Numerical Simulations of the Spreading of Accreted Matter on Stars

By

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Plan of this talk

1) Overview of Binary Stars– Two competing models for boundary layers.

2) Numerical Setup – Ingredients of the model (specialized to WD accretion).

3) Movies and Science from Simulations.

4) Conclusions.

Overview : Binary Stars, Cataclysmic Variables

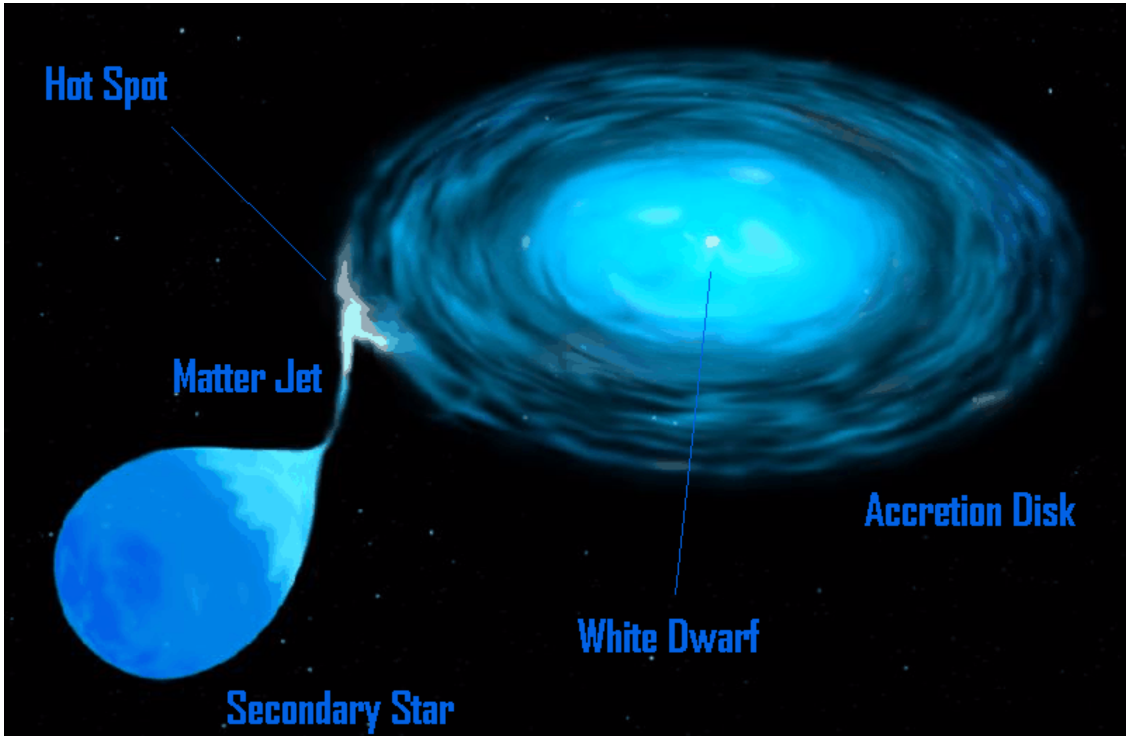
Close binary star system with primary WD and secondary MS/Red Giant star

Roche Lobe overflow

Excess orbital angular momentum forms accretion disk.

Matter drifts in via disk and accretes onto star.

Luminosity varies over 2-5 mag.(DN); 6-19 mag. (CN)



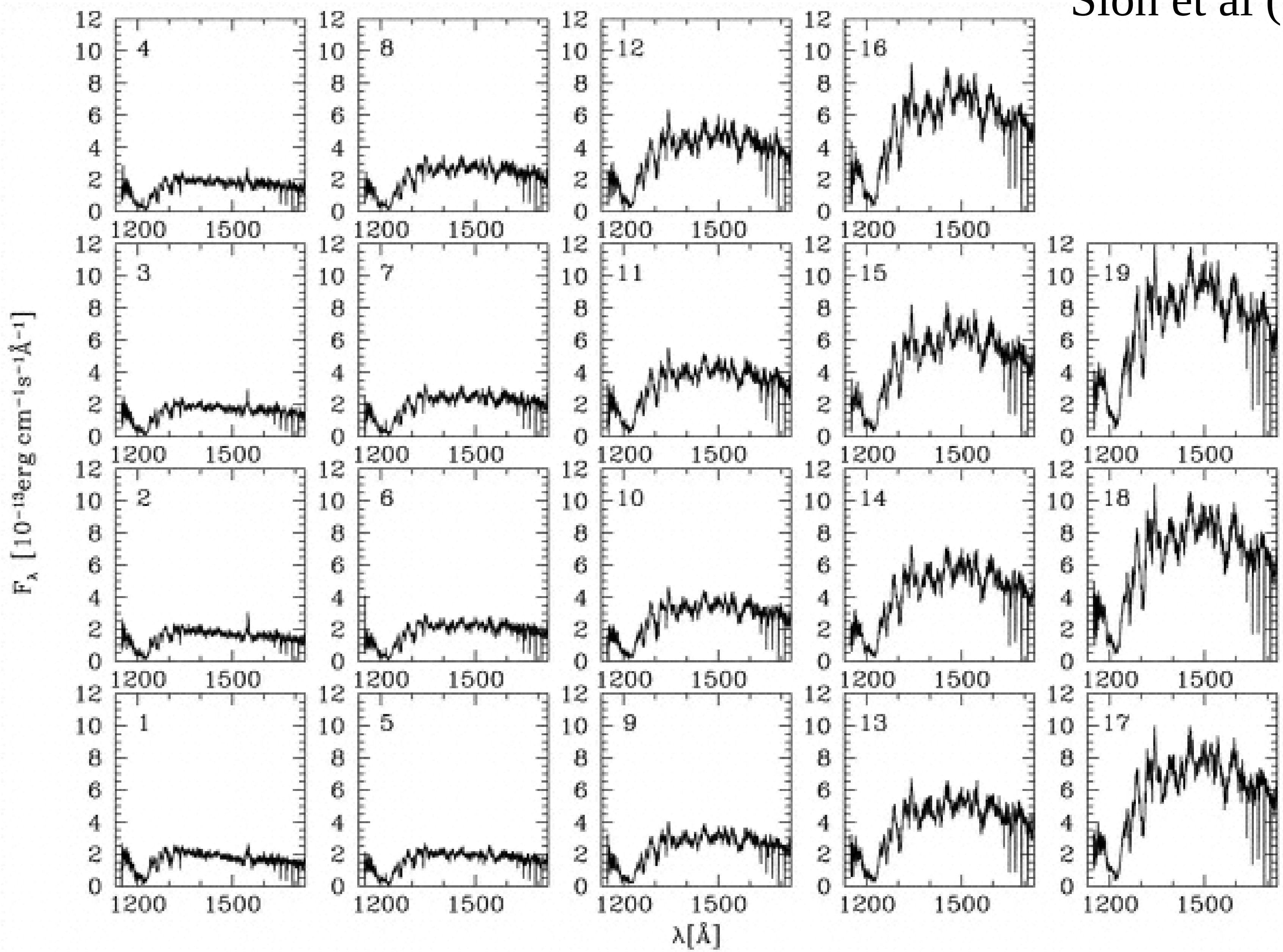
Orbital period : ~ 1 – 10 hrs.

Orbital separation : ~ 300,000 Km

Many Behaviors : CN, RN, DN, NL, IP, Polars

Caught In The Act : Onset of an Outburst in VW Hydri

Sion et al (2004)



Dwarf Novae:

Show recurrent 2-5 mag. outbursts. (disk thermal instability mechanism)

$\dot{m} = 10^{-11}\ M_\odot / yr$ to $\dot{m} = 10^{-8}\ M_\odot / yr$ (for days/weeks) $\dot{m}_{average} = 10^{-9}\ M_\odot / yr$

Scenario Being Explored:-

Episodes with high disk turbulence ➔ high α-viscosity ➔ high accretion rate ➔ outburst

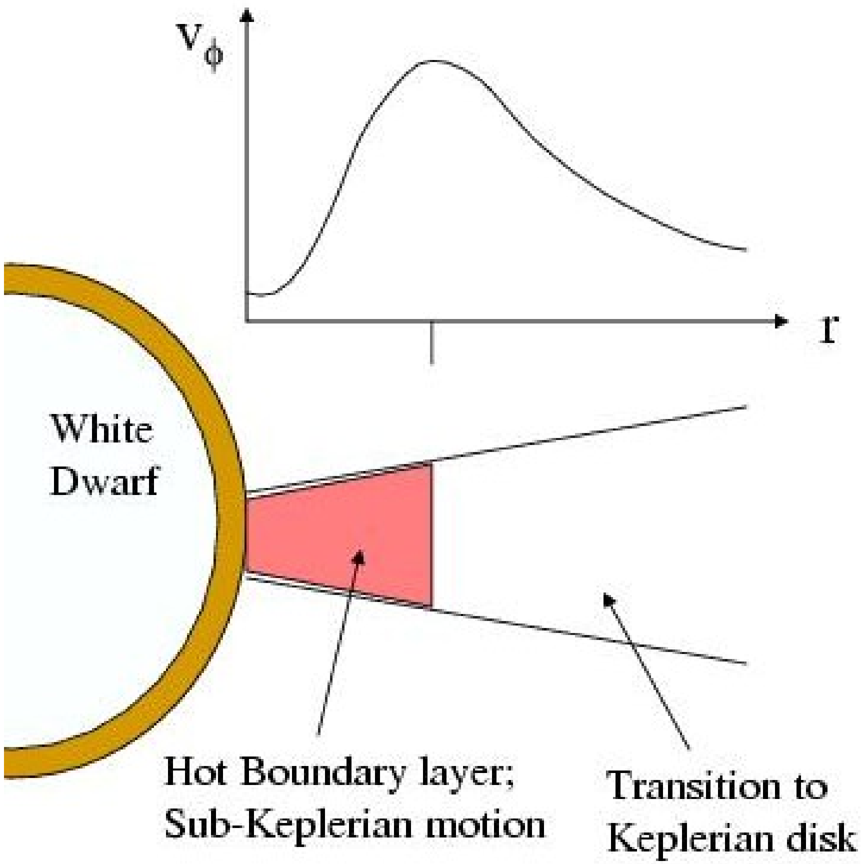
Episodes with low disk turbulence ➔ low α-viscosity ➔ low accretion rate ➔ quiescence

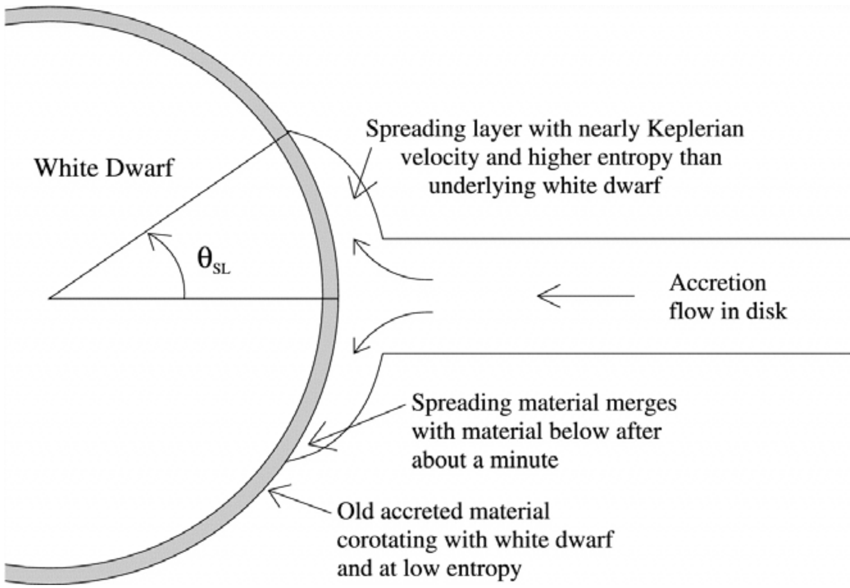
The rise time of outbursts can take a few minutes to ~ hour.

Once established, the outburst can have a duration of hours to days (maybe weeks) before the system returns to quiescence.

The data makes a very strong case for a hot belt of accreted matter around the star during outburst. Hence, we want to understand BL in quiescence and outburst.

Two competing models for Boundary Layer





Average in z; Solve structure in r	v/s	Average in r; Solve structure in θ
$V_z = 0$	v/s	V_z non-zero
Pringle (1981); Regev (1983); Popham & Narayan (1992, 1996)		Inogamov & Sunyaev (1999); Piro & Bildsten (2004)

Numerical Setup

Compressible Navier-Stokes Equns.

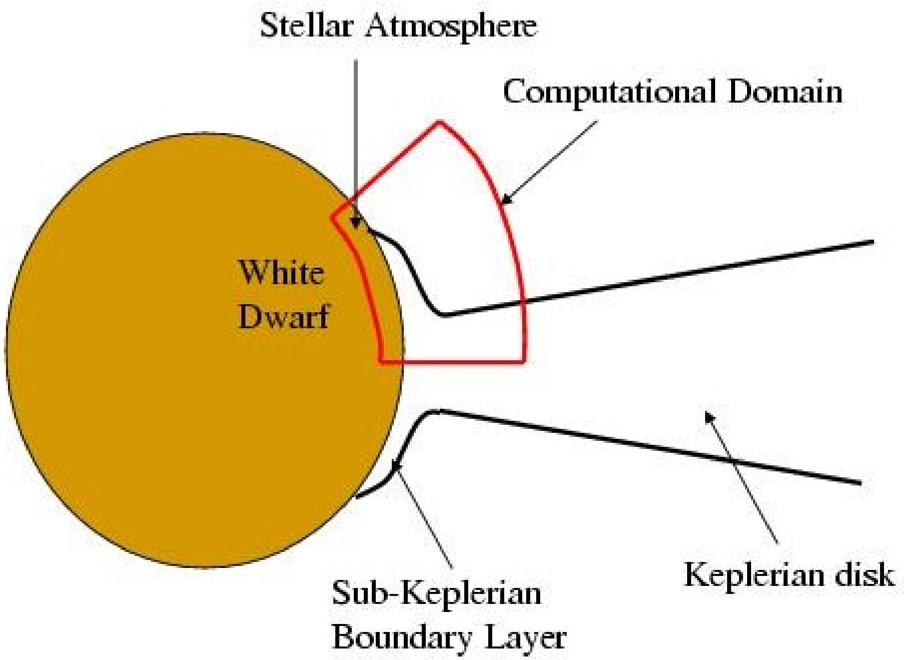
Ideal Gas with solar metallicity, $\gamma = 4/3$.

Second order in space and time hydro/MHD using the RIEMANN code.

Shear Forces are parametrized with an α-viscosity formulation.

Various values of α-viscosity used:
$\alpha = 0.1$ (outburst);
$\alpha = 0.03$; 0.01; 0.005 ;
$\alpha = 0.001$ (quiescence).

Done with & w/o viscous energy feedback – opt. thick & thin limits.



Retain several scale heights of stellar atmosphere/disk

0 to 30 degrees

Movies and Science from Simulations

Why Care about the Structure of the Boundary Layer?

1) Determines 50% of the accreted luminosity.

2) Heats the stellar atmosphere, possibly changing its spectrum. How efficiently? In what directions, r & z? (E.g. Why are magnetic accretors cooler than non-magnetic ones? Why are post-outburst DN hotter?)

3) Determines the most energetic part of the radiated spectrum.
(E.g. In DN : Disk radiates in optical/UV ; BL radiates in UV/X-rays.)

4) Spins-up of the star.

5) Causes turbulent mixing of elements at atmosphere / BL interface.
(E.g. Dredge up of CNO is important for Classical Novae.)

Log Density (with Poloidal Velocity Overlaid) :

Outburst (high α)

High mass accretion rate

Physically thick BL, comparable to disk scale height

Covers large fraction of star's surface

BL is also optically thick

Quiescence (low α)

Low mass accretion rate

Physically thin BL

Smaller fraction of surface covered

BL is optically thin.

Application to U Gem:-

Model suggests an explanation for U Gem during its transition to quiescence.

Many observations have shown a small, hot and slowly decaying continuum component and optically thin line-emitting region during quiescence.

The trends seen from $\alpha=0.1$ to $\alpha=0.001$ models would back up these observations.

Application to VW Hydri:-

The temperatures observed are much lower than the 10^8 K from Popham & Narayan. Multi-d accretion achieves this! Regev & Bertout (1995)

Log Pressure (two movies not on same scale):-

Outburst (high α) Quiescence (low α)

High pressure at base of disk Base of disk not at such hi pressure

Pressure gradient in θ direction drives flow on the surface.

Pressure higher because of:a)Viscous heating & b)Ram pressure by infall.

(The latter will still be present even in optically thin situations, driving BL formation.)

Poloidal Mach # (two movies on same scale) with Velocity Overlay:-

Outburst (high α) Quiescence (low α)

High Poloidal Mach #s in disk. Very sub-sonic Mach #

Hi Mach # partially extends to atmosphere.

Important for Kelvin Helmholz or Gravity wave instabilities.

Toroidal Velocity:-

Outburst (high α)

Significant part of disk decelerated near the equator

Comparable to disk scale height.

Substantial spin-up in atmosphere

Quiescence (low α)

Disk decelerated in narrow region.

Atmosphere not spun up too much.

Large fraction of star's surface has high shear – Imp. For WD modeling!

<u>Species Fraction (showing disk material):-</u>

Outburst (high α) Quiescence (low α)

Thick BL Thin BL

Notice formation of <u>Gravity Wave</u> No Gravity Waves

(could promote mixing at boundary; CNO dredge-up; Relevance to CN ejecta.)

Application to Classical Novae:-

Classical Novae can show an overabundance of CNO material in the ejected envelope.

CNO could come from convective dredge-up during runaway (Starrfield et al ’72).

Alternatively, it could happen before the Classical Nova due to shear mixing (Kippenhahn & Thomas ’78) or splashes from gravity waves (Rosner et al ’01, Alexakis et al ’04). These were local studies.

Our simulations have demonstrated the viability of turbulent instability induced mixing in a global simulation.

Conclusions

1) We have built models for boundary layer physics which have, at last, begun to show the expected trends in : density, temperature, rotation velocity, accretion rate, disk spin-down, atmospheric spin-up, optical depth etc.

2) Some of the observed trends in dwarf novae and their transition to quiescence can also be seen – application to U Gem & VW Hyi.

3) The models even reveal the possibility of new instabilities that may promote turbulent mixing – relevance for classical novae.

4) The models can be used to explore the Boundary Layer physics for various accreting systems: WD, NS, proto-stars.

5) Inclusion of more physics, B-fields (MRI), radiative transfer, on the way.