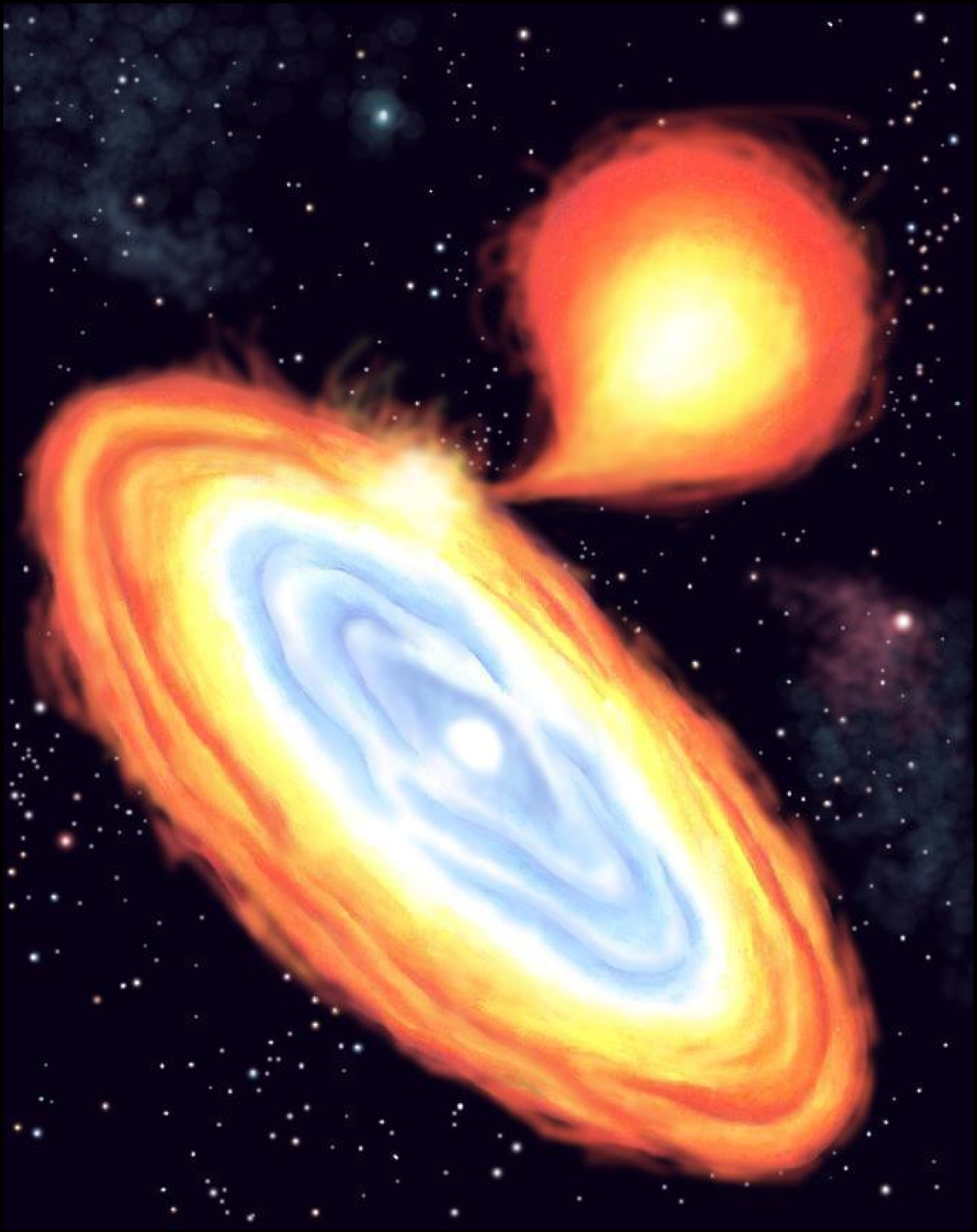


Outline of Talk

Overview of the issues of transitioning from an accretion disk to a WD surface

- General features expected for a boundary layer
- Previous studies of boundary layers
- Overview of the "spreading layer" approach
- Results of our spreading layer calculation

Applications and beyond

- Mixing between deeper layers of envelope
- Future studies

The Boundary Layer “Story”

Many WDs undergo dramatic (semi-periodic) accretion events called DWARF NOVAE. These last ~2-20 days with quiescent intervals of ~10 days to tens of years.

Optically thin BL during quiescence ($\dot{M} \sim 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$)

- Seen in X-rays at a temperature similar to the virial temperature

$$T = \frac{m_p}{k_\mathrm{B}} \frac{GM}{R} \approx 10^8\ \mathrm{K}$$

Optically thick BL during outburst ($\dot{M} \sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$)

- Very bright in outburst

$$\frac{1}{2}\dot{M}R^2\Omega^2 = \frac{GM\dot{M}}{2R} \approx 10^{34}\ \mathrm{ergs\ s}^{-1}$$

- Seen in the soft X-rays and EUV

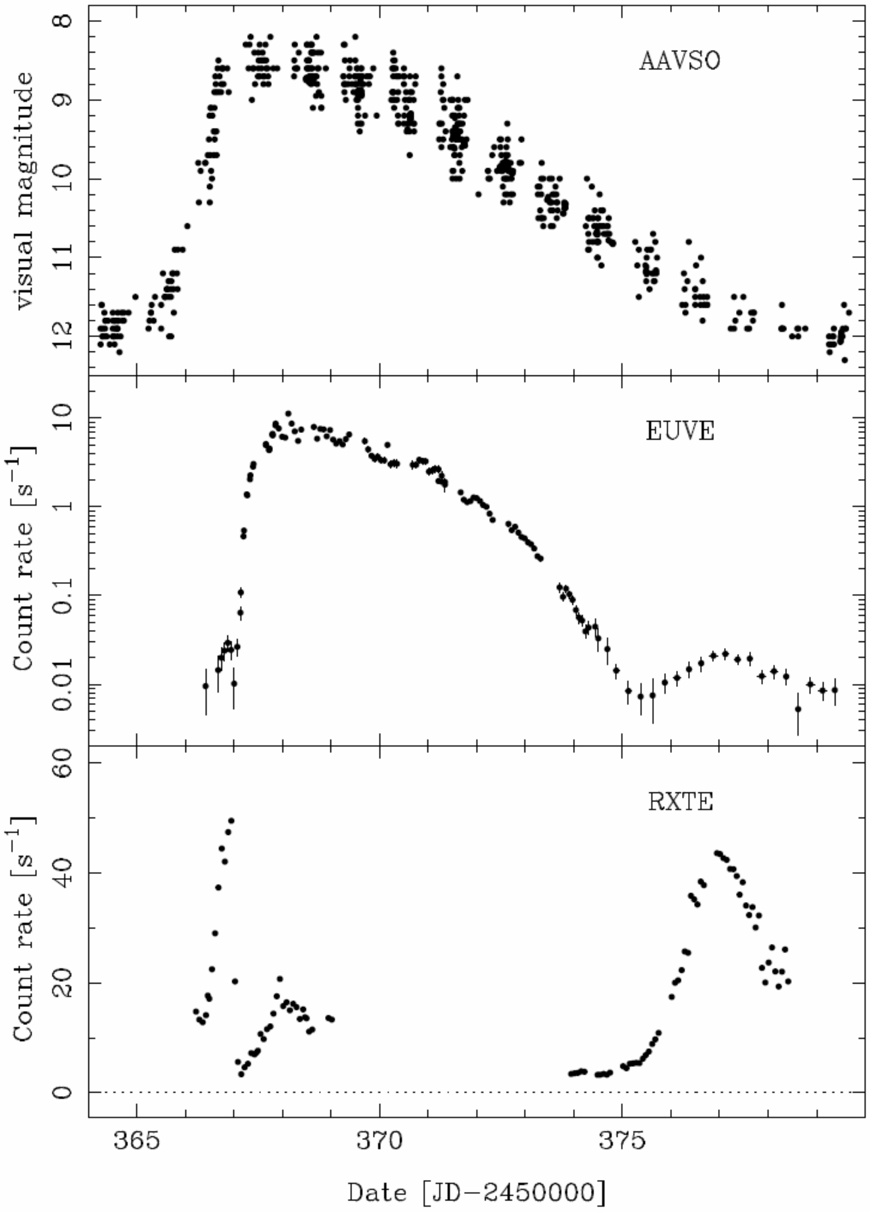
$$4\pi R H \sigma_\mathrm{SB} T_\mathrm{eff}^4 = \frac{GM\dot{M}}{2R} \qquad T_\mathrm{eff} \approx 10^5\ \mathrm{K}\ \dot{M}_8^{1/4}$$

$$\dot{M}_8 \equiv \dot{M}/10^{-8} M_\odot\ \mathrm{yr}^{-1}$$

Observations of BLs in DNe

SS Cyg; Wheatley, Mauche, & Mattei, 2003

By observing and comparing a range of photon energies we can learn a lot about DNe events.



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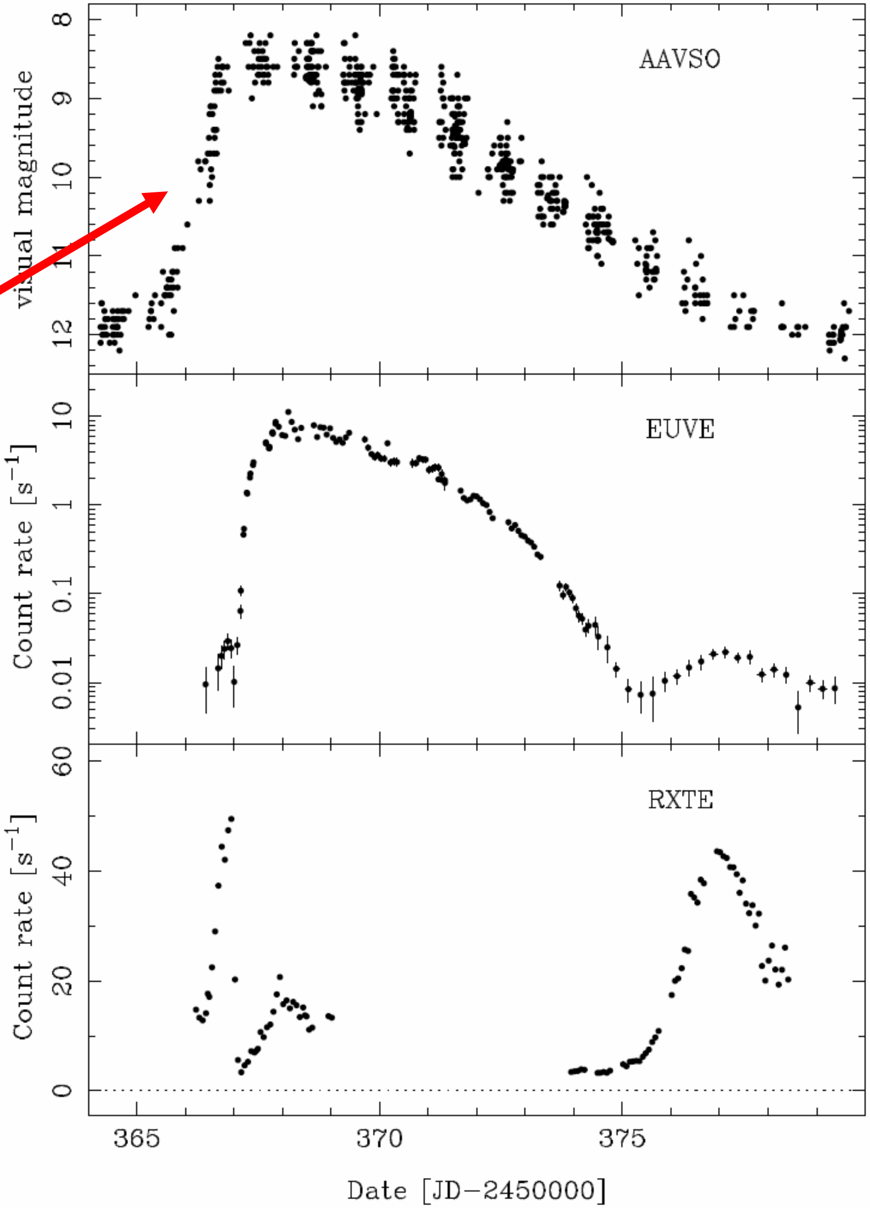

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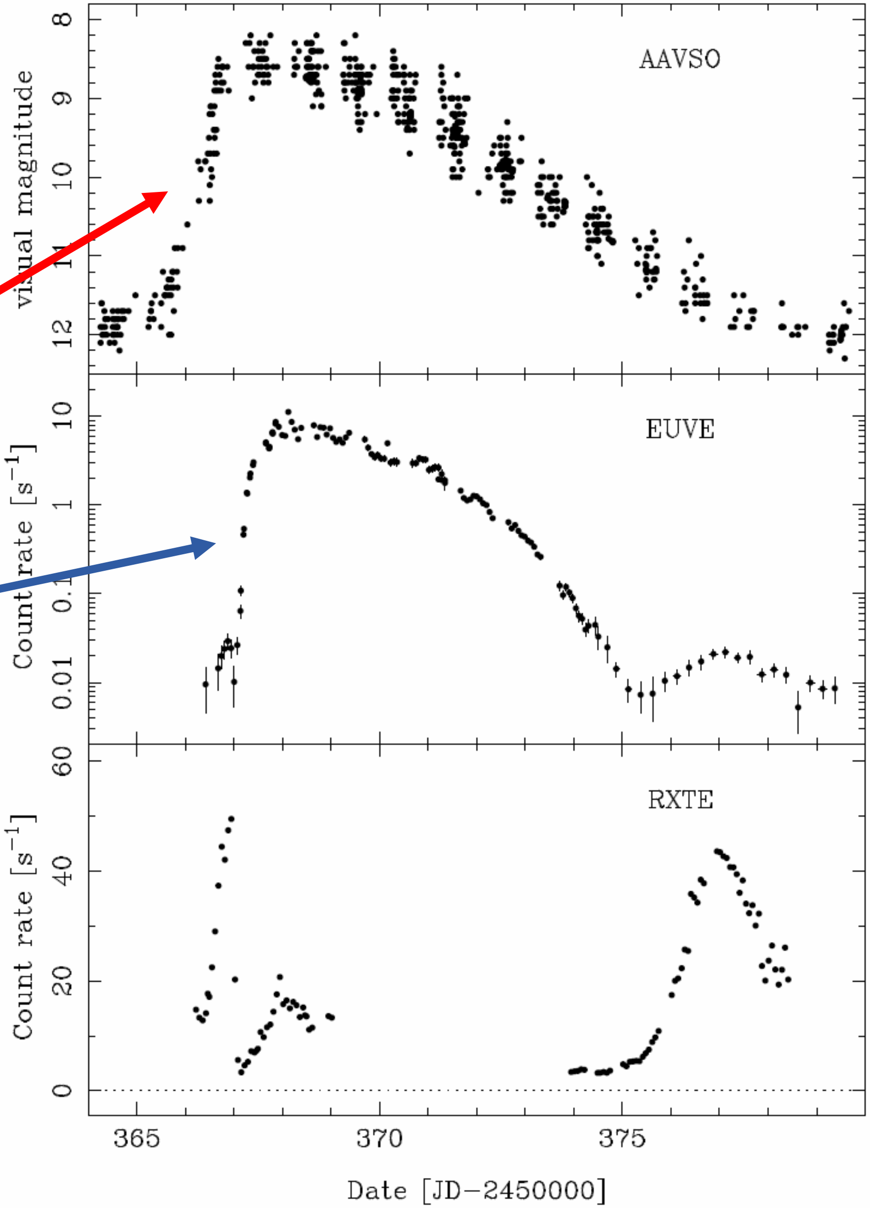

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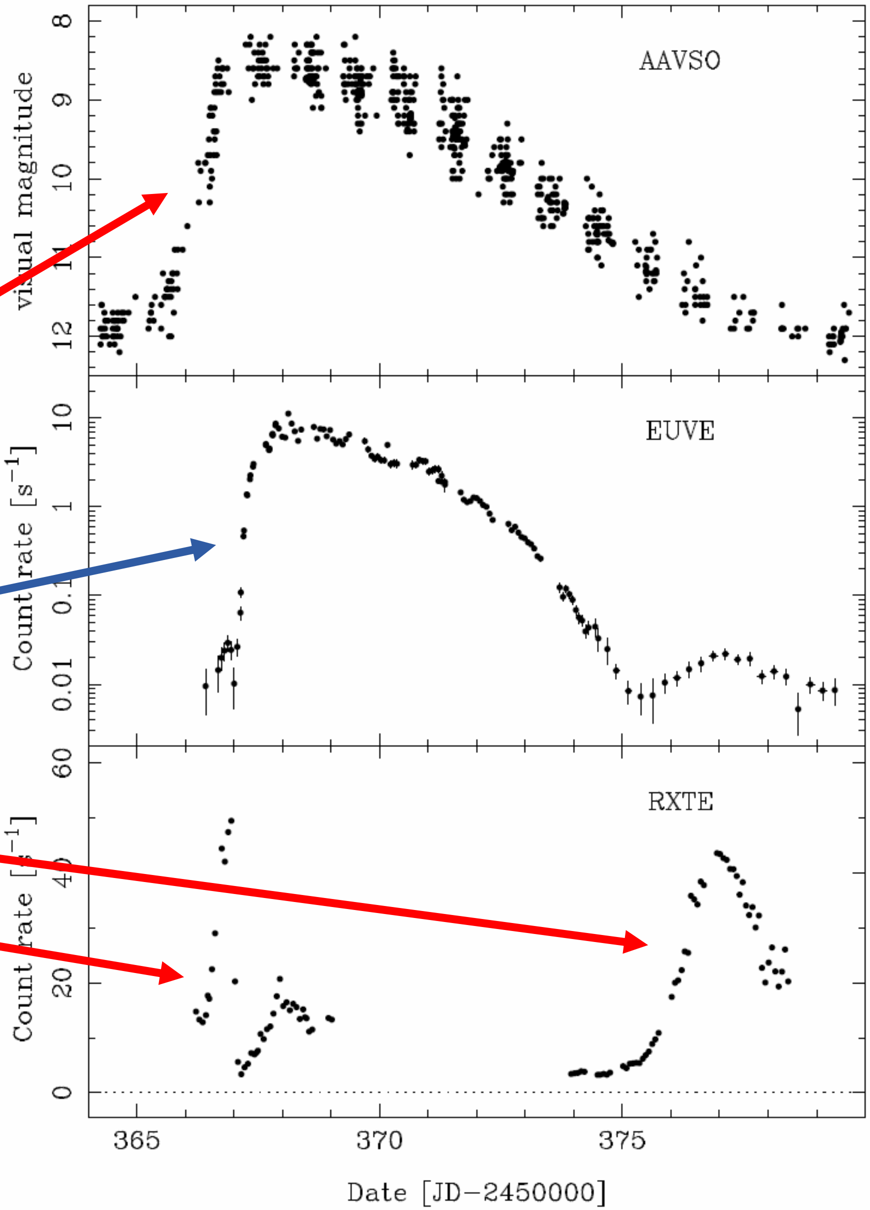

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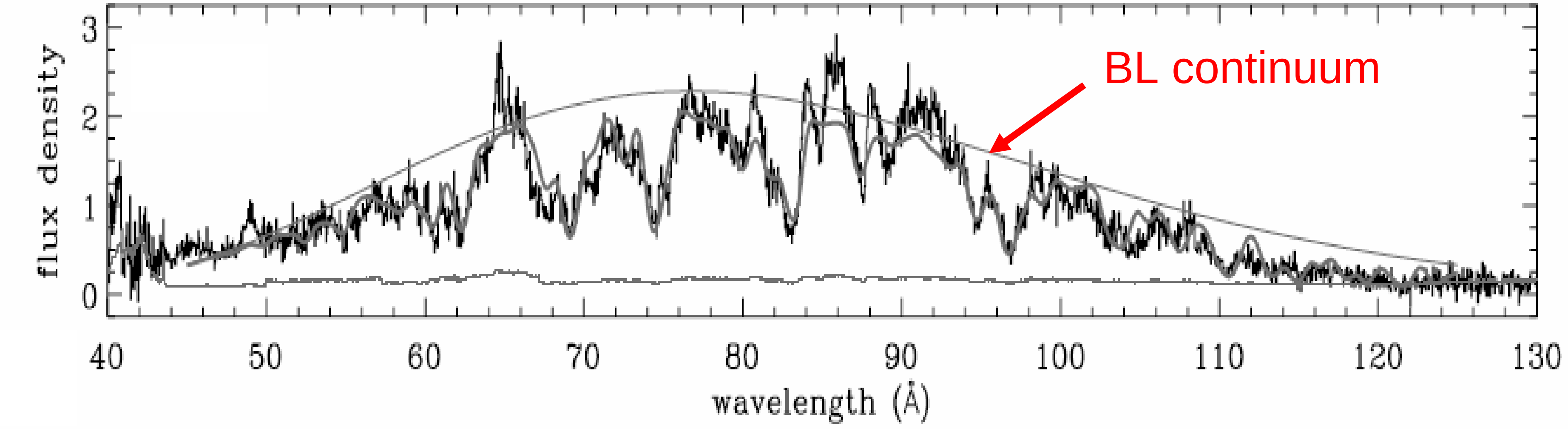
The EUV (72-130 Å) tracks the boundary layer emission.

The X-rays (2.3-15.2 keV) are brightest before and after the EUV, indicating an optically thin boundary layer.

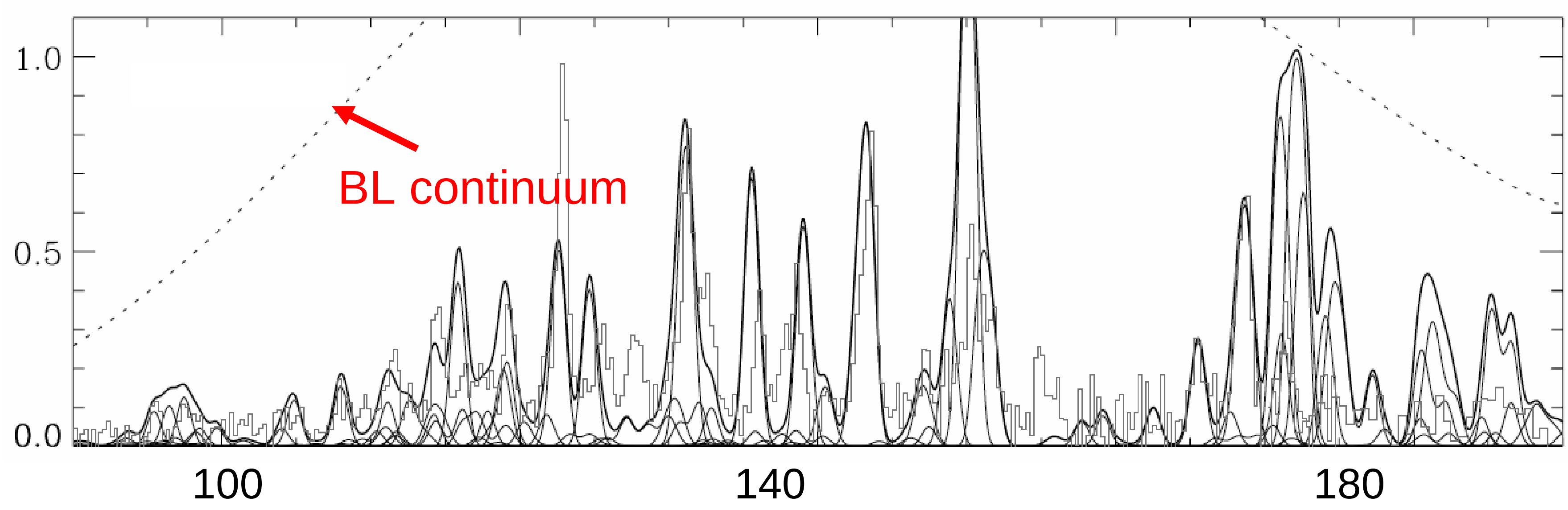
Progress in Modeling EUV as BL

SS Cyg; Mauche ‘04



BL continuum

OY Car; Mauche & Raymond ‘00



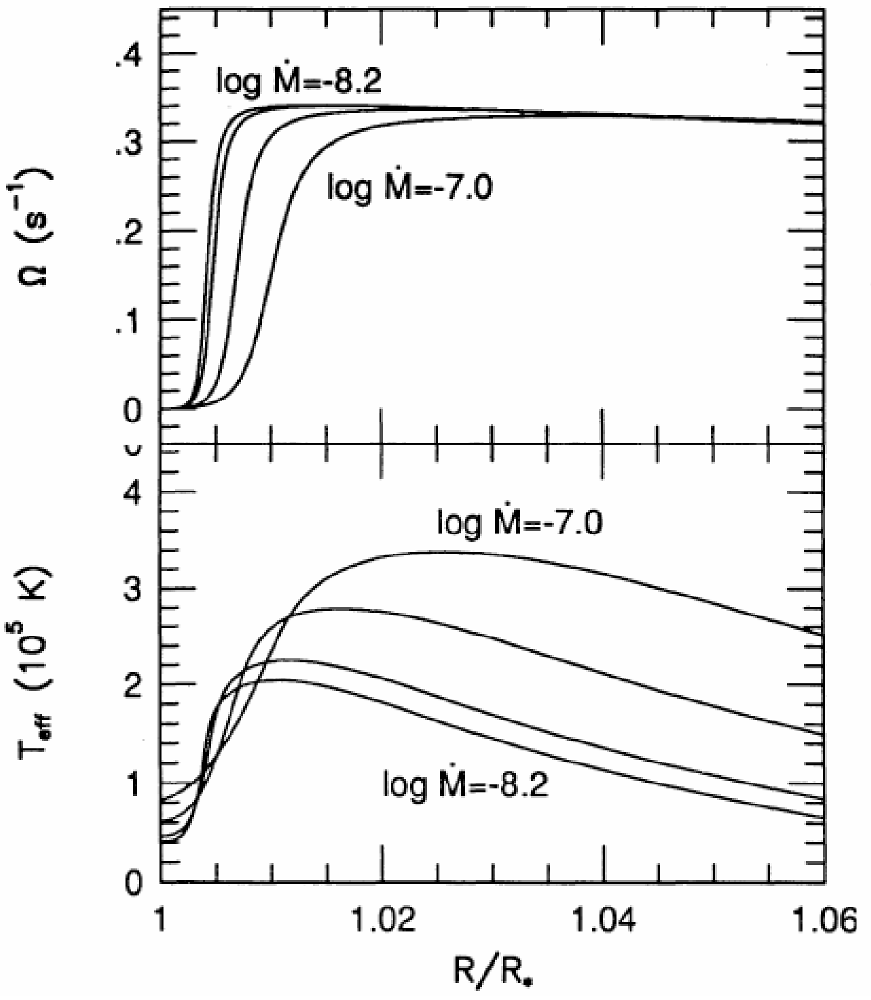
BL continuum

Previous Theoretical Work

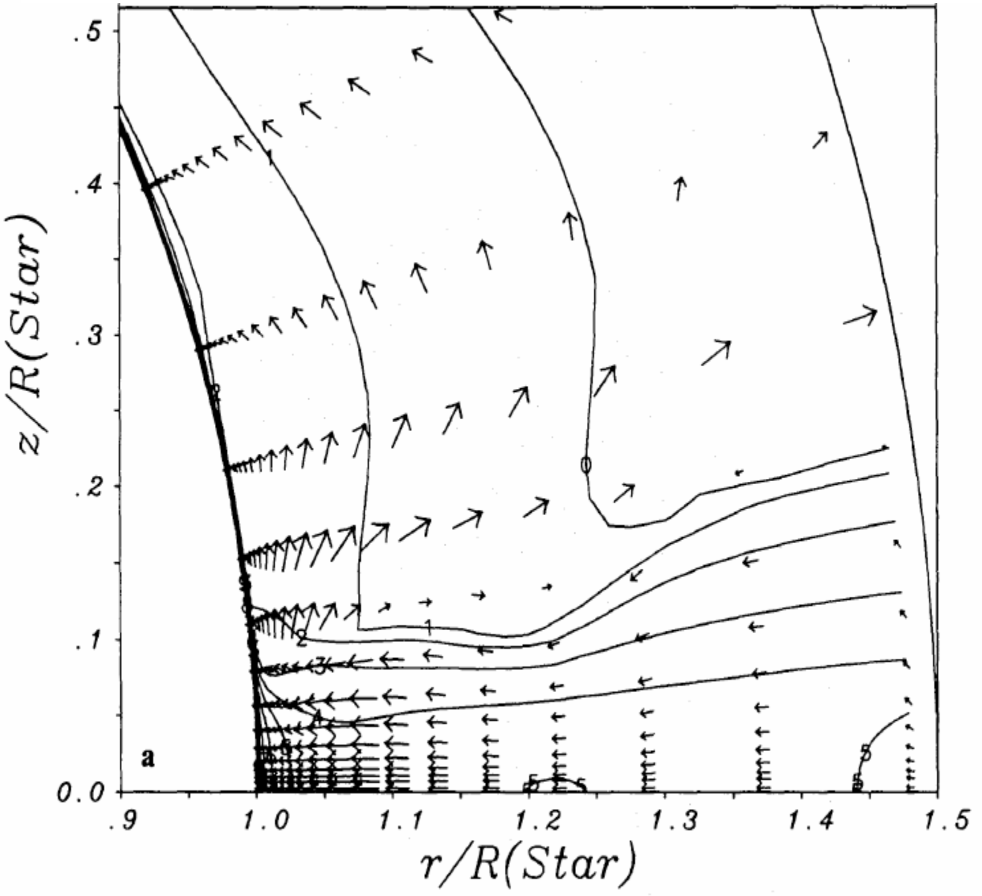
1. Assume a vertical scale height and solve for radial direction

2. Solve for the 2-D structure using simulations

Popham & Narayan ‘95

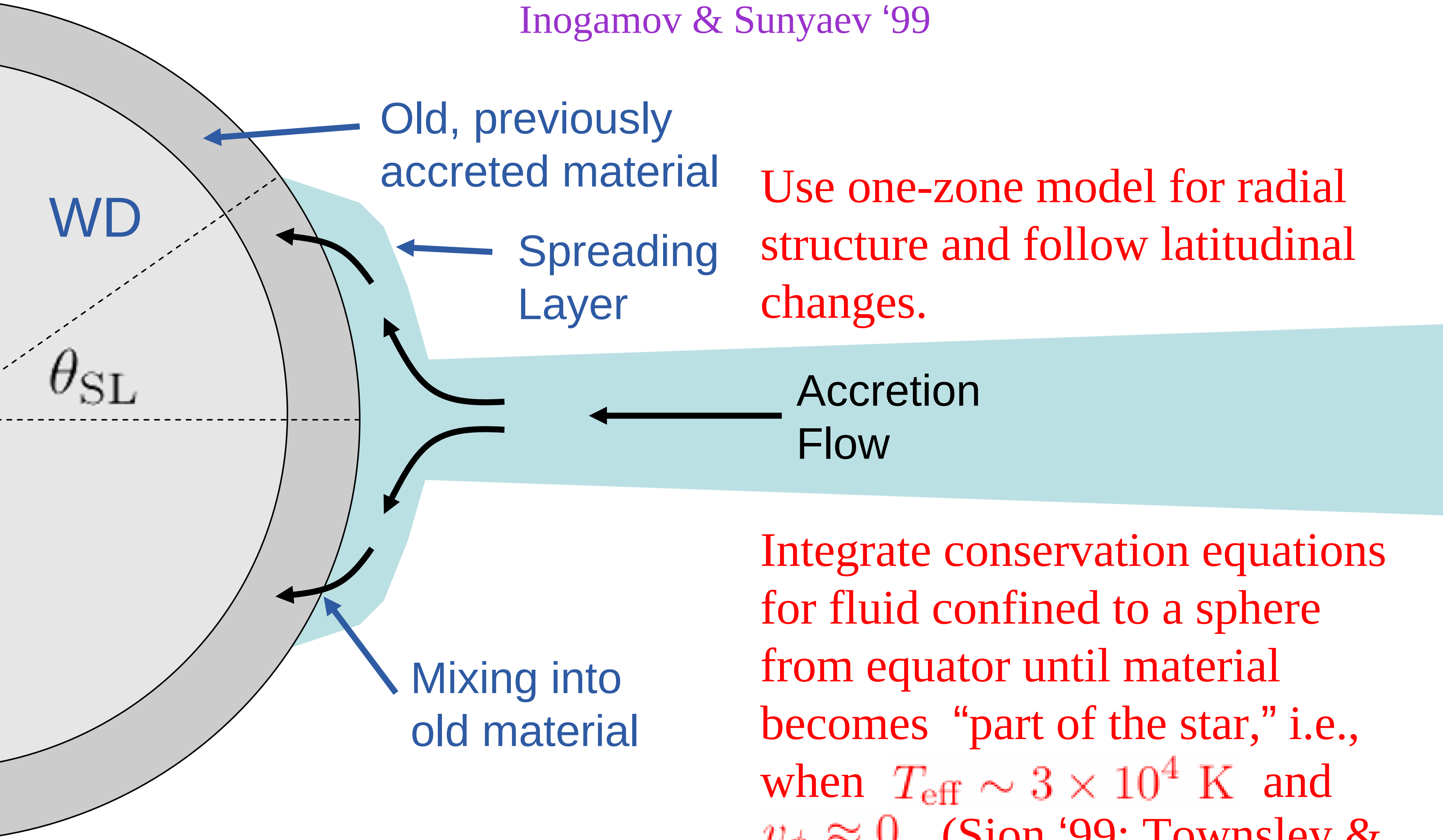


Kley ‘89



The "Spreading Layer" Approach

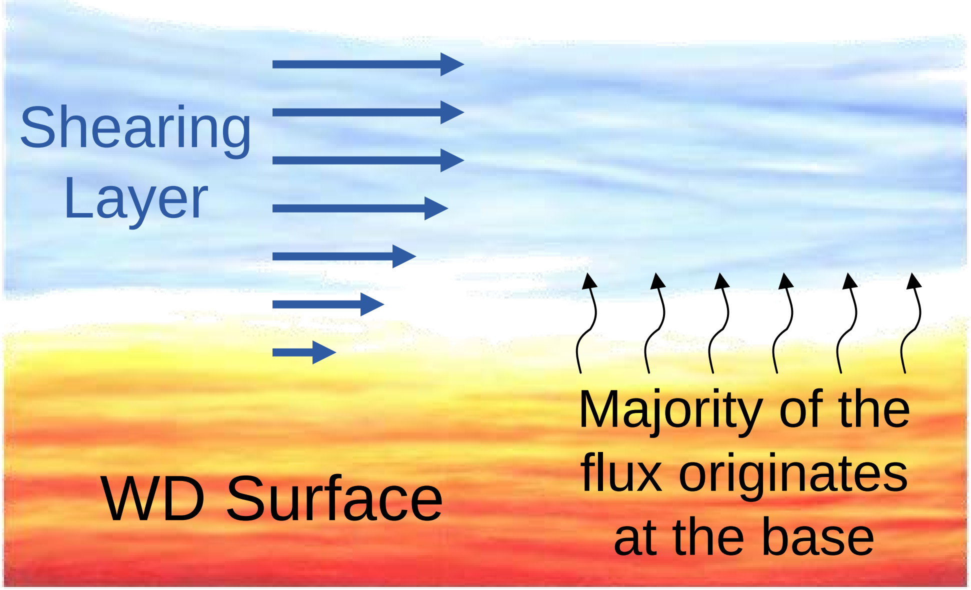
Inogamov & Sunyaev '99



Use one-zone model for radial structure and follow latitudinal changes.

Integrate conservation equations for fluid confined to a sphere from equator until material becomes "part of the star," i.e., when $T_{\rm eff} \sim 3 \times 10^4$ K and $v_\phi \approx 0$ (Sion '99; Townsley & Bildsten '03)

Radial Structure



Construct a one-zone model in plane parallel geometry (*h* << *R*)

$$g_{\rm eff} = \frac{GM}{R^2} - \frac{v_\phi^2}{R} - \frac{v_\theta^2}{R}$$

$$P = g_{\rm eff}\, y$$

Using the radiative flux equation and an equation of state…

$$F = \frac{4acT^3}{3\kappa}\frac{dT}{dy} \qquad P = \frac{\rho k_{\rm B} T}{\mu m_p} + \frac{aT^4}{3}$$

…we simply solve for the radial structure as a function of column

$$T = \left(\frac{3\kappa F}{ac}\right)^{1/4} y^{1/4} \qquad \rho = \frac{\mu m_p}{k_{\rm B}}\left(\frac{ac}{3\kappa F}\right)^{1/4} \left(g_{\rm eff} - g_{\rm rad}\right) y^{3/4}$$

Where $g_{\rm rad} = \kappa F/c$. Cool fact: using $g_{\rm eff} = g_{\rm rad}$ is a helpful trick for remembering the Eddington limit ($\dot{M}_{\rm Edd} = 4\pi R c/\kappa$)

Conservation Equations

Use equations of Inogamov & Sunyaev '99 for radial integrated conserved fluxes (fluxing in the θ-direction), in steady-state.

- Conservation of mass:

$$\frac{1}{R}\frac{d}{d\theta}\left(2\pi R\cos\theta y v_\theta\right) = 0 \quad \Rightarrow \quad \frac{1}{2}\dot{M} = 2\pi R\cos\theta y v_\theta$$

- Conservation of ϕ-momentum

$$\frac{1}{R}\frac{d}{d\theta}\left(2\pi R\cos\theta y v_\theta v_\pi\right) - 2\pi R\cos\theta y \frac{v_\theta v_\phi}{R}\tan\theta = -2\pi R\cos\theta \tau_\phi$$

Plus equations for θ-momentum and energy. Use the viscous stress for a turbulent boundary layer.

$$\tau = \rho v_*^2 = \alpha\rho v^2$$

Analytic Estimates

Friction in the azimuthal direction dominates the fluid motion

Balancing the ϕ-momentum with loses to the viscous stress

$$\frac{1}{R}\frac{d}{d\theta}\left(y v_\phi v_\theta\right) = -\tau_\phi = -\alpha\rho v_\phi^2$$

$$\Rightarrow \quad \frac{1}{R\theta_{\rm SL}} y v_\phi v_\theta \approx \alpha\rho v_\phi^2$$

$$\Rightarrow \boxed{\theta_{\rm SL} \approx \frac{h}{R}\frac{v_\theta}{\alpha v_\phi}}$$

This scaling exhibits all the boundary value problems we face, namely we need to correctly set *h* and v_θ. Using a Shakura-Sunyaev disk to set *T*,

$$\theta_{\rm SL} = 2\times 10^{-2} \alpha_3^{-1/2} M_1^{-5/8} R_9^{-1/8} \dot{M}_8^{11/20}$$

$$T_{\rm eff,SL} = 2\times 10^{5}\ {\rm K}\ \alpha_3^{1/8} M_1^{13/32} R_9^{-23/32} \dot{M}_8^{9/80}$$

What sets v_θ?

- Set T at equator using a Shakura-Sunyaev disk and then vary v_θ

- Plotted are v_θ for

  $M = 0.6 M_\odot$

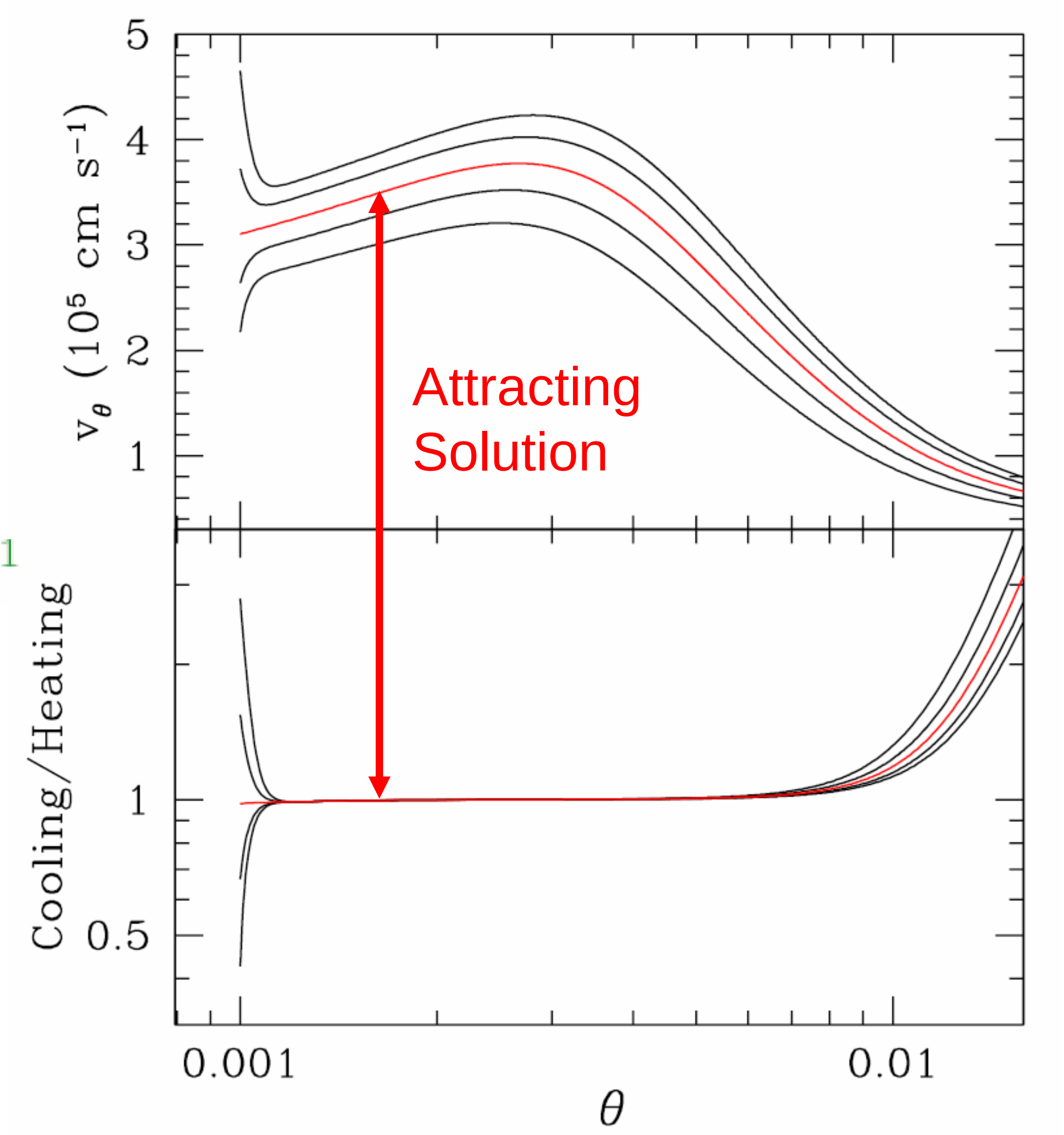
  $R = 9 \times 10^8$ cm

  $\dot{M} = 5 \times 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$

- Clearly there is a preferred velocity that the other curves asymptote to.

- This corresponds to

  Heating ~ Cooling



Attracting Solution

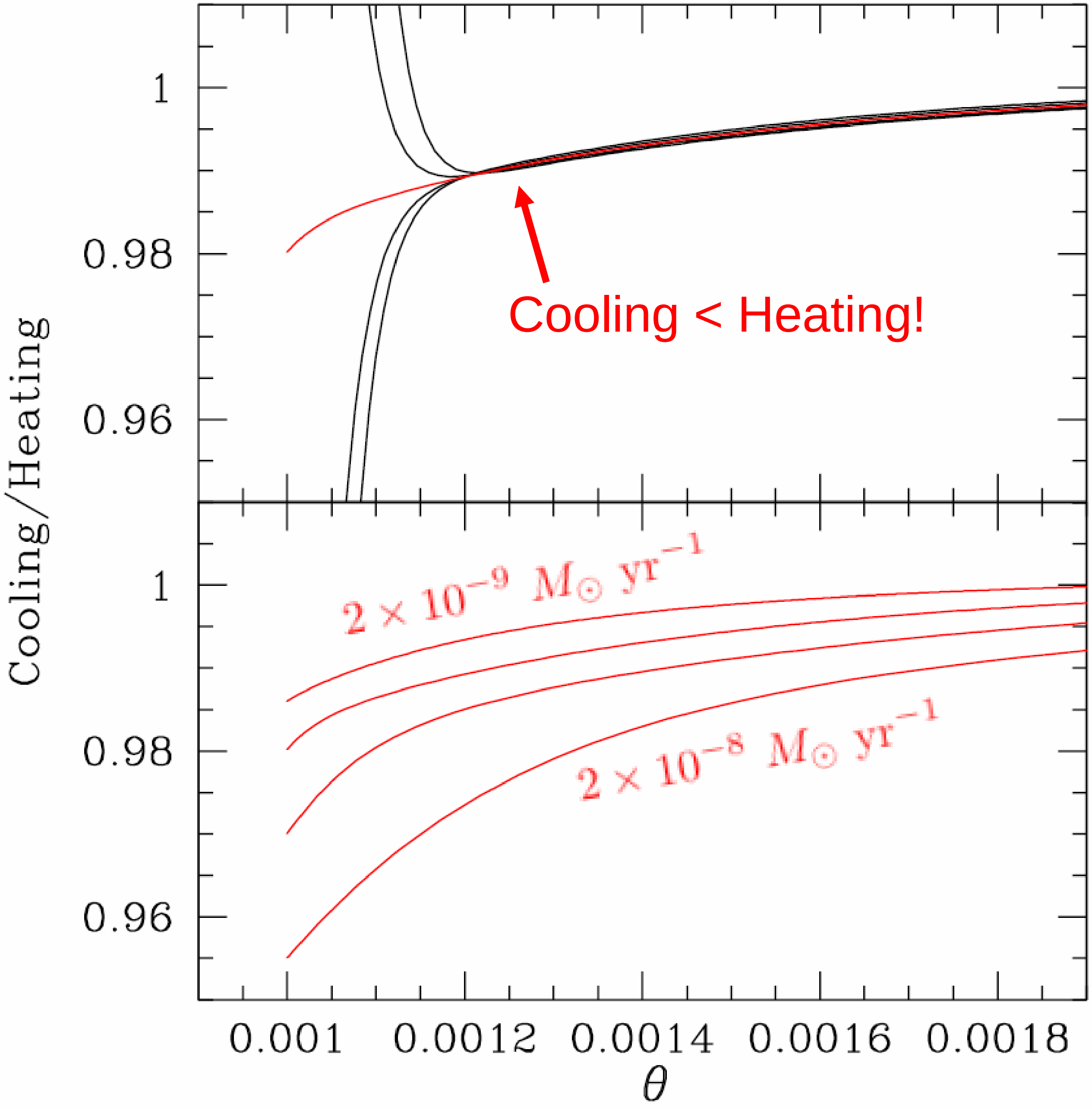
- Set T a
Shakura-
then vary
- Plotted

  $M =$

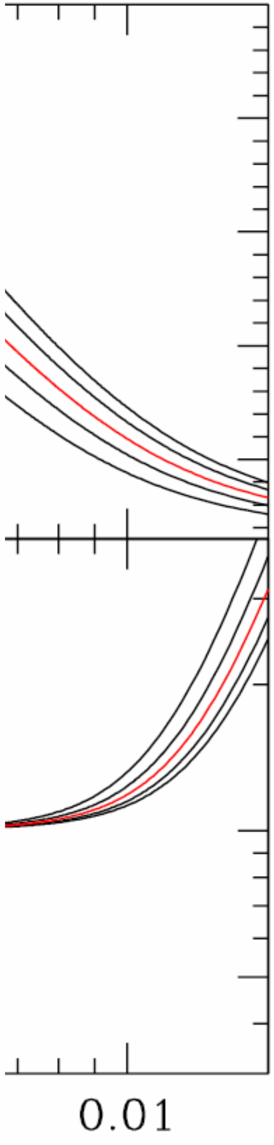
  $R = 9$

  $\dot{M} =$
- Clearly
preferre
other cu
- This c

  Heat



Cooling < Heating!

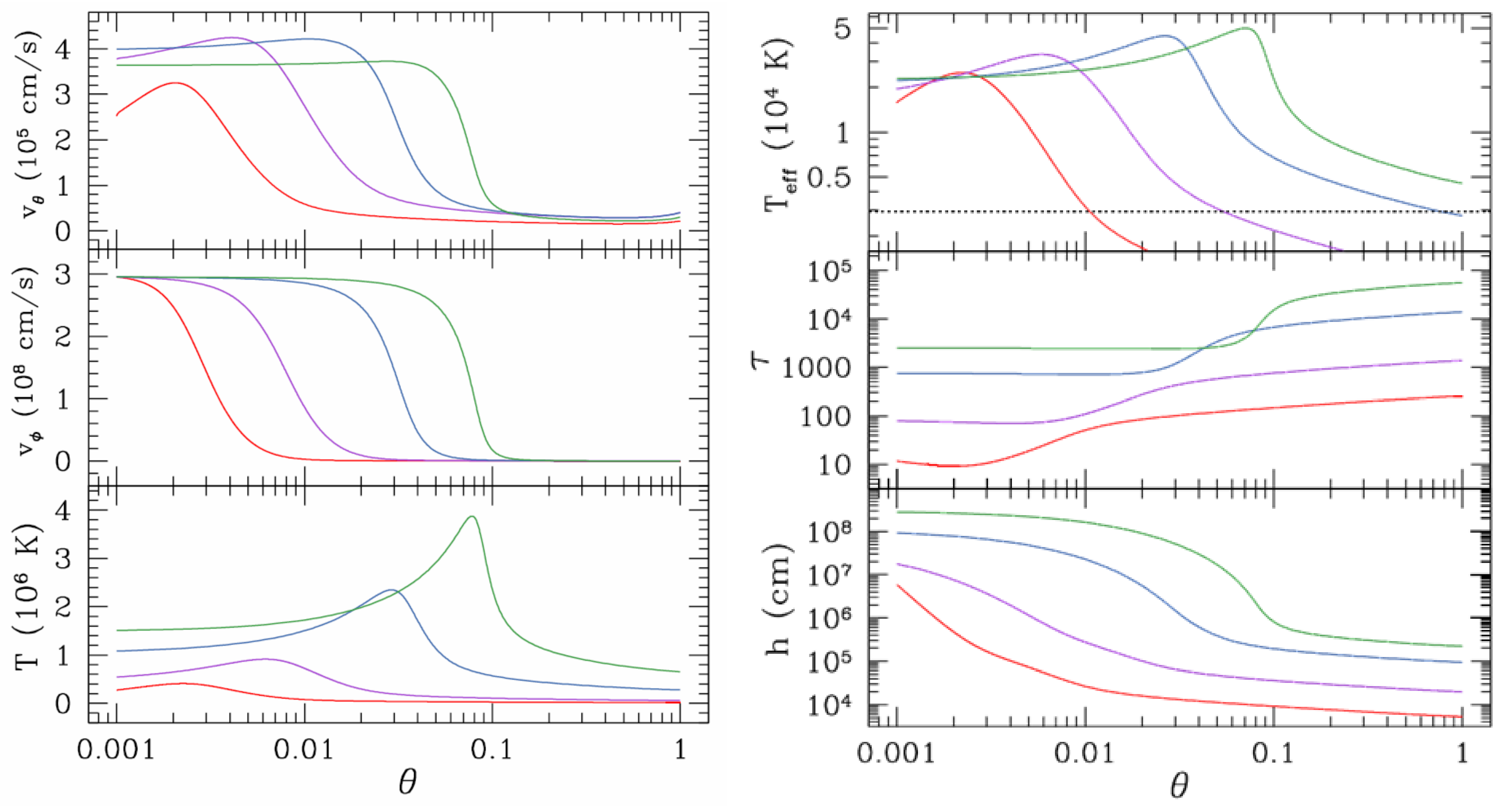


Numerical Calculations

$M = 0.6\ M_{\odot}$ $R = 9 \times 10^{8}$ cm $\alpha = 10^{-3}$

$2 \times 10^{-9}\ M_{\odot}\ \mathrm{yr}^{-1}$ $2 \times 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$

$2 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$ $5 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$



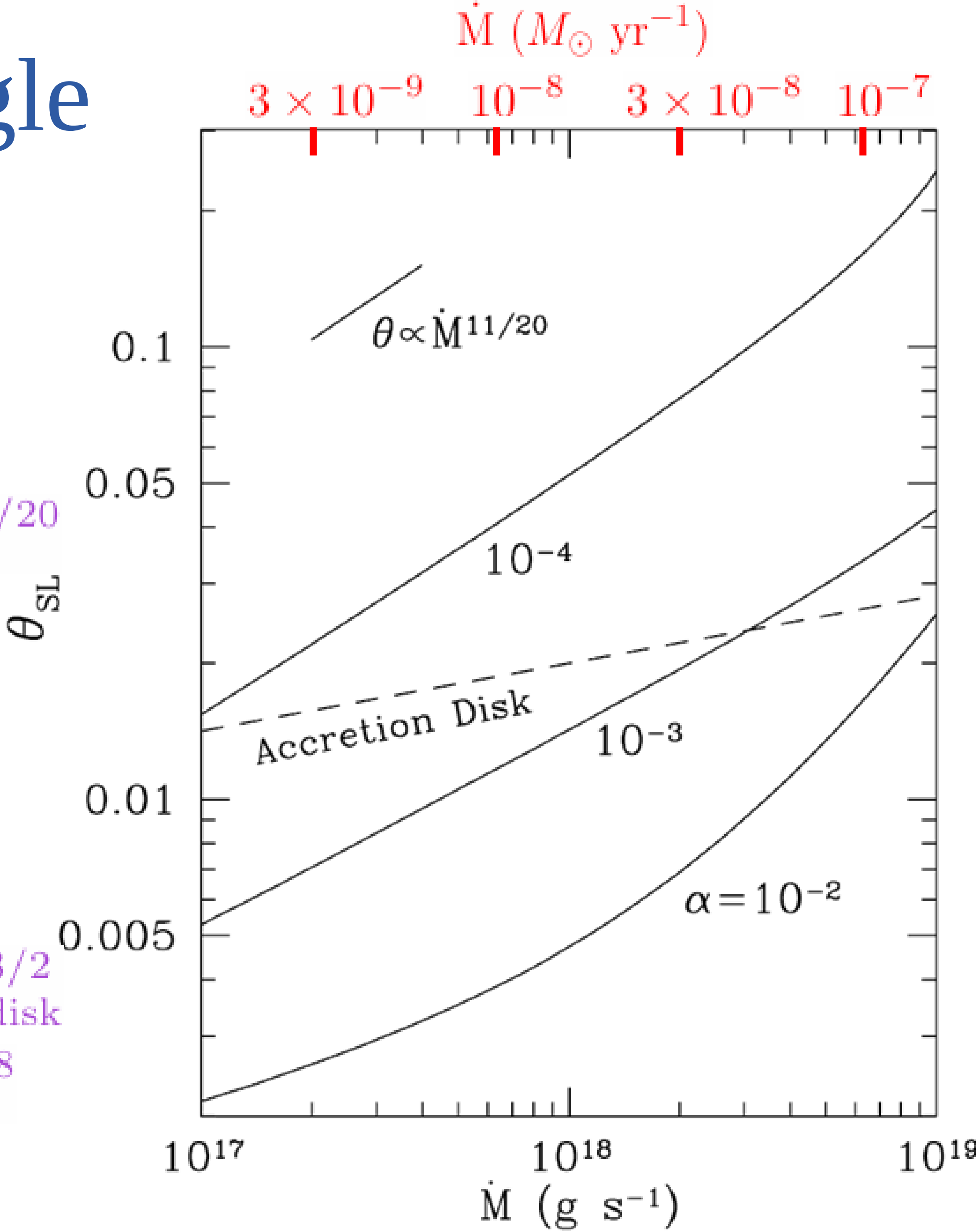
Spreading Angle

- Angle matches scaling predicted analytically

$$\theta_{\rm SL} = 2\times 10^{-2}\alpha_3^{-1/2} \times M_1^{-5/8} R_9^{-1/8} \dot{M}_8^{11/20}$$

- High accretion rate needed to extend above disk!

$$\dot{M}_{\rm crit} = 10^{-8}\ M_\odot\ {\rm yr}^{-1}\ \alpha_{\rm disk}^{3/2} \times \alpha_3^{5/4} M_1^{15/8} R_9^{5/8}$$



Summary of SL Properties

Need a high $\dot{M}$!

$$\dot{M} > 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$$

Possible systems

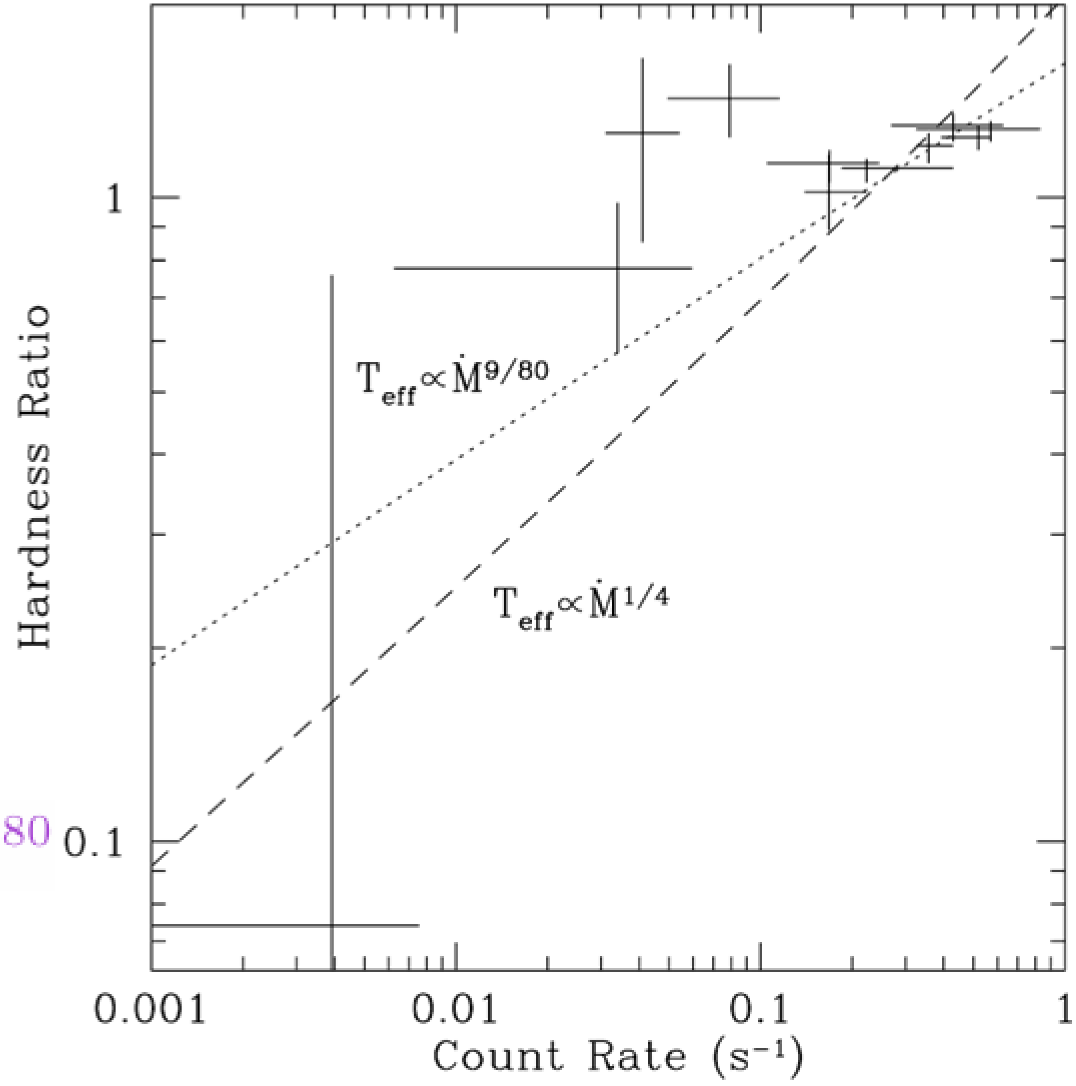
- Symbiotic Binaries
- Supersoft X-ray Sources
- Dwarf Novae

Shallow $T_\mathrm{eff} - \dot{M}$ scaling

$$T_\mathrm{eff} = 2 \times 10^5\ \mathrm{K}\ \alpha_3^{1/8} \times M_1^{13/32} R_9^{-23/32} \dot{M}^{9/80}$$

$$\boxed{T_\mathrm{eff} \propto \dot{M}^{9/80}}$$

SS Cyg; Wheatley, Mauche, & Mattei, 2003



Super-Solar Metallicities in Classical Novae

- Observational data indicate ejected material in CNe can be enriched in C, N, O, and Ne by >30% by mass (Livio & Truran '94; Gehrz et al. '98)

- Enrichment also needed to match fastest CNe (Truran '82)

How does this occur?

- Diffusion of H into underlying C/O causes burning to trigger in a diffusive tail? (Prialnik & Kovetz '84; Kovetz & Prialnik '85)

- Convective overshooting? (Woosley '86). Both 2-D (Glasner et al. '97; Kercek et al. 98) and 3-D (Kercek et al. '99) simulations

- Fluid instabilities leading to shear mixing? (Kippenhahn & Thomas '78; Fujimoto '88)

- Wave breaking between a quickly spinning H/He envelope shearing against the C/O core? (Alexakis et al. '04)

The Deeper Shearing Profile

SL is much shallower than CN ignition depth

$$10^3\ \mathrm{g\ cm^{-2}} << 10^{10}\ \mathrm{g\ cm^{-2}}$$

So AM is deposited at surface. Transferring AM in steady-state…

$$\alpha\rho v^2 4\pi R^2 R = \dot{M}\sqrt{GMR}$$

viscous stress area lever arm angular momentum per unit time

The velocity at the depth of the C/O core (CN ignition depth) is

$$\frac{v}{c_s} \approx 3\times10^{-6}\alpha^{-1/2}\dot{M}_8^{1/2}\left(\frac{y}{10^{10}\ \mathrm{g\ cm^{-2}}}\right)^{-1/2}$$

$$M = 0.6\ M_\odot \qquad R = 9\times10^8\ \mathrm{cm}$$

This implies $\alpha < 10^{-11}$ for a Mach number close to unity!

This is similar to an ion viscosity (Spitzer ‘65), but even a radiative or magnetic viscosity (Spruit ‘02) would rule this out. Perhaps our assumption of steady-state (throughout entire star) is incorrect (?)

Conclusions and Future Prospects

Important Properties of SL

- High $\dot{M}$ needed!
- Shows the differentially rotating profile on surface
    - Mode excitation? (Piro & Bildsten '04; Cumming '05)

Observational tests

- Shallow scaling $T_{\rm eff} \propto \dot{M}^{9/80}$
- Future modeling of emission area during DNe

The Deeper Shearing Profile

- Deep mixing between H/He and C/O needs further study
- Important first step toward understanding deeper AM transport (does this effect SNe Ia?, Yoon & Langer '04)